Abstract
We use the Kelvin-Helmholtz instability (KHI) condition with particle and magnetic field observations from the JADE and MAG instruments on Juno along the dawn flank of Jupiter’s magnetosphere to identify the occurrence of magnetopause crossings that show evidence of being KH (Kelvin-Helmholtz) unstable. We compare the results with previous KHI studies. Of the 62 magnetopause crossings studied here, 24 events satisfied the KHI condition and 38 did not. The results of this study show that there is evidence of KH waves at Jupiter’s dawn flank, including primary drivers such as high velocity shears and changes in plasma pressure. 25% of KHI crossings also exhibit signatures of magnetic reconnection. We discuss these results and their implication for the prevalence of KHI at Juno’s dawn magnetopause as measured by Juno.

Plain Language Summary
The Kelvin-Helmholtz instability occurs when a boundary separating two fluids of different densities is perturbed and these fluids are moving at different speeds, directions, or both. The difference in speeds across the perturbed boundary that separates the fluids creates wave structures as these fluids diffuse into each other. The Kelvin-Helmholtz instability may be observed at the boundary that separates a planetary magnetic field (magnetosphere) from the stream of charged particles emitted by the Sun (solar wind); this boundary is known as the magnetopause. This instability is confirmed to occur at Earth and Saturn, but is not confirmed at Jupiter. This study analyzes the properties of the plasma and magnetic field in Jupiter’s magnetosphere and the surrounding solar wind to identify signatures of the Kelvin-Helmholtz instability. We find that out of the 62 occurrences where the Juno spacecraft crosses the magnetopause, 24 events signify that the Kelvin-Helmholtz instability is possible -- primarily due to large differences in velocities -- and 38 events do not.

Key Points
1. There is evidence of Kelvin-Helmholtz instability (KHI)-driven waves along Jupiter’s dawn flank magnetopause during the Juno primemission.
2. 24 (38.7%) crossings satisfied the KHI condition and 38 (61.3%) crossings did not satisfy the KHI condition.
3. Magnetopause crossings that satisfied the KHI condition had, in general, larger velocity shears than those that did not.

1. Introduction

Plasma inside Jupiter’s magnetosphere is primarily confined to the equatorial or low latitude region, forming a plasma disk [Huscher et al., 2021; Krupp et al., 2004; Khurana et al., 2004]. The plasma disk extends radially outwards and subcorotates in the outer magnetosphere. As a rotationally dominated magnetosphere, with co-rotating high-\(\beta\) magnetospheric plasma interacting with tailward magnetosheath flows, small-scale viscous interactions involving Kelvin-Helmholtz instabilities (KHI) are predicted to occur [Delamere and Bagenal, 2010; Desroche et al., 2012]. If the velocity shear between these two regions is more dominant than the magnetic tension, then perturbations of the boundary are hypothesized to roll into vortex structures, which is a characteristic signature of the Kelvin-Helmholtz (KH) instability in the nonlinear stage [Dungey, 1955; Masters et al., 2009; Johnson et al. 2014]. KH waves may form at Jupiter’s dawnside magnetopause because of the high velocity shear flow between the magnetosphere and magnetosheath plasma. These waves could lead to mass and momentum transfer across the MP [Otto and Fairfield, 2000]. KH waves may form on both dawn and dusk sides; however, this study only considers the low latitude crossings, which only take place on the dawn side during the Juno prime mission.

Observations of KH waves at planetary magnetopauses (e.g. Earth and Saturn) via the Magnetospheric Multiscale (MMS), Cluster, THEMIS, and Cassini missions have resulted in several notable conclusions for this type of solar wind interaction. Masson and Nykyri et al. [2018] show that rolled-up vortices along Earth’s magnetopause can develop as the instability grows and that these vortices can develop under any interplanetary magnetic field (IMF) conditions. Multiple studies indicate that periodic fluctuations of plasma and magnetic field parameters, especially in the radial and azimuthal directions, are clear indicators of KH waves [e.g., Blasl et al., 2022; Burkholder et al., 2020; Delamere et al., 2013; Hasegawa et al., 2004; Masson and Nykyri et al., 2018]. Periodic fluctuations suggest that the spacecraft is travelling through a wave structure that is possibly a rolled-up vortex. The spacecraft moves in and out of magnetosheath and magnetosphere plasma, crossing the boundary several times. At Saturn’s dawn magnetopause, KH vortices were observed at a 14% occurrence rate and an 18% occurrence rate from 10-12 local time (LT), where there may be a stationary KH vortex [Burkholder et al., 2020]. Using a boundary normal analysis approach, Masters et al. [2009] identified regular surface waves present at magnetopause crossings via Cassini observations. They conclude that these surface waves occurred within 24° of Saturn’s magnetic and rotational equators and were characteristic of the growth of the KH instability (KHI). Theoretical approaches of KH waves at Saturn involving MHD simulations find that the models and in situ observations agree; vortex structures are observed both theoretically and experimentally and are caused by the KHI [Delamere et al., 2018; Desroche et al., 2012; Ma et al., 2015]. Using simulations, Zhang et al. [2018] states that KH vortices at Jupiter form regardless of the IMF orientation, and the magnetosheath is hydrodynamically dominated instead of magnetohydrodynamically dominated. Therefore, they conclude that KH vortices may form at higher latitudes. They also conclude that dawnside vortices were simulated to be stationary
compared to the duskside due to the relatively small momentum perpendicular to the boundary normal. A recent boundary normal analysis study of Jupiter dawn magnetopause crossings made by Juno finds that many crossings show a rotation of the boundary normal direction, which suggests KH wave formation [Ma et al., 2022].

In this paper, we identify observational signatures of KHI along the dawn flank of Jupiter’s magnetosphere using Juno data [Bolton et al., 2017]. Section 2 describes the instrumentation used to observe magnetopause crossings and signatures of the KHI. Section 3 explains the methods in which magnetopause crossings and the KHI are identified. Section 4 discusses our results and the implications for the mechanisms driving the transfer of plasma and momentum across Jupiter’s dawn magnetopause.

2. Instrumentation and Datasets

The Jovian Auroral Distributions Experiment (JADE) [McComas et al., 2017] on Juno is an instrument that includes three electron (JADE-E) sensors (two currently in operation), one ion sensor (JADE-I), and an electronics box. During the period studied here, the JADE-E sensors measure electrons with energies from ~0.1 to 100 keV/q. Each electron sensor consists of a spherical top-hat electrostatic analyzer (ESA) and microchannel plate detectors and has a field-of-view (FOV) of 120° in spacecraft azimuth and up to 35° in elevation, achievable by electrostatic deflection. The JADE-I sensor is a spherical top-hat ESA designed to measure ions over an instantaneous FOV of 270° in elevation and 9° in azimuth over an energy per charge range of ~10 eV/q to 46 keV/q. A time-of-flight (TOF) section is used to measure ion mass per charge (m/q) from 1 to >40 amu. For this study, we used the JADE low rate science data with time resolution of 60 s for the ions and electrons.

The Juno Magnetic Field investigation (MAG) [Connerney et al., 2017] provides magnetic field measurements in Jupiter’s magnetosphere and near the planet. MAG consists of two independent sensor suites, each comprising a tri-axial Fluxgate Magnetometer sensor and a pair of co-located imaging sensors. Each magnetometer has a resolution of ~0.05 nT in its most sensitive dynamic range. Both magnetometers simultaneously sample the magnetic field at an intrinsic sample rate of 64 vector samples per second. For more details about the MAG instruments, see Connerney et al. (2017).

3. Identifying Kelvin Helmholtz Instabilities

Studies by Ebert et al. [2017], Hospodarsky et al. [2017], Ranquist et al. [2019], and Montgomery et al. [2022] identified a number of magnetopause crossings, from which we identify and analyze 62 magnetopause crossings when the JADE-E and JADE-I instruments were on. For Juno orbits 1-4, the JADE-E and JADE-I instruments were turned off when Juno was outside of the several hour period bounding perijove. Thermal ion and electron measurements are necessary to make accurate calculations and conclusions based on the KHI condition, therefore previously identified magnetopause crossings during this time were excluded. These were along Jupiter’s dawn flank
based on observing changes in plasma and magnetic field parameters (e.g., proton and electron energy and density, magnetic field components) taken from the JADE, MAG, and Waves [Kurth et al., 2017] instruments onboard the Juno spacecraft. The magnetopause crossings used in this paper are at low latitudes on the dawnside. When performing calculations in this study, we exclude the 1) electron mass density because it is on average four orders of magnitude lower than the proton mass density 2) the heavy ion mass density because the thermal heavy ion distributions are generally above the JADE-I energy range in this region of the magnetosphere and 3) the energetic particle mass density measurements because they are 2-3 orders of magnitude below the proton mass density measurements. The exclusion of mass density of electrons, heavy ions, and energetic particles results in a lower limit when applying the KHI condition. The exclusion of heavy ions, in particular, likely results in a lower limit when applying the KHI condition due to their expected contribution to the magnetospheric mass density.

The KHI onset condition is satisfied when the velocity shear overcomes the magnetic tension force and is stabilized if the magnetic force dominates the velocity shear. Chandrasekhar [1961] gives the onset condition in an incompressible fluid for the ideal MHD case.
\[
\left(k \cdot (v_{\text{MSP}} - v_{\text{MSH}})\right)^2 > \frac{\rho_{\text{MSP}} + \rho_{\text{MSH}}}{\mu_0 \rho_{\text{MSP}} \rho_{\text{MSH}}} \left[(k \cdot B_{\text{MSP}})^2 + (k \cdot B_{\text{MSH}})^2\right]
\]

For our calculation, the \(k\) is the wave vector, \(v\) is the velocity, \(B\) is the magnetic field, \(\rho\) is the mass density, and MSP and MSH denote the magnetosphere and magnetosheath interval, respectively. The condition can also be described as the ratio between the velocity shear and the magnetic tension force. This is accomplished by dividing the left-hand side (LHS) by the right-hand side (RHS) and we will refer to this as the KHI condition ratio

\[
\frac{\rho_{\text{MSP}} \rho_{\text{MSH}}}{\rho_{\text{MSP}} + \rho_{\text{MSH}}} \left(\frac{k \cdot (v_{\text{MSP}} - v_{\text{MSH}})\right)^2}{(k \cdot B_{\text{MSP}})^2 + (k \cdot B_{\text{MSH}})^2} > 1
\]

The wave vector \(k\) is set parallel to the flow shear direction, as this tends to be correlated with the fastest growing KHI mode and describes the direction of the KH wave propagation [Masson and Nikiri, 2018]. For magnetopause crossings that show signatures of KH waves, the plasma in regions near Jupiter’s magnetopause typically contain velocities in the X-Y plane and magnetic field in these regions usually has a large \(B_z\) component, which would satisfy the KHI condition (see Figure 2). We apply this condition to the observed Juno dawnside magnetopause crossings to determine how often KHI is predicted to occur in this region. A KHI condition ratio > 1 indicates the onset of the KHI and that the formation of KH vortices is likely after some growth of the instability to a non-linear level. A KHI condition ratio < 1 indicates that the onset of the KHI is not likely.

Figure 1 shows 62 dawnside magnetopause crossings used in this study and displays Juno’s orbital trajectory as well as a compressed and expanded magnetopause according to the Joy et al. [2002] models. A large majority of the crossings are located in the equatorial region (latitude < ~20°) with the Z values ranging from -26 to 21 jovian radii (1 RJ = 71,482 km). The Juno orbit is plotted in the Jupiter-Sun-Orbital (JSO) coordinate system with the X-axis in the Jupiter-Sun plane, positive X pointing toward the Sun, the Y-axis is positive in the direction of the Sun’s motion relative to Jupiter (opposite of Jupiter’s orbital velocity), and Z is the cross product of X and Y. Additionally, the plot is color-coded showing the crossings in which the KHI condition is satisfied and not satisfied. The purple lines show the 75th percentile (solid line) and 25th percentile (dashed line) magnetopause boundaries modeled in Joy et al. [2002]. In total, 24 crossings satisfied the KHI condition (green symbols) and 38 did not satisfy the condition (red symbols). For each crossing, we identify fluctuations in 1) proton density and electron energy (indications of the spacecraft traveling in and out of magnetosheath, boundary layer, and magnetosphere-like regions) 2) pressure 3) magnetic field components (i.e. \(B_x\) and \(B_y\)) and 4) velocity components (i.e. \(V_x\) and \(V_y\)), which is characteristic of KH wave observations and is considered to be evidence for KHI [Burkholder et al., 2020; Masters et al., 2012; Delamere et al., 2013]. Each of the listed characteristics are considered signatures of KH wave formation in this study.
Figure 2 presents an example of a magnetopause crossing in which the KHI condition is satisfied (KHI condition ratio > 1) and the formation of KH vortices is likely. In Figure 2, we show thermal proton and electron energy spectrograms, proton velocity, proton density, thermal proton pressure, and the magnetic field components and magnitude. There are several observations of periodic crossings into and out of magnetosheath and magnetosphere-like intervals on 2017 day of year (DOY) 126 from 17:25 to 17:55 UT. The spacecraft crosses the magnetopause at 17:28 UT. This magnetopause crossing satisfies the KHI condition with a KHI condition ratio of 2.06. These fluctuations indicate a deformation of the magnetopause boundary due to the velocity shear between the magnetosheath and magnetosphere. The velocity shear for this magnetopause crossing is 204 km/s. This velocity shear leads to a pressure force in the direction of the boundary deformation (toward Jupiter), and continues to grow as plasma from one side of the interface is carried by the flow of the other side, causing KH vortex formation [Johnson et al., 2014]. In some transitions between regions in this interval, we observe minor bipolar fluctuations components (i.e. $B_x$ and $B_y$) of the magnetic field, which is additional evidence for KH vortex formation [Delamere et al., 2013]. At 17:28 UT, Juno is exiting the magnetosheath proper and this is shown by the
decrease in density from $\sim 1.1 \, \text{cm}^{-3}$ to $\sim 0.2 \, \text{cm}^{-3}$. From that time until the end of the interval, the density is lower, even when encountering magnetosheath-like plasma. The intermediate density – a density that is higher than magnetosheath-like plasma but lower than magnetosphere-like plasma – indicates a mixing of plasma across the boundary layer or that the spacecraft is located closer to the magnetosphere side of the magnetopause. Observations of mixed plasma boundary layers are not necessarily evidence of KHI; however, boundary layers are important in the development of KH waves as this solar wind interaction involves a mixing of plasma in a diffuse boundary layer. Panel a) in Figure 2 shows several boundary layer intervals between each dashed line and solid line, which suggests that the spacecraft may be travelling through KH wave structures. Another signature of KH waves is observed in the local minima and maxima of the proton pressure throughout the interval [Blasl et al., 2022; Johnson et al., 2014]. The local minima of the proton pressure correspond to the leading edge of the wave, designated by the dashed purple lines, and the local maxima correspond to the trailing edge, designated by the solid magenta lines.

Figure 3 shows a magnetopause crossing that takes place at 13:06 UT on 2017 DOY 151. This event does not satisfy the KHI condition nor does it show signatures of KHI. While the Juno spacecraft is in the magnetosphere, the velocities are variable. This is because the low-density plasma in the magnetosphere results in higher uncertainties in the JADE-I proton measurements,
not necessarily because there is a mixing of plasma taking place. Thus, we take intervals within
the boundary layer on the magnetosphere side of the magnetopause to minimize these
uncertainties. After the magnetopause crossing, the velocities are less variable. For this crossing,
there is no periodic variation in density or energy beyond the magnetopause crossing itself. There
are also no indications of leading and trailing edges of a KH wave forming, nor are there
correlations between the proton pressure, B field components, and plasma spectra that exemplify
KH waves. Table 1 from the supplemental information lists Juno position, particle, and field data
for each Juno magnetopause crossing analyzed in this study. Using Table 1, we are able to calculate
the KHI condition ratio for each event. Several crossings (58\%) that satisfy the KHI condition
have a large velocity shear (> 100 km/s). However, some events have low shear and satisfy the
KHI condition because the $k$ vector and the magnetic fields are quasi-perpendicular. Quasi-
perpendicular magnetic fields result in the KHI overcoming the magnetic tension force [Johnson
et al., 2014; Southwood, 1968]. This may also occur because of a weak magnetic field across the
magnetopause [Masters et al., 2009; Masson and Nikiri, 2018].

Figure 4 displays the frequency of velocity shears in events that satisfy the KHI condition (green)
and events that do not (gray). In the events that satisfied the condition, eight (32\%) have a velocity
shear over 125 km/s and six (25\%) satisfied the KHI condition while having a velocity shear less
than 75 km/s. In the histogram of events that did not satisfy the condition, the distribution is right-
skewed. A majority of events in this plot has a velocity shear less than 100 km/s and few events
have shears greater than 125 km/s. The mean velocity shear for the satisfied events is 127.1 km/s
while the mean for the events that did not satisfy the KHI condition is 96.6 km/s. The median
values also differ significantly, with values of the satisfied and unsatisfied events of 123.5 km/s
and 82.2 km/s, respectively.
4. Discussion

A multi-instrument analysis including JADE-E, JADE-I, and MAG observations from Juno at Jupiter’s dawn magnetopause was conducted. Observations of in situ plasma and magnetic field observations spanned from 73 – 114 R\textsubscript{J} and 4.3 – 6.2 magnetic local time at low latitudes (~20° or less). We use in situ observations to apply the KHI condition and identify signatures of KH waves at each crossing. From the KHI condition, we calculate the KHI condition ratio for each magnetopause crossing to provide a single value to determine if the KHI condition is satisfied.

We conclude the following from the 62 magnetopause crossing observations:

1. There is observational evidence for KH waves at Jupiter’s dawn magnetopause, which may be responsible for transferring mass and momentum across the magnetopause.
2. 24 (39%) of the crossings satisfied the KHI condition while 38 (61%) did not.
3. Of the 24 crossings that satisfied the KHI condition, 18 showed signatures of KH waves.
4. Of the 38 crossings that did not satisfy the KHI condition, 26 did not show evidence of KH waves.
5. There is some discrepancy between the KHI condition and observational evidence for KH waves. Approximations within the condition may be the cause of these inconsistencies.

This study shows that KHI occurs relatively often at Jupiter’s dawn magnetopause when compared to Earth (~19% of the time) and Saturn (~14% of the time) [Kevosi and Raeder et al., 2015; Burkholder et al., 2020]. These results agree with models and simulations regarding the viscous interactions that take place along the dawn flank of the magnetopause, a region in which KH waves grow and develop from the subsolar region and advect tailward as the solar wind is draped over the highly variable magnetopause [Delamere and Bagenal 2010; Zhang et al., 2018]. We found that the velocity component \( V_x \) was negative (anti-sunward) in all but one magnetopause crossing. This result suggests that the plasma (at this location) in Jupiter’s magnetosphere does not corotate at all locations along the dawn flank. Instead, there may be a cutoff point where plasma detaches and travels down the magnetotail [Delamere and Bagenal 2010]. We note that most of the magnetopause crossings are tailward of the terminator, especially those after the first inbound orbit. In the outer magnetosphere, plasma is hypothesized to corotate with Jupiter sunward of the terminator, transitioning to traveling tailward on the nightside magnetopause, behind the terminator. Even if \( V_x \) is negative in both the magnetosheath and magnetosphere regions, KH waves may still form because a high velocity shear is caused by a large difference in velocities, not necessarily antiparallel velocity components. There are magnetopause crossings that satisfy the KHI condition, yet do not exhibit signatures of KH waves, and vice versa. Twelve events show evidence of KH waves but do not satisfy the KHI condition and six events satisfy the KHI condition but do not show evidence of KH waves. These results suggest that the KHI condition (in the ideal case) may not solely be utilized to investigate KH waves. Instead, it can be used as a tool alongside other techniques to identify KHI’s. However, as noted previously, we use the KHI condition where we align the \( \textbf{k} \) vector with the velocity shear, which would maximize the number of events that satisfy the condition (this method is in line with the fastest growing KH mode). Furthermore, we only use thermal proton measurements from JADE-I and do not use heavy ion mass densities, and as a result may reduce the number of events that satisfy the KHI condition.
Along the dawn flank, KH waves may have developed upstream of the Juno spacecraft. This may lead to in situ observations that do not show clear wave fronts and therefore do not show clear evidence of KH wave structures but rather shows a thick boundary layer. In these cases, we would not know if the solar wind interaction type is a KH wave or a boundary layer formed by another type of perturbation of the magnetopause. Lastly, the intervals in which the magnetosphere and magnetosheath regions were chosen could affect the KHI condition ratio. The intervals were selected within regions directly before and after the magnetopause crossing time. A large majority of these intervals contain an observable boundary layer, which provides a statistically significant plasma density, which lowers the uncertainty of the plasma moments and gives a more accurate value for the KHI condition. In these events, we use the boundary layer plasma as our magnetosphere interval when calculating the KHI condition ratio. In Figures 2 and 3, the uncertainties for the thermal proton velocities in the magnetosheath are (8.18, 5.11, 3.77) and (5.04, 3.50, 2.65) km/s respectively, and the uncertainties for the magnetosphere boundary layer are (39.82, 32.90, 37.67) and (141.47, 103.65, 90.91) respectively. In magnetosphere intervals near the magnetopause where we do not observe a boundary layer, it is common to find uncertainties that are larger than the velocity measurements themselves.

Considering that 18 (29%) magnetopause crossings showed evidence of KH waves and satisfied the KHI condition, we conclude that KH waves are an integral aspect of solar wind interactions at Jupiter’s magnetopause and that this particular solar wind interaction is important in jovian magnetosphere dynamics as it results in the transport of solar wind and magnetospheric plasma across the magnetopause. With the development of KH waves and in turn the transferring of mass and momentum across the magnetopause, a plasma mixing process takes place through a plasma diffusion region or boundary layer [Delamere and Bagenal 2010; Ma et al 2017; Blasl et al 2022]. Boundary layers with mixed plasma showing properties of both magnetosheath and magnetosphere plasma was observed in a large majority of crossings when KH waves were evident. We compare our results to the magnetic reconnection results in Montgomery et al. [2022] and find that six magnetopause crossings – 25% of events that satisfied the KHI condition – show evidence of both magnetic reconnection and KH waves. The outcome agrees with the hypothesis that the geometry of rolled up KH waves twist the local magnetic field structure which may lead to high magnetic shear angles within the wave, inducing localized magnetic reconnection [Hasegawa et al., 2009; Nakamura et al., 2013; Ma et al., 2017]. However, we do not observe magnetic reconnection in 75% of the observed magnetopause crossings that satisfy the KHI condition. This implies that KHI may occur without magnetic reconnection. We also note that we do not have observations near the subsolar point. This limits our conclusions because solar wind interactions like magnetic reconnection and KHI are thought to occur near the subsolar point and evolve as the plasma flows tailward, producing a mixed boundary layer [Fuselier et al., 2014; Ma et al., 2015; Grygorov et al., 2016; Masters et al., 2017; Zhang et al., 2018]. Additionally, reconnection may occur in the presence of KHI independent of the twisting of the local magnetic field structure.
5. Acknowledgements

All Juno data used in this study may be found on the Planetary Data System at https://pds.nasa.gov/. Specifically, the Juno JADE data used was the Level 3 version 04 at https://doi.org/10.17189/1519715, with the ion species 3 data used for the ion moments calculations. The Juno magnetometer data used was the 1s resolution planetocentric version 01 data files at https://doi.org/10.17189/1519711.

6. References


