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Key Points:
- First detailed plasma observations of the solar wind, bow shock, magnetopause, and outer dawn flank magnetosphere as Juno arrived at Jupiter
- Outer dawn magnetosphere filled with flux tubes of varying plasma properties, counterstreaming electron beams, and sunward moving plasma
- Lack of heavy compared to light ions indicating difference from plasma disk and centrifugal separation along Jovian magnetic flux tubes

Correspondence to:
D. J. McComas,
dmccomas@princeton.edu

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Plasma environment at the dawn flank of Jupiter's magnetosphere: Juno arrives at Jupiter

D. J. McComas[1,2,3], J. R. Szalay[3], F. Allegrini[3,4], F. Bagenal[5], J. Connerney[6], R. W. Ebert[3], W. S. Kurth[7], P. Louarn[8], B. Mauk[9], M. Reno[10], M. F. Thomsen[11], P. Valek[3,4], S. Weidner[2], R. J. Wilson[5], and S. Bolton[3]

[1]Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey, USA, [2]Office of the Vice President for the Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey, USA, [3]Space Science and Engineering Division, Southwest Research Institute, San Antonio, Texas, USA, [4]Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, Texas, USA, [5]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, Colorado, USA, [6]Goddard Space Flight Center, Greenbelt, Maryland, USA, [7]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA, [8]Institut de Recherche en Astrophysique et Planétologie, Toulouse, France, [9]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA, [10]Austin Mission Consulting, Austin, Texas, USA, [11]Planetary Science Institute, Tucson, Arizona, USA

Abstract This study examines the first observations from the Jovian Auroral Distributions Experiment (JADE) as the Juno spacecraft arrived at Jupiter. JADE observations show that Juno crossed the bow shock at 08:16 UT on 2016 day of year (DOY) 176 and magnetopause at 21:20 on DOY 177, with additional magnetopause encounters until 23:39 on DOY 181. JADE made the first detailed observations of the plasma environment just inside the dawn flank of the magnetopause. We find subcorotational ions and variable electron beaming, with multiple flux tubes of varying plasma properties. Ion composition shows a dearth of heavy ions; protons dominate the plasma, with only intermittent, low fluxes of O^+/S^{++}, along with traces of O^{++} and S^{+++}. We also find very little H_3^+ or He^+, which are expected for an ionospheric plasma source. A few heavy ion bursts occur when the radial field nears reversal, but many other such reversals are not accompanied by heavy ions.

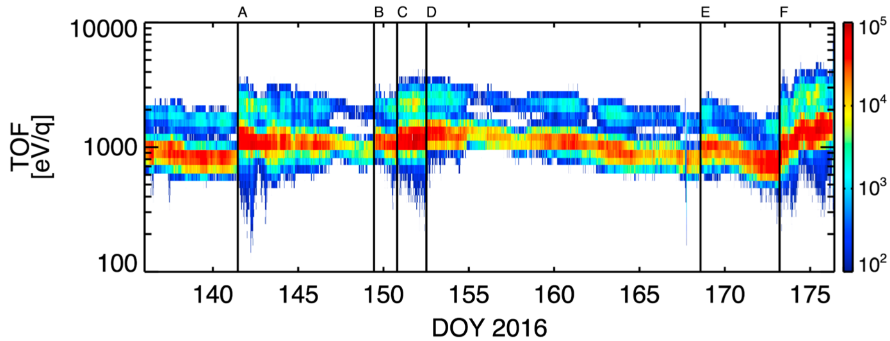
1. Introduction

The Juno spacecraft arrived at Jupiter and was inserted into a polar orbit on 5 July 2016 (Day of Year—DOY 187; all dates/times UT). The Jovian Auroral Distributions Experiment (JADE) [*McComas et al.*, 2013] measured the inbound solar wind, magnetosheath, and magnetospheric plasmas until it was turned off on DOY 181, 23:50 at 73 R_J (Jovian radii; all distances from planet center), 6 days before orbital insertion. JADE comprises both ion (JADE-I) and electron (JADE-E) spectrometers with high sensitivity and excellent spatial coverage, which provide ion composition measurements from 0.01 to 50 keV/q and electron measurements from 0.1 to 100 keV, respectively.

Prearrival reviews of the Jovian magnetospheric plasma environment have recently been provided relevant to JADE observations [*McComas et al.*, 2013] and to the Juno magnetosphere measurements more generally [*Bagenal et al.*, 2014]. In this study, we provide the earliest observations taken by JADE as it arrived at Jupiter and show the upstream solar wind environment as Juno approached Jupiter, the bow shock, magnetosheath crossing, multiple magnetopause encounters, and the first detailed observations of the plasma environment just inside the dawn flank of the magnetopause.

2. Solar Wind and Magnetosheath

JADE-I was powered on at 445 R_J on 2016 DOY 136 and observed the solar wind off the dawn flank of Jupiter continuously for the ~40 days before encountering the Jovian bow shock. Over this time, JADE observed six jumps in the solar wind speed indicative of shocks or compressional waves in the solar wind. Figure 1 shows these and provides the dates, times, locations, and approximate speed jumps for each of the solar wind shocks/waves as Juno approached Jupiter. Prior studies have examined the statistical properties of the solar wind around the distance of Jupiter and their likely effects on the Jupiter interaction [*Jackman and Arridge*, 2011; *Ebert et al.*, 2014]. However, solar wind variations are large enough that good comparisons with other



	Year-DOY	Time [UT]	Pre-speed [km/s]	Post-speed [km/s]	(Post-Pre) / Average	X_{JSO} [R_J]	Y_{JSO} [R_J]	Z_{JSO} [R_J]
A	2016-141	11:04	~380	~450	0.17	37.5	-399.6	52.2
B	2016-149	10:41	~400	~440	0.09	28.3	-340.9	46.0
C	2016-150	19:11	~410	~440	0.07	26.9	-330.8	44.9
D	2016-152	12:19	~440	~470	0.07	25.1	-317.9	43.5
E	2016-168	13:50	~380	~420	0.10	10.9	-192.4	30.0
F	2016-173	05:03	~350	~400	0.13	7.7	-153.5	25.7

Figure 1. (top) Ion counts as a function of energy per charge in the solar wind as Juno approached Jupiter from its dawn flank and (bottom) dates, times, locations, and approximate solar wind speeds associated with values before (pre) and after (post) each of the labeled shock/wave increases; shocks were identified visually and only included if the speed increase was greater than 0.05. The red to yellow colored counts at ~0.7–2 keV/*q* indicate solar wind protons, while the dark to light blue band at twice the *E/q* are solar wind He^{++}. Count rates below 10^2 s^{-1} have been suppressed to remove backgrounds.

Jovian observations can only be made when there is local, in situ solar wind data, such as that provided in this study. Thus, the timing of the structures shown in Figure 1 should be used to compare with remote observations of the Jovian aurora taken as Juno approached Jupiter [e.g., *Nichols et al*., 2017].

As Juno approached Jupiter from the dawn flank (~6 h local time), it was in the foreshock region of Jupiter's immense bow shock. Over this time, the solar wind was traveling ~400 km s^{-1} and looked typical for ~5 AU solar wind [*McComas et al*., 2000; *Ebert et al*., 2010, 2014] until DOY 173 at 5:03, when it crossed the last shock/wave structure. After that, the solar wind speed continued to rise, which is unusual in the solar wind and not expected from the interaction with Jupiter, where foreshock regions generally exhibit slowed flows owing to the interaction with backstreaming particles (the foreshock is the region upstream from a planetary bow shock that is populated by charged particles either reflected at the shock or leaking upstream from the magnetosheath or the magnetosphere and traveling upstream along the magnetic field—e.g., see the ISEE Upstream Waves and Particles special issue of JGR: vol. 86(A6), 1981). During the approach on DOY 167, a Hot Flow Anomaly (HFA) [*Schwartz et al*., 2000] was also observed. HFAs are cavities of heated and deflected solar wind plasma, and this is the first HFA observed at Jupiter [*Valek et al*., 2017].

Figure 2a shows the approach trajectory and color-coded regions identified by JADE. Figures 2b–2e show the corresponding JADE ion and electron spectrograms. Juno crossed the Jovian bow shock at 08:16 UT on DOY 176, as indicated by the slowing and heating of the bulk ions (Figure 2b). In the magnetosheath, JADE observed slowing (lower average energy) and heating of solar wind plasma. Figure 2 shows this temperature increase, both in the broadening of the proton time-energy distribution (Figure 2b) and by sheath plasma being detected over a larger spread of detectors covering look directions (ion anodes) 4–7 (Figure 2c). Anode 4 views along the spin axis in the sunward direction, anodes 7 and 8 look along the spin plane, and anode 11 along the spin axis in the antisunward direction. These look directions indicate flows deflected ~15°–35° away from the antisunward flow seen in the solar wind; this is consistent with the diversion of the magnetosheath around the Jovian magnetopause. Measurements through the magnetosheath reflect the plasma conditions produced upstream at the Jovian bow shock. Over its dawnside magnetosheath transit, JADE observed periods of both stable and highly variable plasma distributions. For example, from 18:00 to 18:45 on DOY 176 (indicated by arrow in Figure 2b), JADE encountered plasma distributions with large density and velocity variations, potentially due to a transition upstream from quasi-perpendicular to quasi-parallel shock conditions.

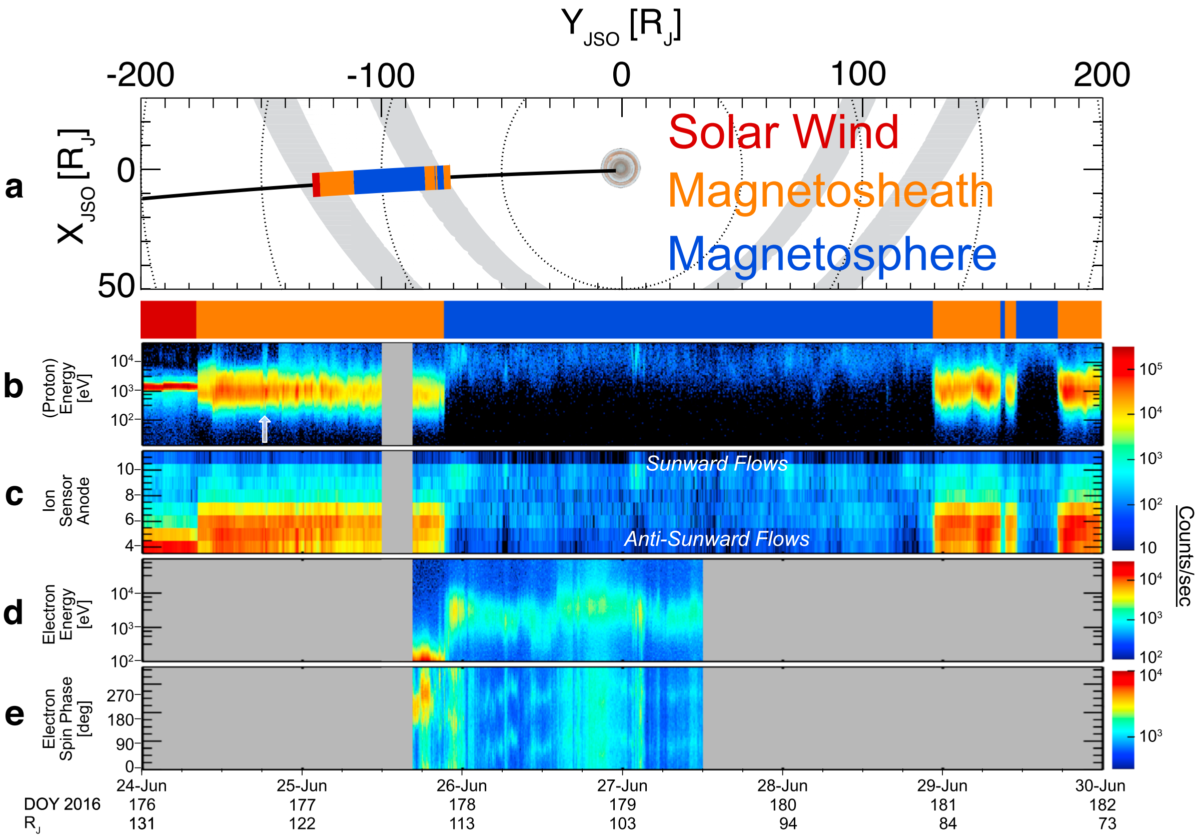


Figure 2. (a) Schematic diagram of Juno trajectory (black curve) and arrival at Jupiter geometry superposed on the 10%–90% range of locations (grey) for the bow shock (outer) and magnetopause (inner) from *Joy et al.* [2002]. Regions identified by JADE are color coded as solar wind (red), magnetosheath (orange), and magnetosphere (blue). The bottom four panels show JADE count rates as a function of the (b) proton channel *E*, (c) directional ion anode, (d) electron energy, and (e) electron spacecraft spin phase. Numbers across the bottom provide the date and radial distance from Jupiter.

After Juno traversed the magnetosheath, it first encountered the Jovian magnetopause at 20:29 UT on DOY 177 at ~114 R_J. After roughly 3 days of continuous magnetospheric observations, Juno crossed back into the magnetosheath and then crossed back and forth two additional times and remained in the magnetosheath all the way into 73 R_J, where it finally crossed back into the magnetosphere at 23:39 on DOY 181, just before being turned off prior to orbit insertion. These observations indicate that the solar wind ram pressure must have increased significantly near the end of DOY 180, compressing the magnetosphere to an unusually small size. We note that a magnetopause distance of 73 R_J at the dawn flank scales to a standoff distance directly upstream of only ~56 R_J, which is below the 10th percentile of standoff distances determined from previous missions [e.g., *Joy et al.*, 2002]; in contrast, the first crossing at ~114 R_J scales to ~81 R_J at the nose. In all, JADE identified seven complete dawnside magnetopause crossings (four in and three back out) over its arrival trajectory. There were also several partial crossings [see *Ebert et al.*, 2017]; these authors also used JADE data to show that there were accelerated ion flows and particle acceleration associated with the magnetic field shears at some of the magnetopause crossings, indicating magnetic reconnection and a locally open magnetopause.

3. Outer Dawn Magnetosphere

Inside the magnetosphere, count rates are significantly lower and show a primary ion population with energies ~4–40 keV (Figure 2b). Plasma flows in the outer magnetosphere can be determined from the distribution of counts observed on the various ion sensor anodes (Figure 2c). In contrast to the generally antisunward flows in the solar wind and magnetosheath, maxima in look directions/ion anodes 9–11 indicate generally

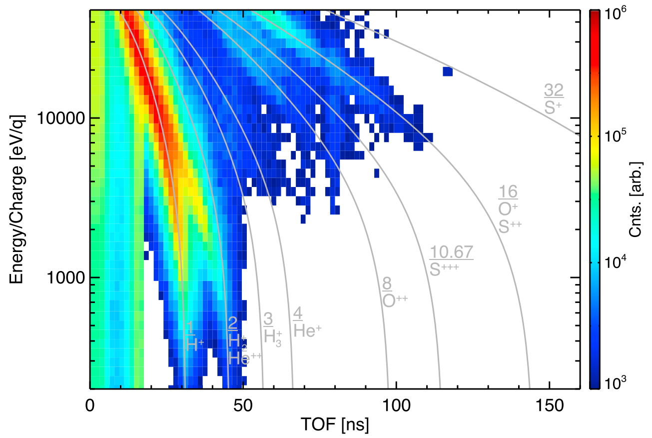


Figure 3. JADE ion E/q versus ion time-of-flight (TOF) collected over the entire magnetosphere interval shown in Figure 2; labeled curves indicate ion mass per charge. Some apparent response near $m/q = 2$ at the lower energies is caused by crosstalk from the protons, so there is probably little He^+, H_2^+, or even H_3^+, which are expected from atmospheric models. Similarly, the iogenic heavy ions are also far less abundant than protons across this region of the magnetosphere, at least in the JADE energy range.

sunward flows. For these dawnside observations (~6 h local time), this indicates motion consistent with the corotational direction for the plasma observed throughout the entire region from ~114 to 74 R_J. Measurement of plasma properties in this region where the magnetospheric plasma sheet merges into a boundary layer inside the dawn magnetopause is a major goal of the Juno mission. Juno data from this approach trajectory and subsequent orbits will address debates about the relative roles of rotation versus the solar wind in driving the dynamics of Jupiter's giant magnetosphere (see review by *Bagenal et al.* [2014]). The dominance of the corotational influence out to the magnetopause has also been seen in Saturn's magnetosphere, which is similarly characterized by a strong planetary field and rapid rotation [e.g., *Thomsen et al.*, 2010].

Near the end of the sheath interval, at 16:31 UT on 2016 DOY 177, the JADE electron instrument was turned on and fortuitously observed the first magnetopause crossing and then a significant region of the dawnside magnetosphere. JADE-E was only turned on for ~43.5 h before being turned off again. Electron observations over the magnetospheric interval show that energies are typically a few keV (Figure 2d). The magnetic field is roughly radial at these times (see below—Figure 4d) so the observed distributions are generally field aligned and show counterstreaming electron beams; these beams are often quite narrow but are variable and sometimes broaden (Figure 2e).

The variability of the outer magnetospheric plasma is evident in Figure 2, in both the electron and ion data. This variability and the discontinuous changes in the plasma distributions indicate that the dawnside of the outer magnetosphere sampled by JADE is filled with multiple flux tubes with differing plasma properties. These flux tubes are mixed together and generally move sunward, which is the corotational direction on the dawnside.

To examine the ion composition in the outer dawn magnetosphere, we analyzed the time-of-flight (TOF) data. Figure 3 shows the integrated counts over the entire outer magnetospheric interval (blue indicated regions in Figure 2) as a function of E/q and TOF. Curves for various mass per charge (m/q) "species" are indicated by the labeled curves. This plot provides a number of important results for the outer dawn magnetosphere: (1) protons are by far the most abundant species compared to both other light ions and all heavy ions in the JADE energy range, unlike prior plasma observations taken closer to Jupiter ($<40\,R_J$) in the plasma disk (see reviews by *Khurana et al.* [2004] and *Bagenal et al.* [2014]); (2) a lack of He^+ and H_3^+, which is surprising since a significant ionospheric source is expected from models [e.g., *Nagy et al.*, 1986] (see also *Glocer et al.* [2007] for the ionospheric source at Saturn); and (3) while $m/q = 16$ (O^+ and/or S^{++}) is the dominant heavy ion species, some O^{++} and S^{+++} are present, in contrast to little S^+, consistent with Voyager observations of composition in the plasma sheet at 10–40 R_J [*McNutt et al.*, 1981; *Bagenal et al.*, 2017].

While only counts are shown in Figure 3, we note that the efficiencies for detecting heavy and light ions are quite similar (differing by much less than a factor of 2), so the light ions clearly dominate the heavies in the JADE observations. Finally, we note that the JADE team has developed a new analysis technique that allows the separation of O^+ and S^{++} for the first time. This technique will be critical for finally resolving the relative abundance of these two ions, which is an important issue unresolved by earlier Voyager observations and

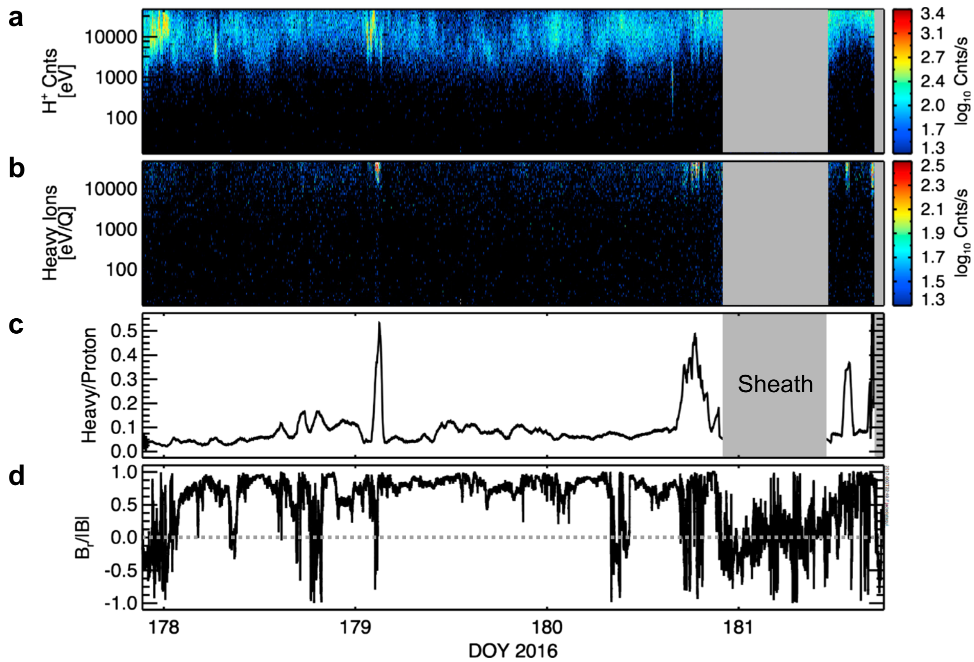


Figure 4. Comparison of (b) heavy and (a) light ion channels with the magnetic field. Correlation between the (c) heavy-to-light ion ratio and (d) reductions in the radial component of the magnetic field indicate that the heavy ion intervals are correlated with times of low $B_r/|B|$ and thus closeness to the plasma disk. On the other hand, other intervals of low $B_r/|B|$ do not show significant heavy ion enhancements.

critical to understanding the relative magnetospheric ion sources, losses, and composition [e.g., *McComas et al.*, 2017, and references therein].

In Figure 4, we include information from the JADE-I heavy ion channel. This channel, like the light ion channel, is produced autonomously on board the spacecraft and sums counts that lie in specific regions of E/q-TOF space (Figure 3) (see *McComas et al*. [2013], for details). As such, the heavy ion channel provides high cadence information about heavy ion abundance and also includes some backgrounds; here we use it more qualitatively to see how variable the heavy ion observations are and to look for correlation with the magnetic field information.

The ratio (Figure 4c) of counts in the heavy (Figure 4b) to light (Figure 4a) ion channels shows that the heavy ion content varies substantially along the path of Juno through the outer Jovian magnetosphere. While most of the time, there are very few heavy ions, significant "bursts" of heavy ions occur on DOY 179 around 2:45, DOY180 from 18:00 to 20:00, and DOY 181 around 13:40. Figure 4d shows the ratio of the radial component of the magnetic field (B_r) to the field magnitude ($|B|$) as measured by Juno's magnetometer [*Connerney et al.*, 2017].

Figure 4 shows that the intensifications of heavy ions occur at times when $B_r/|B|$ is near zero, and thus, when Juno is closer to the magnetic field reversal in the plasma disk. This is not surprising since copious heavy ions have been seen on prior missions inside the plasma disk. On the other hand, there are many other times when $B_r/|B|$ drops to low values that do not show significant heavy ion enhancement, at least within JADE's energy range.

4. Discussion

In this study, we have examined the JADE measurements from Juno's arrival at Jupiter. These observations comprise ~46 days before the Juno instruments were shut off prior to orbit insertion on DOY 187, 2016. JADE observations clearly identify six shock/wave structures in the solar wind, which should be used to compare to remote observations of the Jovian aurora taken prior to Juno's arrival. Juno crossed the bow shock on

DOY 176 at 08:16 and then made multiple magnetopause crossings, spanning a range from ~114 to 73 R_J; crossings near the end of the interval indicate that a strong compression of the magnetosphere occurred late on DOY 180 and the magnetosphere remained highly compressed through DOY 181.

We also provide the first detailed observations of the magnetospheric plasma environment just inside the dawn flank of the magnetopause. We find that this region is filled with numerous, different flux tubes with varying populations of electrons and ions and discontinuous changes between the flux tubes of differing plasma properties. Similar variability in thermal plasma was observed in the inner plasma sheet by Voyager [*McNutt et al*., 1981; *Bagenal et al*., 2017]. Such structure is also frequently seen in Saturn's outer magnetosphere [e.g., *Richardson*, 1986; *Gombosi et al*., 2009] and may be a consequence of the operation of the centrifugally driven flux tube interchange instability [e.g., *Thomsen et al*., 2015].

The dominance of protons in the ion composition observed in the dawn flank of the Jovian outer magnetosphere is important in two ways. First, the lack of discernible H_3^+ ions and little if any He^+ ions is surprising in that both were expected to be present from high-latitude atmospheric escape and atmospheric chemistry [e.g., *Nagy et al*., 1986]. In addition, while we observed some heavy iogenic ions such as O^+/S^{++}, as well as O^{++} and S^{+++}, the abundances observed are again far lower than that of the protons.

While most of the time JADE observed very few heavy ions in the dawnside outer Jovian magnetosphere, there were several brief intervals with a substantial fraction of heavy ions compared to the light ions. These correlated with times that Juno was at lower magnetic latitudes as indicated by small $B_r/|B|$ ratios and likely in or at least near the outer extension of the plasma disk.

A key result of these new observations is the dearth of heavy ions except during a few specific intervals at lower magnetic latitudes. We would thus conclude that this is likely due to a centrifugal separation by ion mass along the Jovian magnetic flux tubes sampled. On the other hand, a number of other intervals of low $B_r/|B|$ showed no enhancements of heavy ions. This suggests that the heavy ions on these flux tubes may have high temperatures that take them out of the JADE energy range, or they may have been depleted through some loss mechanism, possibly by preferential release of heavy ions down the dawn flank of the Jovian magnetotail [*McComas et al*., 2017].

Observations at Saturn [e.g., *Thomsen et al*., 2015] have demonstrated that reconnection of plasma-loaded flux tubes circulating through the magnetotail [e.g., *Vasyliūnas*, 1983] results in the preferential loss of heavy ions, which are centrifugally confined to the equatorial region of the flux tube, i.e., the portion that is pinched off and released downtail as a plasmoid. The lighter ions, which normally extend to higher latitudes, remain on the returning closed flux as it snaps back toward the inner magnetosphere, resulting in light ion-rich plasma on flux tubes that have participated in night side reconnection (the so-called "cushion region" at Jupiter [*Kivelson and Southwood*, 2005; *Went et al*., 2011]). Subsequent interchange between these depleted flux regions and the region inward of them that has not encountered the reconnection region can then redistribute the heated, light ion-rich plasma deeper into the magnetosphere [*Thomsen et al*., 2015].

Even just a few weeks of prearrival data and a few days of plasma observations as Juno entered the dawn flank of the Jovian magnetosphere have shown that JADE is providing outstanding observations that are key to understanding Jupiter's complex and fascinating magnetosphere.

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References

Bagenal, F., et al. (2014), Magnetospheric science objectives of the Juno mission, *Space Sci. Rev*., doi:10.1007/s11214-014-0036-8.

Bagenal, F., L. P. Dougherty, K. M. Bodisch, J. D. Richardson, and J. M. Belcher (2017), Survey of Voyager Plasma Science Ions at Jupiter: I Analysis Method, *J. Geophys. Res. Space Physics*, *122*, doi:10.1002/2016JA023797.

Connerney, J. E. P., et al. (2017), The Juno magnetic field investigation, *Space Sci. Rev*., doi:10.1007/s11214-017-0334-z.

Ebert, R. W., D. J. McComas, F. Bagenal, and H. A. Elliott (2010), Location, structure, and motion of Jupiter's dusk magnetospheric boundary from ˜1625 to 2550 RJ, *J. Geophys. Res*., *115*, A12223, doi:10.1029/2010JA015938.

Ebert, R. W., F. Bagenal, and D. J. McComas (2014), A survey of solar wind conditions at 5 AU: A tool for interpreting solar-wind magnetosphere interactions at Jupiter, *Front. Astron. Space Sci*., *1*, 4.

Ebert, R. W., et al. (2017), Accelerated flows at Jupiter's magnetopause: Evidence for magnetic reconnection along the dawn flank, *Geophys. Res. Lett*., doi:10.1002/2016GL072187, in press.

Glocer, A., T. I. Gombosi, G. Toth, K. C. Hansen, A. J. Ridley, and A. Nagy (2007), Polar wind outflow model: Saturn results, *J. Geophys. Res*., *112*, A01304, doi:10.1029/2006JA011755.

Gombosi, T. I., T. P. Armstrong, C. S. Arridge, K. K. Khurana, S. M. Krimigis, N. Krupp, A. M. Persoon, and M. F. Thomsen (2009), Saturn's magnetospheric configuration, in *Saturn from Cassini-Huygens*, edited by M. K. Dougherty, L. W. Esposito, and S. M. Krimigis, pp. 203–255, Springer, Dordrecht.

Jackman, C. M., and C. S. Arridge (2011), Solar cycle effects on the dynamics of Jupiter's and Saturn's magnetospheres, *Sol. Phys.*, *274*, 481–502, doi:10.1007/s11207-011-9748-z.

Joy, S. P., M. G. Kivelson, R. J. Walker, K. K. Khurana, C. T. Russell, and T. Ogino (2002), Probabilistic models of the Jovian magnetopause and bow shock locations, *J. Geophys. Res.*, *107*(A10), 1309, doi:10.1029/2001JA009146.

Khurana, K., M. G. Kivelson, V. Vasyliunas, N. Krupp, J. Woch, A. Lagg, B. Mauk, and W. Kurth (2004), The configuration of Jupiter's magnetosphere, in *Jupiter: Planet, Satellites, Magnetosphere*, edited by F. Bagenal, T. E. Dowling, and W. B. McKinnon, Cambridge Univ. Press, Cambridge, U. K.

Kivelson, M. G., and D. J. Southwood (2005), Dynamical consequences of two modes of centrifugal instability in Jupiter's outer magnetosphere, *J. Geophys. Res.*, *110*, A12209, doi:10.1029/2005JA011176.

McComas, D. J., B. L. Barraclough, H. O. Funsten, J. T. Gosling, E. Santiago-Muñoz, R. M. Skoug, B. E. Goldstein, M. Neugebauer, P. Riley, and A. Balogh (2000), Solar wind observations over Ulysses' first full polar orbit, *J. Geophys. Res.*, *105*(A5), 10,419–10,433, doi:10.1029/1999JA000383.

McComas, D. J., et al. (2013), The Jovian Auroral Distributions Experiment (JADE) on the Juno mission to Jupiter, *Space Sci. Rev.*, doi:10.1007/s11214-013-9990-9.

McComas, D. J., F. Allegrini, F. Bagenal, R. W. Ebert, H. A. Elliott, G. Nicolaou, J. R. Szalay, P. Valek, and S. Weidner (2017), Jovian deep magnetotail composition and structure, *J. Geophys. Res. Space Physics*, *122*, 1763–1777, doi:10.1002/2016JA023039.

McNutt, R. L., Jr., J. W. Belcher, and S. H. Bridge (1981), Positive ion observations in the middle magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 8319–8342, doi:10.1029/JA086iA10p08319.

Nagy, A. F., A. R. Barakat, and R. W. Schunk (1986), Is Jupiter's ionosphere a significant plasma source for its magnetosphere?, *J. Geophys. Res.*, *91*(A1), 351–354, doi:10.1029/JA091iA01p00351.

Nichols, J. D., et al. (2017), Response of Jupiter's auroras to conditions in the interplanetary medium as measured by the Hubble Space Telescope and Juno, *Geophys. Res. Lett.*, doi:10.1002/2017GL073029, in press.

Richardson, J. D. (1986), Thermal ions at Saturn: Plasma parameters and implications, *J. Geophys. Res.*, *91*(A2), 1381–1389, doi:10.1029/JA091iA02p01381.

Schwartz, S. J., G. Paschmann, N. Sckopke, T. M. Bauer, M. Dunlop, A. N. Fazakerley, and M. F. Thomsen (2000), Conditions for the formation of hot flow anomalies at Earth's bow shock, *J. Geophys. Res.*, *105*(A6), 12,639–12,650, doi:10.1029/1999JA000320.

Thomsen, M. F., D. B. Reisenfeld, D. M. Delapp, R. L. Tokar, D. T. Young, F. J. Crary, E. C. Sittler, M. A. McGraw, and J. D. Williams (2010), Survey of ion plasma parameters in Saturn's magnetosphere, *J. Geophys. Res.*, *115*, A10220, doi:10.1029/2010JA015267.

Thomsen, M. F., D. G. Mitchell, X. Jia, C. M. Jackman, G. Hospodarsky, and A. J. Coates (2015), Plasmapause formation at Saturn, *J. Geophys. Res. Space Physics*, *120*, 2571–2583, doi:10.1002/2015JA021008.

Valek, P. W., et al (2017), Hot flow anomaly observed at Jupiter's bow shock, *Geophys. Res. Lett.*, doi:10.1002/2017GL073175, in press.

Vasyliūnas, V. M. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 395–453, Cambridge Univ. Press, New York, doi:10.1017/CBO9780511564574.013.

Went, D. R., M. G. Kivelson, N. Achilleos, C. S. Arridge, and M. K. Dougherty (2011), Outer magnetospheric structure: Jupiter and Saturn compared, *J. Geophys. Res.*, *116*, A04224, doi:10.1029/2010JA016045.