Survey of Juno Observations in Jupiter’s Plasma Disk: Density

E. Huscher1, F. Bagenal1, R. J. Wilson1, F. Allegrini2,3, R. W. Ebert2,3, P. W. Valek2,3, J. R. Szalay4, D. J. McComas4, J. E. P. Connerney4,6, S. Bolton4, and S. M. Levin7

1Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA, 2Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, USA, 3Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA, 4Space Research Corporation, Annapolis, MD, USA, 5Goddard Space Flight Center, Greenbelt, MD, USA, 6Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, USA

Abstract We explore the variation in plasma conditions through the middle magnetosphere of Jupiter with latitude and radial distance using Juno-JADE measurements of plasma density (electrons, protons, sulfur, and oxygen ions) surveyed on Orbits 5–26 between March 2017 and April 2020. On most orbits, the densities exhibit regular behavior, mapping out a disk between 10 and 50 R$_J$ (Jovian radii). In the disk, the heavy ions are confined close to the centrifugal equator which oscillates relative to the spacecraft due to the ~10$^\circ$ tilt of Jupiter’s magnetic dipole. Exploring each crossing of the plasma disk shows there are some occasions where the density profiles are smooth and well-defined. At other times, small-scale structures suggest temporal and/or spatial variabilities. There are some exceptional orbits where the outer regions (30–50 R$_J$) of the plasma disk show uniform depletion, perhaps due to enhanced ejection of plasmoids down the magnetotail, possibly triggered by solar wind compression events.

1. Introduction

The strong planetary magnetic field of Jupiter makes the magnetosphere the largest object within the heliosphere (e.g., reviewed by Bagenal, 2013). The Jovian magnetosphere extends toward the Sun for typical distances of 63–92 R$_J$ (where the radius of Jupiter, R$_J$ = 71,492 km) with the magnetopause location varying over time in response to solar wind pressure (Joy et al., 2002). Io’s SO$_2$ atmosphere escapes the moon at a rate of over a ton/second. Neutral material that escapes is then dissociated, ionized, and trapped in the planet’s magnetic field. The dense plasma (~2,000 particles/cm$^3$) in Io’s torus corotates with Jupiter’s ~10 h spin period. Ions of sulfur and oxygen (with ion temperatures $T_i \sim 100$ eV) are excited by electrons (electron temperatures $T_e \sim 5$ eV) and radiate UV emission (~1.5 terawatts). Contrary to the expectation that the plasma would cool on expansion, the ionogenic plasma is heated to temperatures of ~10 s keV as flux tube interchange motions transport the plasma radially outwards over time scales of weeks. The magnetospheric plasma is coupled to Jupiter’s rotating atmosphere with rotation dominating the dynamics of the magnetosphere. The ensuing strong centrifugal forces produce an extended, equatorially confined plasma disk. The electrical currents that couple the magnetospheric and ionospheric plasmas control the intense auroral emissions that span the spectrum from X-rays to radio, peaking in the ultraviolet. The hot plasma in Jupiter’s plasma disk inflates the magnetosphere, making it ~2X larger and more compressible than a system in which the magnetic field is purely due to a dipole. The early flybys of the Jupiter system (Pioneers 10 & 11, Voyagers 1 & 2, Ulysses missions) provided a clear sense of the scale of the magnetosphere, as well as the basic disk-like structure. Galileo was the first spacecraft to orbit Jupiter and in 34 orbits from 1995 to 2003 mapped out the general magnetosphere structure and began to investigate the plasma and magnetic field interactions with the moons.

Dessler’s (1983) presents the pre-Galileo understanding of Jupiter’s magnetosphere. Advances made by the Ulysses and Galileo missions are reviewed in chapters of Jupiter: The Planet, Satellites, and Magnetosphere (edited by Bagenal et al., 2004). Overviews of the structure and dynamics of Jupiter’s magnetosphere are presented by Khurana et al. (2004), Krupp et al. (2004), and more recently by Bagenal et al. (2017) which also outlines the magnetospheric goals of NASA’s Juno mission.
The Juno spacecraft has been orbiting Jupiter since July 2016. This study provides a preliminary survey of ~4 years of plasma data obtained by the Jovian Auroral Distributions Experiment (JADE) instrument (McComas et al., 2017) on the Juno spacecraft through Orbit 26 (April 2020). We focus on measurements of density (electrons, protons, and heavy ions of sulfur and oxygen) in the plasma disk between 10 and 50 \( R_J \). The recent study by Connerney et al. (2020) fits Juno data with a current sheet that extends from 7.8 to 51 \( R_J \) with a vertical half-thickness of 3.6 \( R_J \). We note that it is traditional to use the term “sheet” for the equatorial structure associated with the azimuthal and radial currents that flow in the magnetosphere. The plasma density in the inner/middle magnetosphere has a similar vertical spread with a scale height of 3–4 \( R_J \) (Bagenal & Delamere, 2011) but the presence of hot populations of ions off the equator, particularly farther from the planet (Kim et al., 2020b), spreads out the plasma vertically, and makes the term “disk” more appropriate for the plasma.

In Section 2 of this study, we describe the data we have selected to analyze. In Section 3, we describe the density structure of the plasma disk, which is compared to previous studies in Section 4. In Section 5, we summarize our conclusions.

### 2. Juno Plasma Disk Data

NASA’s Juno spacecraft entered the Jupiter system in July of 2016. Juno carries two instrument suites that make in-situ measurements of charged particles as well as two instruments that measure electric and/or magnetic fields. These instruments map out the plasma conditions in Jupiter’s magnetosphere.

#### 2.1. Spacecraft Trajectory

Juno was inserted into a highly inclined and elliptical 53-days orbit with an apojove of ~110 \( R_J \) and a peri­jove as close as 3,500 km over the cloud tops (i.e., 1 bar level) or 1.05 \( R_J \) from the center of Jupiter. The spacecraft speed is nearly 60 km/s at perijove, with Juno taking only ~2 h to pass from pole to pole. This eccentric orbital trajectory was designed to neatly pass the spacecraft between Jupiter’s upper atmosphere and the extreme radiation belts (Bolton et al., 2017). In this way, Juno both avoids atmospheric drag and protects the instruments from the most intense areas of radiation. Due to the oblateness of Jupiter, Juno’s polar orbit precesses with its semimajor axis tilting increasingly southwards, bringing the location where the spacecraft crosses the jovigraphic equator during the inbound trajectory closer to the planet with each orbit.

We focus in this study on data taken in the inbound leg of Orbits 5 to 26 from 50 to 10 \( R_J \) where Juno made multiple crossings of the plasma disk between March 2017 and April 2020. In Figure 1, we show Orbits 5 through 26 in jovigraphic coordinates (cylindrical \( \rho \) and \( z \)) with relation to the four Galilean moons at the spin equator. This figure illustrates that Juno was far from the plasma disk on the outbound legs where the particle fluxes are significantly lower. Hence, we focus on the inbound leg of the trajectory in this study. In the four years since orbit insertion, Jupiter has moved roughly a third of its orbit around the Sun so that the apojove of Juno’s orbit has evolved in local time from dawn through midnight. The Orbits 5–26 studied in this study cover 04:00 to 22:00 h in local time.

#### 2.2. Instruments

The JADE takes in-situ measurements of electrons (JADE-E) and ions (JADE-I) (McComas et al., 2017). The JADE instrument includes three electron sensors designed to measure energies from ~0.1 to 100 keV, each separated by a 120° viewing angle. One of these three sensors was turned off due to a high voltage op-to-coupler malfunction, but the primary science is largely unhindered with two healthy sensors to take electron data. JADE also includes a single-ion sensor designed to measure energies from ~10 eV to ~46 keV/q. The measured energy resolution (\( \Delta E/E \)) of JADE-E has a minimum of 10.4% and a maximum of 13.2% and JADE-I has an energy resolution of 18%–28%. The Juno spacecraft spins about an axis perpendicular to the solar panels every 30 s.

JADE-I uses a Time of Flight (TOF) spectrometer to determine the mass/charge of the incident ions. JADE-I has a mass resolution of \( M/\Delta M > 5 \) and can measure up to 64 amu/q. The mass resolution can vary in practice because ions that enter the JADE-I TOF section pass through an ultrathin carbon foil.
Secondary electrons are liberated from the carbon foil, and are accelerated toward the detector to begin the timing window. The incident ion's energy and direction are modified as it passes through the carbon foil. The magnitude of the change depends on the incident ion's energy and mass. These carbon foil effects result in a nonconstant mass resolution across the measurement range of JADE-I. See Allegrini et al. (2016) for how carbon foils impact the incident ions, and Kim et al. (2020a) for a detailed discussion of the JADE-I TOF section, including the carbon foil effects. Due to telemetry limitations, the high mass resolution data are collapsed in angular space. The high spatial resolution data used here are bundled into mass ranges of protons, light ions (2–5 amu/q), and heavy ions (>5 amu/q). See Section 3.4.

These energy ranges are extended by the energetic particle detector on Juno, the Jupiter Energetic Particle Detector Instrument (JEDI), which measures electrons and ions at higher energies for a more complete picture of the plasma environment (Mauk et al., 2017). The local electron density can also be measured sometimes via detection of plasma waves measured by Juno’s Waves instrument (Kurth et al., 2017). Comparing measurements from the different instruments is valuable for cross-calibrations. The magnetometer on Juno consists of two triaxial fluxgate sensors located at the end of one of the three 8.9-m-long solar panels (Connerney et al., 2017).

2.3. Analysis of JADE Data via Numerical Moments

The plasma densities used in this study are derived by taking numerical moments of the JADE data. The product of geometric factor and efficiency used to convert the data from counts/second to distribution function for moments calculations are provided as equation E2 of Kim et al. (2020a). For a velocity distribution function \( f(v) \), the number density is given by the zeroth order moment (e.g., Equation 6.2 of Paschmann & Daly. 1998).

\[ n = \int f(v) \, dv \]

This technique uses weighted flux summations over velocity and direction. Standard procedures involve background removal and the spacecraft potential is assumed to be zero. The electron moments are one-dimensional (1D) (assuming an isotropic velocity distribution) and the ion moments are three-dimensional. The ions comprise protons plus a single heavy species which we assume to have an atomic mass-to-charge
The uncertainties (sigma) for the JADE particle density are based on the uncertainties provided in input level 3 data that are then propagated through the numerical moment equations. The data uncertainties include a term from Poisson statistics of the total counts, a term accounting for the lossy-compression used in transmission of the data back to Earth from two or four byte values to one byte, as well as terms for the uncertainty in the background signal that has been removed from the data. The electron error percentage is generally significantly lower due to higher fluxes of (lighter) electrons relative to (heavier) ions. The electron moments are also 1D, a mean over all 48 look directions in low-rate science, which reduces uncertainties. By comparison, the low-rate science ion moments are three-dimensional (3D) over 78 look directions, the majority of which do not see significant signal. Low count bins with high proportional uncertainties increase the moments uncertainty to make the uncertainties for the 3D ions much larger than uncertainties for the higher flux 1D electrons. While one might consider alternative data processing techniques (such as summing or averaging over longer time intervals) we chose to limit the processing for this preliminary survey of plasma densities. Future studies should involve more the sophisticated approach of forward fitting the energy distributions of each species and full error analysis of the derived parameters (temperature and flow speed as well as density).

In the radial profiles and zoomed-in crossings (Figures 2–5), we filter out noisy lower-quality data to focus on the data with higher confidence. We chose to omit electron data with a sigma greater than 10% and ion data with a sigma greater than 1,000% of the derived density. To pick these filtering factors, we plotted sample orbits with different factors and selected the factor that showed clear plasma disk signatures. In some orbits, filtering with this error threshold leaves distinct gaps between each plasma disk crossing and in others the data remain continuous.
The JADE-E (electrons), JADE-I (ions), and magnetometer sensors operate independently and therefore produce data sets with different cadences. Juno’s location, as well as the operational status of the spacecraft and instruments, influence the data collection rates at any specific time. We take the ion data and select the nearest electron and magnetometer data within 30 s of the ion records.

**Figure 3.** Same as Figure 2 for Orbit 19, spanning April 2–6, 2019. The white gap in the spectrogram at 37 $R_J$ is a pause in data collection from an engineering calibration.

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**Figure 4.** Radial inbound density ($n$) for Orbits 5–26, spanning March 2017 to April 2020. Electrons are filtered out above 10% uncertainty (sigma > 0.10$n$); protons and heavy ions are filtered out above 1,000% uncertainty (sigma > 10$n$). The right-hand axes for the middle and bottom panels shows the vertical displacement of the spacecraft from the centrifugal equator (Phipps & Bagenal, 2021) as shown by the thin gray lines in the plots.
3. Plasma Disk Density Structure

The main purpose of this study is to survey the structure of Jupiter’s plasma disk as shown by JADE measurements of plasma density on the first 26 orbits. We derive an average density structure and explore significant temporal and spatial variabilities.

3.1. Example Inbound Passes

Figures 2 and 3 show inbound radial profiles for Orbits 6 and 19, respectively. Spanning a distance of 10–50 $R_J$, these plots provide a broad view of the plasma disk from around the orbit of Europa, through the middle magnetosphere ($\sim$10–25 $R_J$), and into the outer magnetosphere ($\sim$25–50 $R_J$). For comparison, we show the densities derived from the numerical moments (middle panel) alongside the count rates from each TOF energy bin (top panel). The intervals where JADE is in high-rate science mode, recording a data point every second for electrons and every two seconds for ions, is indicated by a thicker purple line at the top of the middle panel. JADE is most often in low-rate science mode, collecting a data point every 30 s (≈1 spin period) or multiples of 30 s (e.g., 60, 120, 300, or 600 s). The bottom panel shows the three components of the magnetic field vector. These two orbits were chosen because the densities of the heavy ions remained primarily inside JADE’s energy range, allowing for more accurate density measurements.

In a rotation-dominated magnetosphere such as at Jupiter, we expect the plasma to be centered around the farthest point along the magnetic field from the spin axis—the centrifugal equator (Hill et al., 1974). For a tilted dipole, the centrifugal equator is located at $\sim$2/3 of the tilt of the magnetic equator from the jovigraphic equator. This dipole approximation works well within the Io plasma torus ($5–10 R_J$). Farther out, the effect of the current sheet (aligned with the magnetic equator) is to stretch the field lines and make the centrifugal equator align with the magnetic equator. In this study, we employ a hyperbolic tangent function...
developed by Phipps and Bagenal (2021) to attain a more accurate centrifugal equator inside 20 R_J, smoothly transitioning from a plane with a tilt of 2/3 that of the magnetic dipole to one aligned with the magnetic equator. This function produces a vertical separation between the equators up to a maximum of ~0.4 R_J at 10 R_J from Jupiter and aligns the centrifugal equator exactly with the magnetic equator outside 20 R_J. The dashed horizontal lines denote the centrifugal equator and a gray curve represents the vertical displacement of the spacecraft from this equator.

On the right side of the middle and bottom panels of Figures 2 and 3, there is a y-axis scale for vertical height of the spacecraft with respect to the Phipps and Bagenal (2021) centrifugal equator at the time of the JADE measurements. The density is expected to peak when the spacecraft crosses the equator so that vertical lines through locations of equator crossings should align with the density peaks.

Figure 2 shows JADE data on the inbound leg of Orbit 6 with 10 peaks in density and TOF count rates, the inner-most and outer-most peaks being partly truncated. The outer five peaks are double-peaked due to the spacecraft fully crossing the plasma disk and then returning back through from the other direction. The locations of the peak density occur approximately when the spacecraft crosses the equator (as illustrated in the middle panel by the intersection of the thin gray lines with the horizontal dashed line of the centrifugal location of the peak density occur approximately when the spacecraft crosses the equator (as illustrated in the middle panel by the intersection of the thin gray lines with the horizontal dashed line of the centrifugal equator). Inside ~35 R_J, the spacecraft only approached the plasma disk without crossing it, producing a distinct single peak. The bottom panel shows the magnetic field components in spherical coordinates. Inside ~15 R_J the field is largely dipolar, dominated by the radial component B_r, a moderate latitudinal component B_\theta and negligible azimuthal component B_\phi. Farther out, the equatorial current sheet affects the field geometry with diminishing B_\theta, small B_\phi (due to the radial current in the current sheet) and the sign of B_r flipping when the spacecraft crosses the current sheet. This general morphology of the current sheet is consistent with the model of Connerney et al. (2020). Any radial displacement of the current sheet crossings from the model (illustrated by the gray lines crossing the centrifugal/magnetic equator) indicates the temporal and/or spatial variability of the current sheet, mostly occurring beyond ~30 R_J.

Between disk crossings the plasma density is low. Within the plasma disk the protons remain fairly constant while the heavy ions are closely confined to the equator (most clearly illustrated in Figure 3), consistent with plasma observations by Voyager (McNutt et al., 1981), Galileo (Bagenal et al., 2016), and in the Juno TOF data analyzed by Kim et al. (2020a, 2020b). At the center of the disk protons comprise ~10% of the ion density, increasing in fractional contribution with distance from the center of the disk.

By the time of PJ19 shown in Figure 3 (April 2019), Juno’s orbit has precessed downward so that the spacecraft crosses the centrifugal equator as close as 17 R_J from Jupiter and most of the plasma disk crossings show double peaks. The minimum plasma density off the equator is about 5 \times 10^{-3} \text{ cm}^{-3} and remains detectable throughout the inbound leg. Similar plots to Figures 2 and 3 for all inbound passes from PJ5 to PJ26 are shown in the online Supporting Information.

### 3.2. Global Overview

In Figure 4, we combine the radial density profiles of Orbits 5–26. This gives a good overview of temporal and spatial variability of the plasma disk structure. As with Figures 2 and 3, the periods of high-rate JADE-I data are shown with thicker purple lines at the top of each plot and the light gray lines show the spacecraft height off the centrifugal equator. As Juno’s orbit evolves (Figure 1), the plasma disk crossings on these inbound legs change. Initially there are full (double) crossings farther out and the spacecraft only approaching the disk from above closer in. Later, the spacecraft only approaches the disk from below farther out with full (double) crossings closer in. After orbit 8 only rarely do the densities drop below the 10^{-3} \text{ cm}^{-3} selection threshold. We expect the low densities to return as the orbit precesses farther south later in the mission.

Throughout these orbits the peaks in plasma density coincide well with crossing or approaching the centrifugal equator (same as the magnetic equator beyond ~20 R_J). There are some orbits where the plasma disk is particularly well-ordered. PJ6 and PJ19 were chosen as best examples for Figures 2 and 3, but good examples of ordered behavior are also PJ5, 7, 8, 14, 16, 17, and 25. Conversely, there are examples where the density is uniformly low: PJ5 12 and 26. Then there are cases that are hard to characterize except as highly structured: PJ5 20–24. On either side of the particularly uniformly low-density case of PJ12, there are peaks...
corresponding to plasma disk crossings but the densities are lower than usual. We discuss the implications of these variabilities in Section 4.

3.3. Individual Crossings

Figure 5 shows four individual plasma disk crossings from different orbits (Orbits 14, 15, 16, and 8), zoomed-in for closer analysis. As shown in Figure 4, during these plasma disk crossings the spacecraft moves only ~1–2 $R_J$ in radial distance but the flapping of the plasma disk over the spacecraft (due to the tilt of Jupiter's magnetic dipole from the planetary spin axis) means that the variation with time is mostly due to passing vertically through the plasma disk.

We find that a majority of the crossings show the heavy ions closely confined to the centrifugal equator. With a lower mass, protons tend to have a larger scale height and therefore often have flatter curves. The electron densities are roughly consistent with charge neutrality. With particle density data plotted against radial distance, a Gaussian function was fit to the density profile each time Juno passed through the plasma disk to quantify the disk structure. We use the standard form of the Gaussian function.

$$\text{Gaussian: } n(r) = a \exp\left(-\frac{(r-b)^2}{2c^2}\right)$$

where $r$ is radial distance, $a$ is the peak particle density, $b$ is the radial distance where the peak density is located, and $c$ is the width of the curve. Deviations of the measured densities from this idealized curve suggest small and/or irregular structures. The primary purpose of these fits is to obtain the location and value of the peak densities.

For each individual crossing of the plasma disk, a separate Gaussian curve was fit to the electron density, the proton density, and the heavy ion density. With the 95 best fits, we record the peak densities, radial distances from the planet, and height of the spacecraft from the model centrifugal equator. Figure 5 shows four typical crossings. We analyze these crossings for unique features, and organize them subjectively into three categories: (a) "smooth" crossings, which tend to have good fits for the electrons, protons, and heavy ions, but have minimal structure above or below the fitted curve. These curves can be wide (Figures 5a and 5b) or narrow (Figure 5c); (b) structured crossings, where gaps and/or irregularities are present making it difficult to fit Gaussian curves to these crossings and they are therefore omitted from further analysis; and (c) crossings, where fits are generally good but there is notable structure in the density profile in the form of blobs of plasma protruding above the Gaussian curve (Figure 5d). We note that the magnetic field strength is much lower for this crossing, perhaps related to the irregular structure in the density profile.

While we are not presenting temperatures in this study, we note that often the times that the densities protrude above a smooth curve correspond to times of a dip in temperature, consistent with similar "cold blob" features seen in Voyager data (Dougherty et al., 2017; McNutt et al., 1981).

To summarize, we define four groups of crossings used in this study:

**Set 1** As represented in Table S1, is the complete group of 198 crossings with which we obtained a Gaussian fit to the radial heavy ion densities.

**Set 2** As shown in Figure 7, is defined as the 167 crossings where we were able to obtain a Gaussian fit to the radial heavy ion densities and that also exhibited a distinct flip in the sign of the magnetic field's radial component within 2 $R_J$ of the peak heavy ion density.

**Set 3** As shown in Figure 6a, is defined as the 86 crossings where we obtained the best Gaussian fits to the radial heavy ion densities out of all crossings observed in Orbits 5–26. These crossings tend to have less structure and the most clearly defined peaks.

**Set 4** As shown in Figure 6b, is defined as the 50 crossings where we obtained a scale height measurement by taking the difference of Juno's centrifugal distance at peak density and at 1/e peak density. Of these 50, 14 crossings ("best") had the Juno trajectory passing entirely through the centrifugal equator. The other 36 crossings ("moderate") either skimmed the centrifugal equator or only just passed through before returning back.
3.4. Heavy Ion Composition

Conversion of ion density to charge density depends on the assumption of the ion charge state. In the Jupiter system, there are factors that complicate the procedure of determining ion density from numerical moments. There are multiple ion species with different mass-to-charge ratios ($M/Q$) that are not easily distinguished. While protons ($M/Q = 1$) are easily separated from heavy ions, the known range of heavy ions ($O^{++}, S^{++}, O^+, S^+, \text{and} S^+$) spans a range of a factor of 4 from $M/Q = 8$ to $M/Q = 32$ which are not separated by most plasma measurements. Moreover, the fact that the dominant two ion species in the Io plasma torus and the Jovian plasma disk ($O^+\text{,} S^{++}$) have the same $M/Q = 16$ adds to the challenge. Early analysis of Voyager plasma data relied on assuming the heavy ions all had the same temperature in the few places where the plasma was cold enough to produce separate $M/Q$ peaks (Bagenal & Sullivan, 1981; McNutt et al., 1981). Later analysis of both the Voyager and Galileo data sets (Bagenal et al., 2016; Dougherty et al., 2017) assumed that the composition were determined by the physical chemistry processes in the Io plasma torus and that as the density dropped (e.g., beyond $\sim 10 R_J$), the chemical interactions between species ceases and the composition of the heavy ions were set (Delamere et al., 2005).

Part of the Juno-JADE instrument suite is the TOF instrument that is able to measure ion composition as a function of mass per charge (McComas et al., 2017). Kim et al. (2020a) demonstrated that the TOF instrument was able to separate $O^+$ and $S^{++}$ ions in the magnetosphere of Jupiter. Furthermore, Kim et al. (2020b) presented a survey of the ion composition, density and temperature between 10 and 50 $R_J$, finding that the composition was largely consistent with Voyager and the physical chemistry models, but showed significant variability (factors 2–5) in the density ratio of $O^+/S^{++}$ species with space and time. Analysis of the basic density structure presented in this study is not particularly sensitive to assumptions of composition ($M/Q \sim 16$ is sufficient) for the heavy ions, but forward fitting that includes local measurements of composition from JADE-TOF would refine the plasma parameters presented here.

The best way to calibrate such conversion of ion density to positive charge density is to compare with an independent measure of electron density, for example, via a wave cut-off frequency as measured by field
sensors. This was the approach taken by Bagenal et al. (2016) in analysis of the Galileo PLS and PWS data where an average ion charge state of 1.5 produced a good match between in-situ plasma data and wave data. Comparisons of charge density derived from Juno JADE and Waves data awaits better determination of density via forward fitting of the JADE spectra.

3.5. Radial Profiles of Charge Density

In Figure 6a, we show the radial location of heavy ion peak densities for each of the 86 clean crossings in Set 3. The heavy ion densities are multiplied by 1.5 to produce an effective charge density. As we discuss in the previous section, this factor of 1.5 is based on several factors and should be treated as a “rule-of-thumb” rather than a well-determined number.

The density profiles from Dougherty et al. (2017) and Bagenal and Delamere (2011) are overlaid for comparison. The Voyager reanalysis by Dougherty et al. (2017) took the data from the single flyby and extrapolated the density to a dipole-based centrifugal equator, assuming a diffusive equilibrium in a dipolar magnetic field. The net result was probably an overestimate of the net charge density at the equator beyond distances of ~15 RJ where the field becomes distorted from a dipole due to the current sheet. On the other hand, the Bagenal and Delamere (2011) profile was based on a combination of Voyager PLS (from McNutt et al., 1981) and PWS (from Barnhart et al., 2009) as well as Galileo PLS. The profile was derived by Bagenal and Delamere (2011) by drawing a curve through a wide range of values (likely reflecting both temporal and spatial variations), rather than picking the higher values (which would reflect values at the center of the plasma disk). Subsequent reanalysis of Galileo PLS data by Bagenal et al. (2016) shows the mission-averaged density profile matches the Bagenal and Delamere (2011) profile quite well, at least out to the 30 RJ limit of the Galileo data.

Since only clear signatures were included in the analysis, there is likely a bias toward higher densities derived from stronger signatures. Furthermore, there is some selection associated with the evolution of Juno’s orbit (discussed related to Figure 4 in Section 3.2). The average density profile derived from the Juno plasma densities matches the Voyager-based profile of Dougherty et al. (2017) but shows variability of factors of 5–10.

Figure 7. Each plasma disk crossing in Set 2 (167 total) in which the density could be fit with a Gaussian and the radial component of the magnetic field switched sign within 2 RJ of the density peak. The maroon circles indicate Juno’s distance to the centrifugal equator (Phipps & Bagenal, 2021) at the time Br flips, and the green squares indicate the centrifugal distance at the time when Jovian Auroral Distributions Experiment (JADE) measures the peak density.
As discussed in Section 3.2 above, Orbit 12 was particularly notable with exceptionally low density (~0.1 cm⁻³) and little variation with latitude. We include this low radial profile in Figure 6 where outside ~25 R\(_J\) the Orbit 12 profile lies about a factor of 2 below the Bagenal and Delamere (2011) profile and a factor of 10 below more typical Juno-JADE plasma disk densities. We discuss the implications further in Section 4.

In Figure 6b, we picked the clearest 50 plasma disk crossings (Set 4) and derived a scale height by evaluating the vertical separation (centrifugal Z) of the peak density and the location where the density has dropped by 1/e. Theoretically, in a static, uniform, single-ion-species plasma disk in a dipolar magnetic field, this exponential scale height is related to the centrifugal scale height \( H = (2/3kT_i/[m_iA_i\Omega^2])^{1/2} \) where \( T_i \) is the ion temperature, \( m_i \) is the mass of a proton, \( A_i \) is the average ion mass (in amu), and \( \Omega \) is the angular velocity of rotation of Jupiter (Bagenal, 1994). In Figure 6, the gray curve shows the scale height profile derived by Bagenal and Delamere (2011) from ion temperatures measured by Galileo PLS. Note that measured heavy ion temperature derived from different instruments depends on a variety of factors (e.g., energy range and resolution of the instrument, assumed ion composition, analysis method, etc.). The ion temperatures derived from the Galileo PLS instrument (peak \( E/q = 52 \text{ keV} \)) tended to be higher than those measured by Voyager PLS (peak \( E/q = 6 \text{ keV} \)) as discussed in Bagenal et al. (2016). Similarly, the ion temperatures derived from the JADE-TOF instrument (peak \( E/q = 46.2 \text{ keV} \)) by Kim et al. (2020b) are similar to those derived from Galileo data. We note that the scale heights in Figure 6 derived from the JADE density profiles at plasma disk crossings are significantly smaller than the temperature-based curve. This could be due to a selection bias by picking disk crossings that are narrow and steep. Second, there are likely real spatial and/or temporal variabilities in the plasma disk, as we discuss in the next section.

### 3.6. Plasma Disk and Current Sheet Variabilities

The plasma disk is expected to be centered on the farthest point along a magnetic flux tube from Jupiter’s spin equator, the centrifugal equator. As discussed above, in the simple situation of a static current sheet structure, the centrifugal equator is aligned with the magnetic equator and tilted by ~10° from the spin axis. In reality, however, the current sheet and plasma disk flap up and down and are compressed/expanded in response to time-variabilities of conditions—external or internal—in the magnetosphere.

For each plasma disk crossing that produced a density peak that allowed a reasonable Gaussian fit (as discussed in Section 3.3), we further examine those crossings with a nearby change in sign of the radial component of the magnetic field which we associate with the center of the current sheet. This gives us 167 disk crossings of Set 2 which we plot in Figure 7, showing the location of peak heavy ion density (maroon dots) and the nearby change in sign of Br (green squares), connected by dotted lines. At the top of the plot, we show the separation between centrifugal and magnetic equators with radial distance, illustrating that the maximum separation between the equators is ~±0.4 R\(_J\) at a radial distance of 10 R\(_J\) and is insignificant in the region beyond 15 R\(_J\) that we are concerned with here.

The coverage inside ~20 R\(_J\) is probably too sparse and biased toward northern locations because of Juno’s trajectory. Outside ~20 R\(_J\), the vertical displacement of the plasma disk shows values of <±2 R\(_J\), increasing to ±3–4 R\(_J\) beyond ~35 R\(_J\). This plot shows that the center of the plasma disk often coincides quite closely with the corresponding crossing of the current sheet. The deviations increase with radial distance but are generally <6° in latitude. With a single spacecraft it is not possible to separate spatial from temporal variability. Nevertheless, Figure 9 is consistent with relatively small-scale flapping of the plasma disk and current sheet, increasing in amplitude beyond ~35 R\(_J\).

### 4. Discussion

In this section, we summarize the average density structure of the Jovian plasma disk as observed by Juno and compare with previous observations and theoretical models. We also address what kind of mass transport might explain the large variations seen on some orbits.
4.1. Density Maps

Juno’s evolving orbit generates plasma data in new locations continuously, as well as improving statistics by providing more data in previously covered areas. The 10-h rotation period of Jupiter creates a “wiggle plot” when observing the spacecraft trajectory in the tilted magnetic coordinate system. Beyond 20 $R_J$ from the planet the magnetic field is reasonably approximated by a dipole tilted by 9.5° toward System III west longitude of 201° (VIP4 model of Connerney et al., 1998). This is basically the same as the tilt of the current sheet derived from Juno data by Connerney et al. (2020). Figure 8 comprises wiggle plots of the electron, proton, and heavy ion densities along the Juno trajectory relative to the magnetic dipole equator from Orbit 5 to Orbit 26. The color in the 3 panels shows the local number density. These wiggle plots show the basic structure of higher density in the inner magnetosphere ($<20 R_J$) and a few-$R_J$ thick disk in the outer magnetosphere ($>20 R_J$).

In order to average the data into an overview map, we create spatial grids with a cell size of 2 $R_J$ wide and 1 $R_J$ tall in cylindrical $\rho-Z$ centrifugal coordinates. The top of Figure 7 shows that this is very close to the simple tilted magnetic dipole coordinates. The data shown in the wiggle plots in Figure 8 are then mirrored about the equator and the medians of all density data points within each cell are shown in Figure 9 for each species. The magnetic field lines from the JRM09 + CON2020 field model (Connerney et al., 2020) are overlaid for reference. The number of points in each colored cell is in the thousands, except for those cells near the edges which contain several hundreds. Cells are colored gray if the spacecraft passed through the region but the median density was below 0.001 particles per cubic centimeter (our validity threshold).

These color maps are a useful way to visualize the vertical thickness of the plasma from Jupiter out to 50 $R_J$. Inside $\sim 15 R_J$, the plasma follows the dipolar magnetic field lines. Beyond $\sim 15 R_J$, where the field lines are stretched out, the plasma takes on a disk-like form, with the heavy ion density greatly enhanced in the inner magnetosphere and in the disk confined to a few-$R_J$ off the equator. In contrast, the protons are spread quite uniformly with height. This confirms the preliminary study of Kim et al. (2020b) who analyzed the JADE-TOF data for Orbits 1–22 to map out the ion composition in the plasma disk.

Theoretical models of the Jovian plasma disk have focused on the dynamical coupling between Jupiter’s conducting ionosphere and the out-flowing plasma (see reviews by Kivelson, 2015 and Achilleos et al., 2015). Nichols (2011) built a self-consistent current sheet model that included mass-loading in the Io plasma torus, subsequent radial transport, coupled via parallel currents to a conducting ionosphere. The model was primarily constrained by observed magnetic field perturbations due to the current sheet. Nichols et al. (2015) applied the Bagenal and Delamere (2011) density profile and explored the effects of pressure gradients and anisotropy on the stability of the disk. In this study, we show that the plasma disk density structure can be quite variable both in small structures (e.g., Figures 5d and 6) as well as from orbit to orbit (e.g., Figure 4). However, we will need quantitative measurements of plasma pressure, preferably including the higher energy (JEDI) components, in order to further constrain models.
In the meantime, let us look at the sequence of events associated with Orbit 12. This orbit is unique in that it exhibits a particularly flattened profile outside 30 $R_J$ with values of 0.2 cm$^{-3}$ at 50 $R_J$. Moving inward, the absolute values of the density are only a factor of $\sim 2$ below the other values and the Voyager-based curve (Figure 6), but the noticeable feature is a lack of peaks, suggesting a uniform disk that is either very low density or the plasma is hot and the density is very spread out vertically. The energy-time spectrogram for this period shows low fluxes at all energies (suggesting low density) rather than fluxes peaking at higher energies (which would suggest high temperatures).

Figure 9. Color map of densities from Orbits 5 to 26. Each cell is 2 $R_J$ wide and 1 $R_J$ tall, containing the median value of all Jovian Auroral Distributions Experiment (JADE) measurements in that spatial location. Gray cells denote regions where Juno collected data but the density was below 0.001 particles cm$^{-3}$. Magnetic field lines are overlaid in white from the JRM09 + CON2020 model. (Top) Electrons; (middle) heavy ions; and (bottom) protons.
Note that Connerney et al. (2020) found Orbit 12 to have an anomalous current sheet (compared with the other first 24 orbits) with the azimuthal current weaker by 11% but with a 57% stronger radial current, though these values were derived from Juno data at distances <30 Rp. Reduced azimuthal current is consistent with reduced mass-loading and/or reduced plasma pressure gradients.

With just a single spacecraft within the Jupiter system, it is impossible to separate spatial and temporal variabilities. But it is worth noting other pieces of evidence of substantial compressions during this epoch come from the fact that Juno passed into the magneto sheath for a couple hours on two occasions, January 6, 2018 6 days before apojove 10 and on August 4, 2018 a week before apojove 14, according to Ranquist et al. (2019). The spacecraft was in the magnetotail at radial distances of 109 and 107 Rp and local times of 03:30 and 02:30, respectively. The Juno orbit had precessed south over these dozen orbits but these crossings at 16° and 21° south latitude support the idea of a flattened shape for the magnetopause (Ranquist et al., 2020) and major compressions of the magnetosphere. Such compressions could well enhance plasma transport down the magnetotail, either as large-scale plasmoids (as first proposed by Vasyliunas, 1983) or as small-scale “drizzle” (Kivelson & Southwood, 2005).

The New Horizons spacecraft, taking a Jupiter gravity-assist to speed up its journey to Pluto, passed directly down Jupiter’s magnetotail. McComas et al. (2007) reported that the Solar Wind At Pluto (SWAP) instrument measured ion fluxes continuously to 1,700 Rp, downtail, including plasmoids of heavy ions as well as H+ and H3+ ions. Bagenal (2007) took early indications of plasmoid ejection from auroral spots (Grodent et al., 2004) as well as in-situ particles (Woch et al., 2002) and fields (Russell et al., 2000) to estimate that large-scale (~25–50 Rp) plasmoids ejected down the tail at a rate of ~1/day (in the midrange of observational time scales of 4 h to 3 days) would remove ~500 tons/plasmoid or ~0.2 tons/second. Such a rate of plasmoid ejection would not remove the ~1 ton/s of plasma produced by Io, suggesting that under normal, equilibrium conditions most of the iogenic plasma would need to be lost via some other mechanism such as a magnetopause boundary layer (Delamere & Bagenal, 2010, 2013 or small-scale “drizzle” (Kivelson & Southwood, 2005).

To make a rough estimate of the mass involved in the changes to the plasma disk suggested by Orbit 12, we take a uniform disk from the especially depleted region from 30 to 50 Rp with a vertical thickness of 6 Rp and density of 0.1 cm^-3 to get a net mass of ~50,000 tons of plasma. Removing this amount of material would require ~100 large-scale plasmoids (perhaps fewer if particularly large). With the limited spatial and temporal coverage of a single spacecraft in the system it is difficult to estimate the time scale over which such material might be ejected. Strong solar wind compression of the magnetosphere might well enhance the losses significantly. McComas et al. (2014) used Ulysses observations of typical solar wind conditions at Jupiter’s 5 AU orbit to argue that passing Corotating Interaction Regions (CIRs) could explain the observed bimodal nature of the magnetopause stand-off distance as shown by Joy et al. (2002)’s statistical analysis. They estimated such CIRs would take about 8 h to travel from the nose of the magnetosphere to the terminator and last 2–4 days. The question is whether a powerful CIR might perhaps be capable of ejecting the material missing from the plasma disk on Orbit 12 via ~1 large plasmoid per hour for ~4 days. The time scale of a few days is consistent with the enhanced aurora observed by Nichols et al. (2020) during the previous orbit.

McComas et al. (2014) point out that even when there is a major CIR compressing the magnetosphere and expelling material, the ~1 ton/s production rate at Io and the estimated radial outflow 10–50 km/s (Bagenal & Delamere, 2011) indicate refilling rates for the plasma disk of just 5–20 h. Dividing the above estimate of ~50,000 tons of plasma missing between 30 and 50 Rp on Orbit 12 by 1 ton/s one finds a replacement time scale of 14 h.

Analysis of Juno data and Hubble Space Telescope auroral emissions around the time of Orbit 11 led Nichols et al. (2020) to conclude that the plasma disk at the time of the three crossings (between 30 and 15 Rp) exhibited enhanced (factor ~2) plasma pressures, perhaps consistent with compression by the solar wind, leading to expulsion of plasmoids down the tail, exciting aurora in the dawn polar regions. This might explain the subsequent depletion of the plasma disk observed when Juno returned to the outer regions on Orbit 12. By Orbit 13, roughly 53 days later, the depletion has stopped and the plasma disk has partly recovered, especially inside 35 Rp. This scenario is consistent with analysis of Vogt et al. (2020) who looked at magnetic field data on Juno’s first 16 orbits and found 232 reconnection events between 37.5 and 113.4
with a median distance of 84 $R_J$. Similar to the Vogt et al. (2010) study of Galileo data, there seemed to be a clumping of 3–5 events every ∼3 days. Most notable is that Orbit 11 featured 25 events while Orbit 12 contained just two events. While the 25 events are probably not sufficient to explain the tenuous plasma disk of Orbit 12, it is quite possible that many more plasmoids were ejected while Juno was at large southerly latitudes on the return from apoijove to perijove 12. It will be interesting to explore the occurrence of reconnection events in the magnetic field data around Orbit 26 to see if similar behavior can be connected to similarly low densities in the outer section of the plasma disk.

5. Summary and Conclusions

We have combined Juno JADE and magnetometer data obtained on Orbits 5–26 between March 2017 and April 2020 to examine Jupiter’s plasma disk from 10 to 50 $R_J$. We present in-situ measurements of ion densities (protons and heavy ions) and electron density plus the strength of the magnetic field components on the inbound leg of Juno’s orbit. The ∼10° tilt of the magnetic dipole causes the spacecraft to oscillate relative to the magnetic equator. We show that for most orbits Juno approaches or crosses the plasma disk, measuring local peaks in the density, controlled by the geometry of the centrifugal equator (as defined by Phipps and Bagenal, 2021). The density profiles through the plasma disk crossings show quite a variation in amplitude and vertical thickness as well as scatter about the equator, the variability increasing beyond ∼35 $R_J$ from Jupiter. Some of the crossings are relatively smooth while others show variability, suggesting considerable small-scale structures, consistent with the cold blobs observed in the Voyager plasma data (recently cataloged by Dougherty et al., 2017). While on most orbits the JADE densities showed regular crossing of the plasma disk there was a notable exception on Orbit 12 where the plasma disk between 30 and 50 $R_J$ was particularly uniformly depleted with no density peaks at crossings of the centrifugal equator. Observations during Orbit 11 of enhanced aurora by Nichols et al. (2020) and multiple reconnection events observed by Vogt et al. (2020) are consistent with a picture of increased compression by the solar wind triggering enhanced loss down the magnetotail between Orbits 11 and 12.

We conclude from this survey of Jupiter’s plasma disk with Juno that:

1. On average the density in Jupiter’s plasma disk is consistent with previous observations by Voyager and Galileo.
2. The average thickness of the plasma disk, as measured by the 1/e decrease in density of electrons and heavy ions, is about ±3 $R_J$ between 15 and 50 $R_J$.
3. Protons comprise about 10% of the ion density in the center of the plasma disk and are more uniformly spread vertically through the disk.
4. The plasma density shows considerable small-scale structure on spatial scales sometimes smaller than 1 $R_J$ and on time scales of minutes.
5. On some occasions the outer plasma disk (∼30–50 $R_J$) shows uniformly low (∼0.02) densities suggesting depletion, perhaps due to enhanced ejection of plasmoids down the magnetotail, possibly triggered by solar wind compression events.

Next steps will be to calculate plasma flows, temperatures and pressures, extending Kim et al. (2020b)'s study of ion composition using the JADE-TOF measurements as well as compare local electron densities measured by JADE-E with the Juno-Waves instrument (as carried out for some sample cases by Allegrini et al., 2020). The remainder of Juno’s prime mission (through perijove 33) and recently approved extended mission (through perijove 75 in 2025) will take the spacecraft around toward noon local time and include many more crossings of the plasma disk, particularly inside 20 $R_J$, perhaps providing the opportunity to record changes in the plasma disk due to Io’s volcanism.

Data Availability Statement

The JADE data used in this study can be found on the Planetary Data system (https://pds.nasa.gov) in data set JNO-J/SW-JAD-3-CALIBRATED-V1.0; version 03 files for JADE-E and version 02 files for JADE-I. The magnetic field data are also from the Planetary Data System, data set JNO-J-3-FGM-CAL-V1.0 with the *pc_r1s_v01.sts files. All data presented in this paper are available here https://doi.org/10.25810/JRZJ-MW20.
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