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Key Points:

- The duskside of the Jovian magnetotail is dominated by light ions instead of heavy ions from Io all the way back to over 2500 Jovian radii
- The tail is highly structured and has two dominant periodicities of 3.53 and 5.35 days; the shorter one matches Europa's orbital period
- There is no evidence for plasma acceleration or entry, suggesting that light ions may preferentially move toward dusk via ambipolar diffusion

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Jovian deep magnetotail composition and structure

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Abstract We analyze plasma ion observations from the Solar Wind Around Pluto instrument on New Horizons as it traveled back through the dusk flank of the Jovian magnetotail from ~600 to more than 2500 Jovian radii behind the planet. We find that at all distances, light ions (mostly protons) dominate the heavy ions (S^{++} and O^+) that are far more abundant in the near Jupiter plasma disk and that were expected to be the primary ions filling the Jovian magnetotail. This key new observation might indicate that heavy ions are confined closer to the equator than the spacecraft trajectory or a substantial addition of light ions via reconnection and/or mixing along the magnetopause boundary. However, because we find no evidence for acceleration of the tail plasma with distance, a more likely explanation seems to be that the heavy ions are preferentially released down the dawn flank of the magnetotail. Perhaps, this occurs as a part of the process where flux tubes, after expanding as they rotate across the near-tail region, need to pull back inward in order to fit within the dawnside of the magnetopause. A second major finding of this study is that there are two dominant periods of the plasma structures in the Jovian magnetotail: 3.53 (0.18 full width at half maximum (FWHM)) and 5.35 (0.38 FWHM) days. Remarkably, the first of these is identical within the errors to Europa's orbital period (3.55 days). Both of these results should provide important new fodder for Jovian magnetospheric theories and lead to a better understanding of Jupiter's magnetosphere.

1. Introduction

Jupiter's strong magnetic field produces an interaction with the solar wind that generates the largest magnetosphere in the solar system [e.g., see *Dessler*, 1983; *Kivelson*, 2007]. Unlike the Earth's magnetosphere, which is driven by its coupling to the solar wind, the Jovian magnetosphere is largely driven internally by large sources of new ions and the planet's rapid (~10 h) rotation rate. Volcanoes on Jupiter's moon Io provide a time variable source, injecting on average about a ton per second (current best estimate ~800 kg s^{-1} [*Bagenal and Delamere*, 2011]) of material—largely SO_2—that dissociates and becomes ionized, producing S^{++} and O^+ as the dominant ions [*Thomas et al.*, 2004].

The heavy ions are picked up by Jupiter's strong and rapidly rotating magnetic field, forming a dense (~2000 cm^{-3}) plasma torus. Roughly, two thirds of these ions are currently thought to be lost through charge exchange [*Bagenal and Delamere*, 2011], and thus radiate away as energetic neutral atoms. The remaining ions, approximately one third of the ~800 kg s^{-1}, are heated to tens of keV and spread radially outward to form an extended equatorial plasma disk [*Khurana et al.*, 2004; *Krupp et al.*, 2004]. These ions are ultimately expected to escape the system down Jupiter's magnetotail. *Delamere and Bagenal* [2013] used the size of the magnetosphere and the length of the tail to estimate the momentum transfer from the solar wind (via a KHI-mediated viscous interaction) and concluded that the mass-loading rate is consistent with a 600–1500 kg s^{-1} heavy ion source.

The Jovian inner magnetosphere has been studied by multiple spacecraft. The magnetometers and particle detectors on *Pioneer 10* (1973) and *Pioneer 11* (1974) exposed the vastness of Jupiter's magnetosphere and made in situ measurements of energetic ions and electrons. Additional data came from subsequent traversals of Jupiter's magnetosphere by the two *Voyagers* (1979), *Ulysses* (1992), *Cassini* (2000), and *New Horizons* (2007) spacecraft, but it was the 33 orbits of *Galileo* (1995–2003) around Jupiter that mapped out the equatorial magnetospheric structures and monitored their temporal variability. Galileo had an orbit that sampled as far as ~200 R_J back along the dawn tail flank [*Frank et al.*, 2002]. This is comparable to roughly twice the Jovian standoff distance [*Joy et al.*, 2002], and thus not very far very back into Jupiter's magnetotail. On approach to Saturn, Voyager 2 observed signatures that were interpreted as being associated with the very deep Jovian magnetotail intermittently from ~5000 to ~9000 R_J (nearly 5 AU) [*Scarf et al*., 1981; *Kurth et al*., 1982; *Lepping et al*., 1983]. These included intervals of relatively radial magnetic field orientations and radio wave observations of kilometric continuum radiation, which were interpreted as indicative of magnetic regions with low electron densities. While the results were not definitive, several ideas were advanced, including evidence for draped magnetosheath fields, Earth-like tail lobes, filamentary structures, and comet-like tail reconnection/detachments.

Most recently, the Solar Wind Around Pluto (SWAP) instrument [*McComas et al*., 2008] on the New Horizons spacecraft measured the plasma within Jupiter's magnetosphere from entering it near the nose, through closest approach at ~32 R_J on the duskside, and back to more than 2500 R_J (>1 AU) down the Jovian magnetotail [*McComas et al*., 2007]. These authors showed that the magnetosphere was highly structured, with a remarkable and diverse array of plasma populations, from cold, low-energy heavy ions overlaid with the low-energy tail of a hot population clearly extending above SWAP's ~7.5 keV/q energy range near closest approach, to highly variable and sometimes discontinuous fluxes and energies of plasma ions throughout the tail. They also showed that the spacecraft repeatedly exited the tail—back and forth into the deep magnetosheath—at distances from ~1650 to 2430 R_J down tail. *McComas et al*. [2007] argued for a partially or intermittently open deep magnetopause boundary as evidenced by some boundary layer intervals that simultaneously contained both magnetosheath and tail ion populations. Finally, these authors showed that there were indications of Jupiter's 10 h period at both ~450 and ~1500 R_J and evidence for intermittent 3–4 day periodicities that might indicate plasmoids being ejected near Jupiter and traveling down the magnetotail [*Woch et al*., 2002; *Kronberg et al*., 2005, 2007, 2009; *Vogt et al*., 2010, 2014; *Kasahara et al*., 2013].

Ebert et al. [2010a] catalogued and further examined the 16 magnetopause crossings observed by SWAP. These authors showed that the crossings were statistically consistent with expected solar wind deflections and argued that the crossings could be well explained by expansions/contractions and deflections of the tail arising from the typical solar wind stream structure at ~5 AU. *Nicolaou et al*. [2014] subsequently developed a forward model of plasma parameters through the SWAP instrument, minimized the differences between this output and the observations, and thereby quantified the bulk plasma parameters in the distant magnetosheath, magnetosheath/tail boundary layer [*Nicolaou et al*., 2014, 2015a], and for 64 analyzable intervals in the deep Jovian magnetotail [*Nicolaou et al*., 2015b]. These latter authors also quantified the interval of cold coflowing H^+ and $H_3{}^+$ in the tail found by *McComas et al*. [2007] and showed that these two species had roughly equal densities even though H^+ is expected to dominate theoretically [*Nagy et al*., 1986]; we note that for hotter populations generally found in the magnetotail, the energy per charge (*E/q*) spectra of H^+ and $H_3{}^+$ substantially overlap and are therefore not distinguished by SWAP.

Energetic particle measurements were also made over the New Horizons tail passage by the Pluto Energetic Particle Spectrometer Science Investigation (PEPPSI) instrument [*McNutt et al*., 2008]. Energetic particle observations [*McNutt et al*., 2007; *Haggerty et al*., 2009; *Hill et al*., 2009; *Kollmann et al*., 2014] collectively showed multiple species, compositional variation, velocity dispersions, intermittent ~3 day periodicities, and particle anisotropies. Several dispersive events drive the largest variability seen in energetic particles and confirm that there is at least intermittent magnetic connection between tail and boundary layer and between boundary layer and magnetosheath. Differences between the tail and deep magnetosheath were much less clear in the energetic particles than in the plasma data, and while energetic protons and helium ions are more abundant in the magnetosheath and energetic electrons, oxygen, and sulfur ions are more abundant in the tail, their collective variability is larger than any consistent difference between the two [*Kollmann et al*., 2014].

Other work has been more theoretical. *Fukazawa et al*. [2010] used MHD simulations to examine possible dynamics in the distant Jovian magnetotail and simulated plasmoid ejections down the tail. Subsequently, *Cowley et al*. [2015] argued that the near-planet mass loss rates observed at Jupiter and Saturn were only a fraction of the likely mass loss rate via plasmoids down these bodies respective magnetotails.

Despite all of the prior work, Jupiter's global interaction with the solar wind is still surprisingly uncertain. It is the purpose of this study to examine the Jovian magnetotail in more detail, to resolve the heavy versus light composition of ions up to a few keV/q, to examine the structure within the tail, and to develop an integrated understanding of the deep Jovian magnetotail.

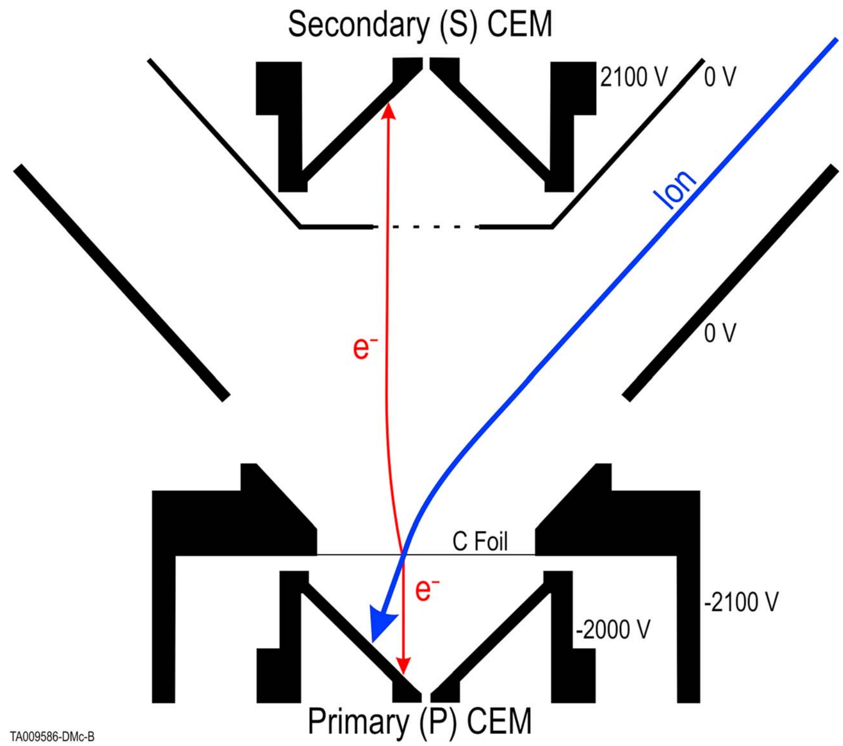

Figure 1. Schematic diagram of SWAP detector section. Incident ions can produce primary (P) and secondary (S) events, which also produce coincidence (C) events if they both occur within a 100 ns window. Light ions are best measured by using the C data, which provides an exceptional signal to noise. Heavy, iogenic ions, however, have a hard time transiting the foil and thus produce significantly more S than P events. The S/P ratio therefore provides the critical information about different distributions of ion masses and thus their origins. Adapted from *McComas et al.* [2016] to indicate applied voltages at the time of the Jupiter observations.

2. Resolving Heavy and Light Ions in SWAP Data

The SWAP instrument design [*McComas et al.*, 2008] is based on a top-hat style electrostatic analyzer (ESA) that filters ions by their *E/q*. After passing the ESA, selected ions cross a nearly field-free conical region and are focused into a coincidence detector section (Figure 1). When an incident ion enters this detection section, it is accelerated by the negative potential on the ultra-thin (~10 nm) carbon foil [*McComas et al.*, 2004; *Allegrini et al.*, 2016] and surrounding guard ring, gaining ~2.1 keV per charge (*q*). Most light ions (e.g., ionospheric H^+ and $H_3{}^+$ and solar wind H^+ and He^{++}) transit through the foil to be detected as primary (P) events in the primary channel electron multiplier (CEM) detector. Any secondary electrons emitted from the exit surface of the foil may be simultaneously detected as the same P event, while secondary electrons emitted from the entrance surface of the foil as the ion enters it are accelerated up to the secondary CEM detector, generally triggering a secondary (S) event. If a P and S event both occur within an ~100 ns window, the event is labeled a coincidence (C) event by SWAP's electronics and all three P, S, and C are registered; if no coincidence is found, then only the single P or S is registered for that event. The probability of detecting a P, S, or C depends on the incident ion's energy and mass.

As pointed out by *McComas et al*. [2007] and studied via detailed laboratory testing of a nearly identical "SWAP-2" instrument [*Ebert et al*., 2010b], the S/P ratio provides some statistical information about the ion masses being measured. This is because (1) heavier ions produce, on average, more secondary electrons off of the front surface of the SWAP detector section's entrance foil [*Ritzau and Baragiola*, 1998], increasing the probability of an S detection, and (2) heavier ions at lower energies often do not make it all the way through the foil, and thus cannot register as P (or C) events [*Allegrini et al*., 2003, 2006]. Together, these effects make the S/P ratios much larger for heavy ions than for light ones on a statistical basis.

The initial analysis of the SWAP data from the New Horizons spacecraft flyby of Pluto [*Bagenal et al*., 2016] was not able to separate heavy versus light ions. Subsequently, *McComas et al*. [2016] showed new S/P ratio data

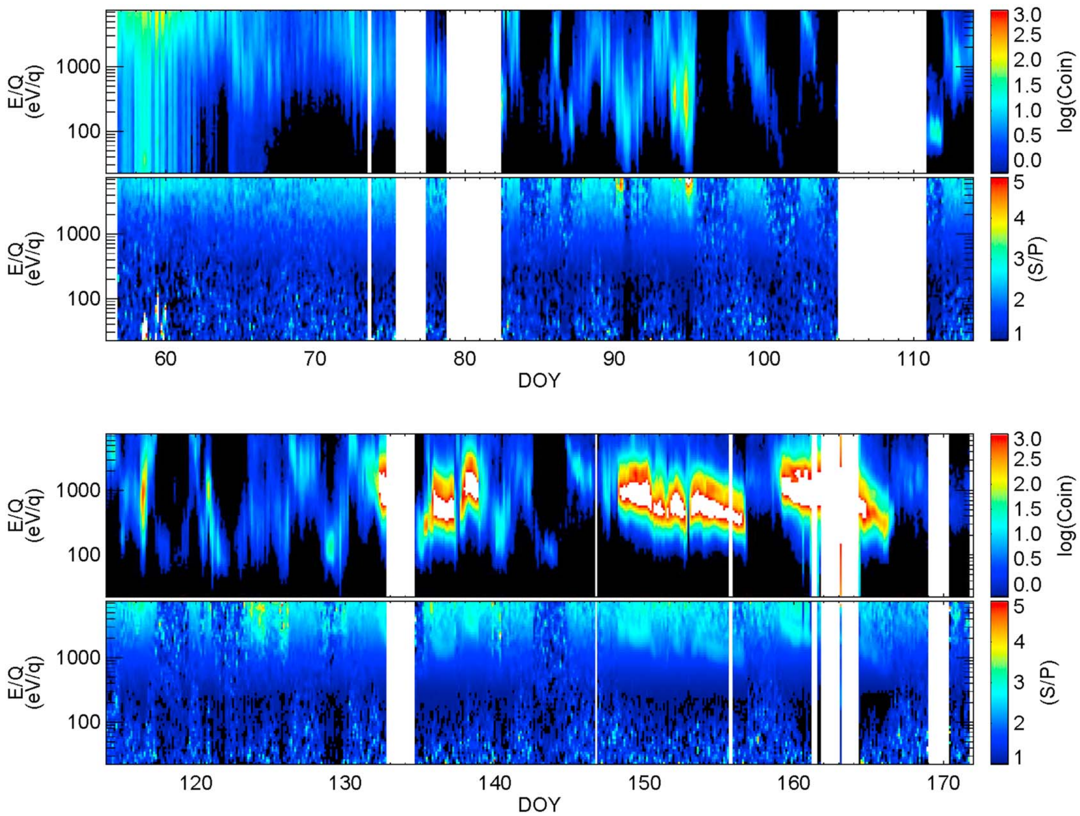

Figure 2. Color spectrograms of (first and third panels) coincidence counts and (second and fourth panels) secondary/primary events in the SWAP detector as a function of energy per charge and day of year in 2007 as New Horizons transited down the Jovian magnetotail. The white saturated regions of counts starting around DOY 130 (Figure 2, third panel) are from times when NH crossed out of the tail into the much higher fluxes of the Jovian magnetosheath. The white saturated intervals below ~100 eV/q on DOYs 58 and 59 in the S/P ratio (Figure 2, second panel) are the only intervals of heavy plasma ions detected by SWAP anywhere in the Jovian magnetosphere and magnetotail. Note that the New Horizons spacecraft was three axis stabilized before DOY 80 and continuously spinning thereafter.

for CH_4^+ and used this ratio to identify heavy Plutogenic ions (most likely CH_4^+) and measure them separately from the impinging (light) solar wind ions. That work provided numerous discoveries about the Pluto-solar wind interaction, including identification of a Plutopause and heavy ion tail extending back >100 Pluto radii behind Pluto. Here we similarly use the S/P ratio to quantitatively examine the heavy versus light ion composition through New Horizons extended traversal down the deep Jovian magnetotail.

3. Plasma Ion Composition in the Jovian Magnetotail

Figure 2 shows the full time interval of SWAP observations from the 2007 Jupiter flyby, beginning on day of year (DOY) 56 and extending through the end of DOY 175. Closest approach to Jupiter was on DOY 59 at ~32 R_J. Prior to DOY 81 the spacecraft was three axis stabilized with the high gain antenna mostly pointed back to Earth and was fixed at various roll angles around that axis in order to facilitate imaging and other observations from New Horizons. After DOY 81, the spacecraft was spinning at ~5 rpm about its nearly Earth-pointing high gain antenna axis. The panels are in pairs—the first and third panels provide contiguous color coded spectrograms of coincidence count rates as a function of energy per charge (E/q) and time; these data show the extreme variability of the SWAP observations throughout the Jovian magnetosphere and magnetotail. The second and fourth panels show color spectrograms of the S/P ratio for the same two intervals. Heavy ions are only evident in the very narrow saturated (white) structure at less than 100 eV/q near closest approach on DOYs 58 and 59. Otherwise, the S/P ratio shows statistical variability but is remarkably self-similar throughout the tail interval, increasing from values ~1.5 at low energies to ~2–3 at high energies.

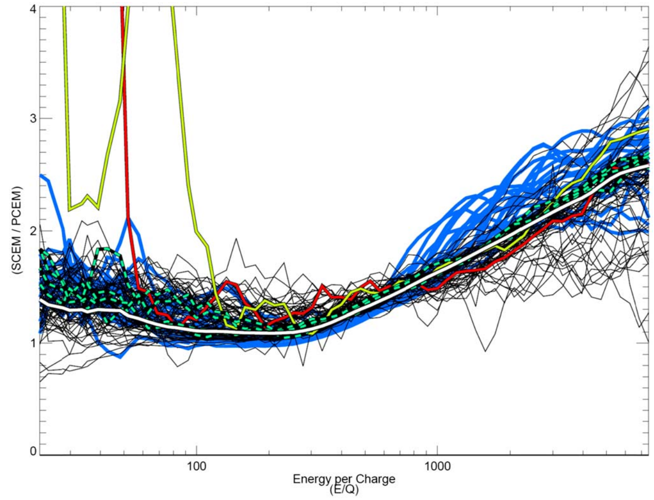

Figure 3. Secondary to primary ratio for each DOY from the entire flyby. High S/P ratios indicate heavy ions from Jupiter on DOYs 58 (red) and 59 (green). The small enhancements in S/P at ~0.7–4 keV/q indicate He^{++} ions from the solar wind on days when the spacecraft was outside the magnetotail and in the adjacent magnetosheath (blue lines). The white line provides the average of the remaining days, which represent almost entirely light ions at all energies up to ~4 keV. We also show with green dashed lines the DOYs 99, 120, 126, and 130, where energetic particle dispersion events from PEPPSI appear to extend down into the SWAP energy range; the SWAP data show no evidence for heavy ions on these days either.

In order to provide a more quantitative analysis, Figure 3 shows the S/P ratio integrated separately over each individual day of SWAP data. DOYs 58 (red) and 59 (green) clearly show heavy ions at <100 eV/q. The blue lines are from days when New Horizons was at least partially in the magnetosheath (white, saturated times in the first panel of Figure 2). These magnetosheath intervals show a distinct enhancement in S/P from ~0.7 to 4 keV/q, which arises from the few percent (typically ~4%) alpha particle (He^{++}) content of the solar wind. Clearly, the other days (black lines, white line is their average) are highly self-similar, and similar to the sheath intervals with the exception of the lack of alpha particles. The overall shape of this curve is produced by the competing effects of (1) the energy-dependent backward (entrance surface) secondary electron efficiency, which increases with increasing energy [*Ritzau and Baragiola*, 1998], and (2) the decreasing likelihood of an ion transiting through the foil at the lowest energies, as described above.

It is a remarkable result that the SWAP data show essentially no significant heavy ions over the energy range up to ~4 keV (above this energy the heavy and light ions cannot be distinguished by the S/P ratio technique [*Ebert et al.*, 2010b]). Some, but not all, of the dispersion events identified in the energetic particle data [*McNutt et al.*, 2007; *Hill et al.*, 2009], appear to extend down into the SWAP energy range. In particular, there are several events that started at higher energies about a day before and then extended down into the SWAP energy range on DOYs 99, 120, 126, and 130 [see *Hill et al.*, 2009, Figure 2]. In Figure 3 these four days are indicated by the green dashed curves. Clearly, all four are consistent with the curves from the bulk of the other days, and in fact do not even show the S/P enhancements from ~0.7 to 4 keV/q seen for the sheath intervals. Since O^+ and S^{++} are much heavier than the He^{++} that produces these enhancements, we conclude that the low-energy tails of the PEPSSI dispersion events are generated by light ions, at least as they extend down into the SWAP energy range below 4 keV/q. Thus, from Figure 3, we conclude that the portions of the Jovian magnetotail sampled by New Horizons contain far more light ions, primarily protons, compared to the number of heavy iogenic ions at these energies on all days when the spacecraft was in the magnetotail or deep magnetosheath.

4. Plasma Moments and Mass Loss Down the Jovian Magnetotail

Plasma moments are extremely difficult to produce from the low fluxes and diverse distributions observed by SWAP in the Jovian magnetotail. Nonetheless, *Nicolaou et al.* [2014, 2015a, 2015b] developed a technique as described above. Figure 4 shows the *Nicolaou et al.* [2015b] moments ultimately provided by this technique. At the time, those authors had to assume a composition for the ions, and based on *McComas et al.* [2007] and *Ebert et al.* [2010a], they assumed that they were protons. With the results in section 3 of the current study, we have now validated this assumption and shown that they are not only light as opposed to heavy ions, with most likely the vast majority being protons. The moments characterize the bulk parameters for 64 intervals when the spacecraft was between 600 and 1700 R_J back in the magnetotail and provided the tailward flow speed (plus signs in the first and third panels of Figure 4), and density (n) and temperature (T) in the second

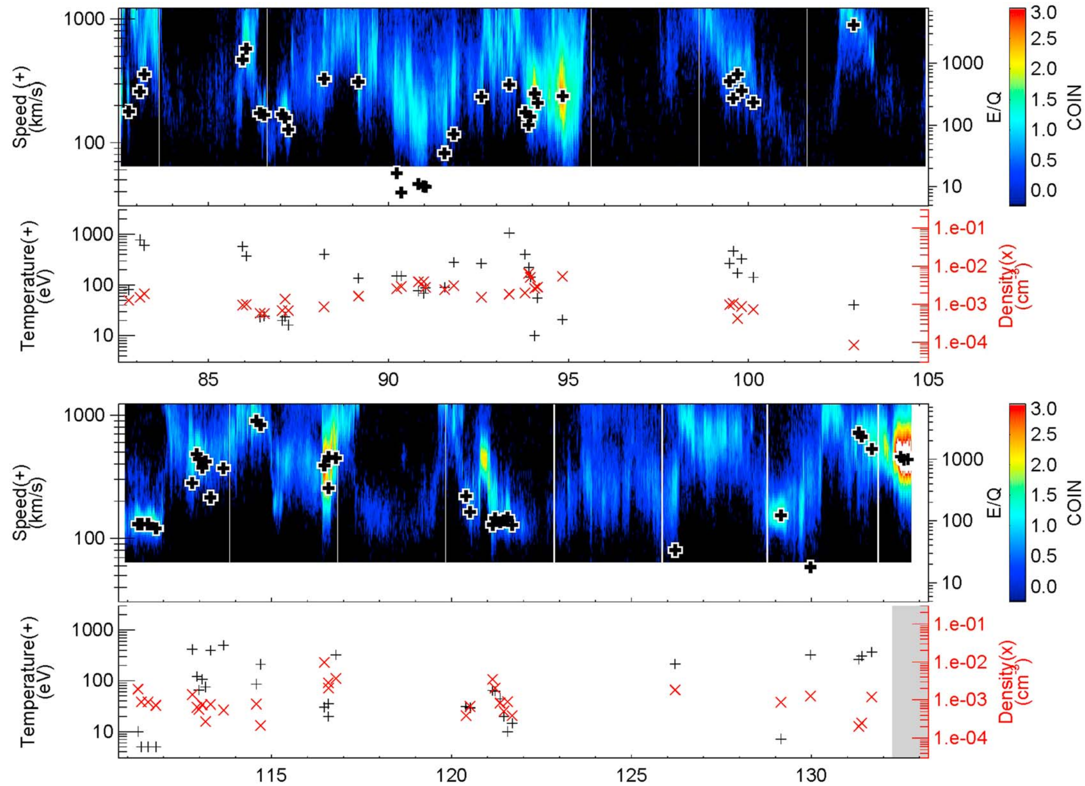

Figure 4. SWAP color spectrogram of coincidence counts and proton plasma parameters for 64 intervals determined by *Nicolaou et al.* [2015b]. The first and third panels show counts and plasma flow speed (crosses), while the second and fourth panels give the density (red Xs) and temperature (black + signs).

and fourth panels of Figure 4. We note that when the plasma is hot (~keV), the speeds can be quite low (~100 km s^{-1}) even for relatively high mean *E/q* values.

The SWAP observations show a very broad array of plasma parameters, with speeds from <50 to ~1000 km s^{-1} and variations in both the density and temperature of 2 orders of magnitude. *Nicolaou et al.* [2015b] found no evidence for a characteristic variation or evolution of the plasma parameters with distance down the tail. We interpret this result to mean that, in general, tail structures were already largely developed by ~600 R_J down tail and no longer, on average, significantly accelerating/slowing or expanding/contracting at greater distances. The results do, however, support the suggestion of *McComas et al.* [2007] that the tail acts as a conduit for blobs with varying plasma properties that are ejected from the near tail region. Here we have learned that at least along the trajectory through tail sampled by New Horizons, the vast majority of this material is composed of light ions.

Nicolaou et al. [2015b] used their derived moments to make a rough estimate of the mass loss rate down the tail. Assuming an average tail radius of ~170 R_J [*Joy et al.*, 2002], they calculated a flux of ~3.2×10^8 m^{-2} s^{-1}; for protons this amounts to a mass loss rate of ~250 kg s^{-1}, 7 to 8 times larger than the estimated ionospheric source rate from *Nagy et al.* [1986]. It is important to note, however, that the moments these authors provided were preferentially calculated for intervals with higher count rates, and thus denser times than on average. Many intervals in the tail have counts in SWAP just barely above the noise level, so this sampling bias could well explain the larger value and looking at the times when moments were calculated in Figure 4, it is easy to believe an average mass flux that is at least an order of magnitude smaller.

5. Structure in the Jovian Magnetotail

As originally observed by *McComas et al.* [2007], the Jovian magnetotail is highly structured with diverse plasma populations that vary widely in their *E/q* distributions and intensity. Section 3 showed that the

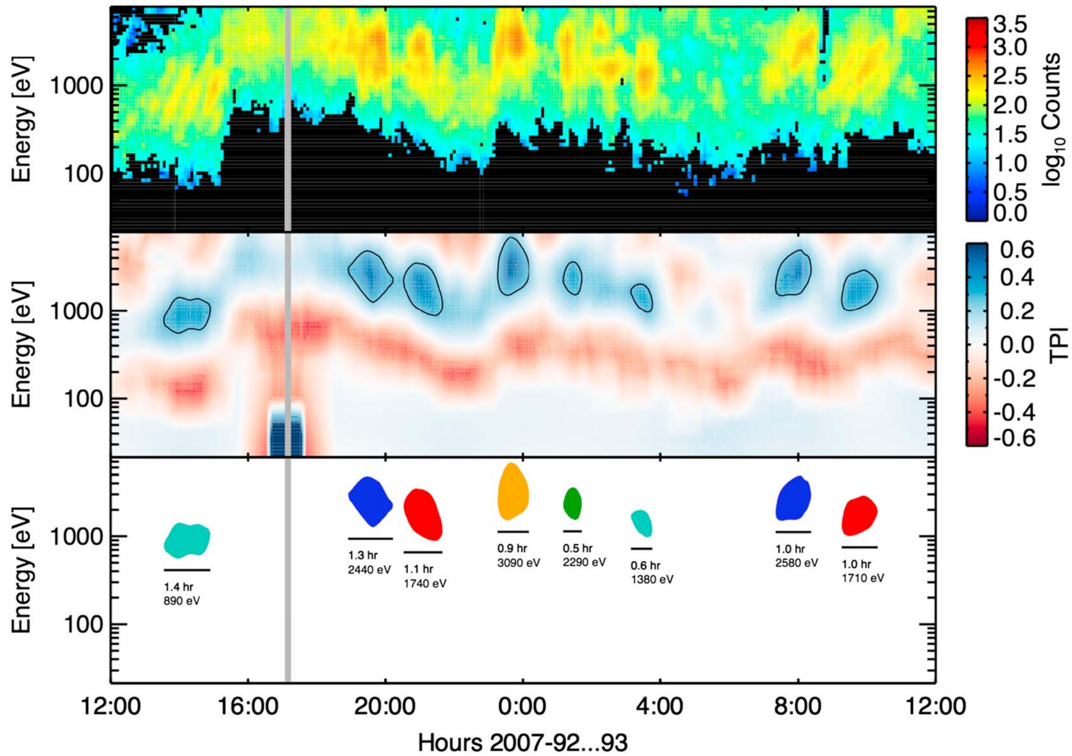

Figure 5. (a) SWAP total count rates as a function of time and energy for a typical 24 h magnetotail interval. (b) The topographic position index. (c) The plasma structures identified with TPI ≥ 0.3. The gray vertical bar indicates a short period when SWAP was off. The algorithm identified false structures near on/off boundaries due to the averaging that were removed from our analysis. Durations and average energy/charge are listed below each structure.

composition of the Jovian tail at energies <4 keV was essentially the same, with light ions significantly dominating (at least by number) over heavy ions. Therefore, we found no compositional boundaries to aid in the identification of the plasma structures.

Even without compositional boundaries, however, the Jovian tail clearly has significant structure on a variety of time scales and it is important to find some way to characterize and quantify these structures. We tried several of the more standard techniques, for example, by searching for discontinuities in different one-dimensional quantities including peak flux, peak energy, and total flux as a function of time. However, we found that analysis in any of these domains alone was not adequate. The information in the discrete transitions apparent in the *E/q* of the ions provides critical information needed to uniquely identify the structures. Thus, we turned to a technique that allowed identification based simultaneously on information in both the time and *E/q* domains. After assessing several options, we settled on a standard analysis tool from another field that was already optimized to discern structures in a two-dimensional space—one from topographic analysis—but here we use it to analyze the "terrain" in *E/q* versus time.

5.1. Structure Identification

To identify structures observed by SWAP, we treat the SWAP total corrected count rates in the time-*E/q* domain as a topographic map and utilize existing analysis tools designed to classify features in this two-dimensional terrain. The topographic position index (TPI) [*Weiss*, 2001] is a simple metric used to classify terrain as well as to characterize wildlife behavior [*Guisan et al.*, 1999; *Dickson and Beier*, 2007]. TPI is the difference between the elevation ε of a given point and the average elevation μ in a neighborhood around this point. In topographic analysis, ridges and mountains have large TPI values, while valleys and canyons have low TPI values. TPI is scale-dependent, such that using a small averaging neighborhood would identify small-scale structures, while using a large neighborhood ignores the smaller variations and finds larger-scale structures.

We implemented TPI analysis to identify "mountains" of ion flux in the SWAP spectrograms, corresponding to discrete plasma structures with enhanced ion densities. We focus on data taken after 2007-087 once New

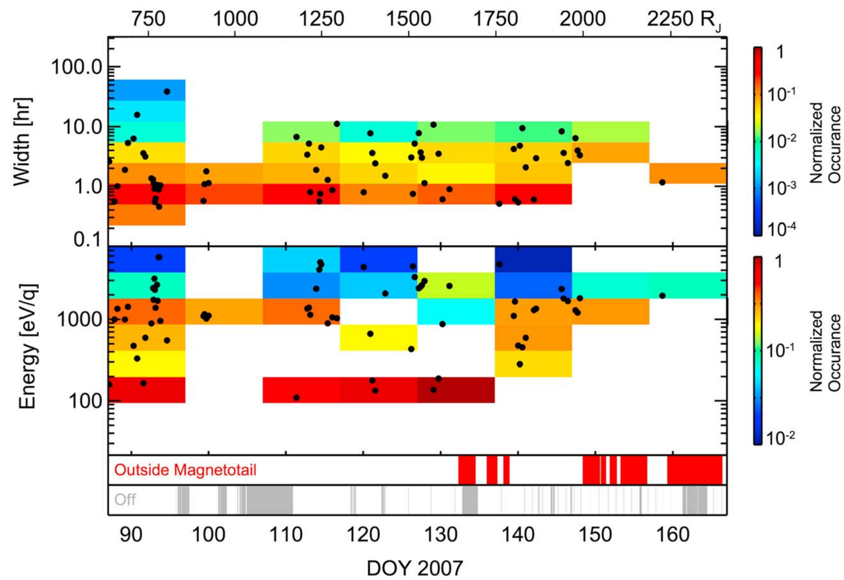

Figure 6. The structure distributions as a function of duration (width) and energy per charge for the entire interval that NH was spinning as it traveled back down the magnetotail. The gray and red vertical bars indicate that time SWAP was not taking measurements and was outside the magnetotail, respectively. Colors indicate the number of particles in each region normalized by SWAP on-time inside the magnetotail and total width and energy spanned by each bin. Magnetosheath structures have been removed from this analysis.

Horizons was continuously spinning. Figure 5a shows the total coincidence count rates. To identify structures, we first normalize $\log_{10}$(count rate) by subtracting off the mean count rate over the entire data set and dividing by the standard deviation. We then calculate TPI = $\varepsilon(t, E/q)$-$\mu(t, E/q)$ for each time t and energy per charge E/q bin (in $\log_{10}$ scale), where $\varepsilon(t, E/q)$ is the normalized count rate. The neighborhood $\mu(t, E/q)$ is calculated by using a simple rectangular average from $t - 10\,dt$ to $t + 10\ dt$ over all energies, where $dt \approx 320$ s. We then apply an additional square average over the nearest ±5 points in (t, E/q) space, which corresponds to approximately 27 min in time and 0.2 in $\log_{10}(E/q)$, to remove residual small scale structures. Plasma structures are identified in this figure as regions with TPI ≥ 0.3 (Figure 5); we also tried other cutoff values of TPI and found similar results for a range of TPI cutoffs around this value.

We calculate the distribution of these structures as a function of duration (width), energy per charge, and time as shown in Figure 6. With the exception of a single large, ~38 h, structure on DOY 94, all structures in the magnetotail had duration of <16 h. After DOY 132, New Horizons experienced multiple magnetopause crossings along the northern side of the dusk flank of Jupiter's magnetotail [*McComas et al*., 2007; *Ebert et al*., 2010a]. TPI analysis naturally identifies large-scale structures associated with intervals of magnetosheath observations, with the largest of these lasting approximately 8 days from DOY 148 to DOY 156.

The identified structures had a differential duration distribution of $f(w) \propto w^{-1.7 \pm 0.3}$, where the error bar is derived from varying the structure identification parameters. We limited our analysis to find structures larger than 5 SWAP measurement periods, corresponding to a minimum threshold of 27 min. Many of the identified structures exhibit further substructure, which would skew the distribution toward larger (steeper) exponents if these substructures were classified as separate structures. The analysis presented here uses a simple implementation of TPI to characterize structures in our plasma data. We tested a variety of TPI thresholds and neighborhood schemes and converged on a setup that produced structure identifications consistent with what we identified by visual inspection.

If we take a typical width for such events to be ~1 h (Figure 6, top) and typical speeds to be 100–1000 km s^{-1} (Figure 4), then we estimate typical tailward extent of these structures (along NH's trajectory) to be 5–50 R_J. This is consistent with plasmoids identified from Galileo magnetic field data (<100 R_J) by *Vogt et al*. [2014] to be sized 2.6–20 R_J in length by 45–70 R_J in width by 2–12 R_J in height. Dividing the 64 events shown in Figure 6 by the 61 days between DOY 87 and 148, we get about 1 event per day. This is a little below the 2–5 plasmoids per day found by *Vogt et al*. [2014].

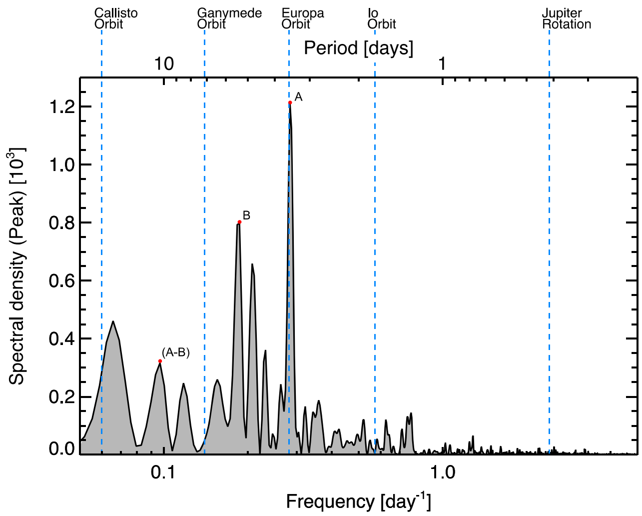

Figure 7. The Lomb normalized periodogram for the peak energy time series while in Jupiter's magnetotail. The largest peak is coincident with Europa's orbital period to within the measurement uncertainties.

Figure 6 demonstrates that both the width and peak energies (a combination of speed and temperature) remain essentially constant on average as the structures move back from ~600 to 2500 R_J down the tail. The fact that the widths remain roughly constant on average indicates that the expansion of plasmoids and "blobs" of plasma has been essentially completed by ~600 R_J and that the tail is fully inflated and acts mostly as a conduit for structures to pass down beyond that distance. The constancy of the average peak energy, on the other hand, indicates that significant energy (e.g., from the surrounding solar wind flow) is not being added over this large range of distances, nor is significant energy being lost (e.g., cooling via expansion). Again, this points to a region from ~600 to 2500 R_J where the Jovian magnetotail acts largely as a conduit that already expanded structures simply transit down.

5.2. Periodicities

Periodicities in the near-Jupiter plasma environment have been studied by multiple authors (see *Kronberg et al*. [2009] for a summary). Visual inspection of the SWAP data indicated 3–4 day periodic structures frequently through New Horizons' transit down the Jovian magnetotail [*McComas et al*., 2007]. To quantify these and any other periodicities, here we calculate the Lomb normalized periodogram [*Press et al*., 1988] on the peak energy time series from DOY 087 to DOY 167 for measurements that SWAP took while inside the magnetotail (excluding magnetosheath intervals identified in *Ebert et al*. [2010a]), as shown in Figure 7.

We find the largest spectral peak (A) at a period of 3.53 (0.18 full width at half maximum (FWHM)) days. The second largest peak (B) occurs at a period of 5.35 (0.38 FWHM) days. We note that the somewhat smaller peak at 10.3 (1.5 FWHM) days in Figure 7 also appears to be real as it is precisely the beat period between peaks A and B within uncertainties. In fact, this peak also further supports the reality of the A and B periods found, since only frequencies from real physical processes can actually beat together; if one or both of these were simply some statistical fluctuation, then there would be no beat frequency peak. Thus, we conclude that the peaks at 3.53 days (A) and 5.35 days (B) both represent real physical periodicities in the Jovian magnetotail and hence the Jovian magnetosphere more generally. Remarkably, the dominant peak we find at 3.53 days is less than 30 min different from Europa's orbital period of 3.55 days and the two are equal well within the uncertainties.

Because of the completely unexpected coincidence of the ~3.53 day dominant period for tail structures with Europa's orbital period, we further examined the data to see if the detected periodicity was driven by a particular event or subset of the tail data. Figure 8 shows a color-coded spectrogram, the spectral density (power) at various periods (T) taken with a sliding window (bottom left) as a function of time (distance down the tail). The figure clearly shows that the ~3.53 day period is persistent and observed at essentially all distances. In contrast, the ~5.35 day period, while quite strong in the region of the tail from ~750 to 1100 R_J, is largely not present at other times. Thus, we conclude again that the ~3.53 period represents a real and potentially quite important aspect of Jovian magnetotail physics.

6. Discussion and Implications

In this study we have examined the plasma composition and structure of the deep Jovian magnetotail as observed with the SWAP instrument on New Horizons. We provide the remarkable result that the plasma observed as the spacecraft passed down the northern side of the dusk flank of the magnetotail from ~600

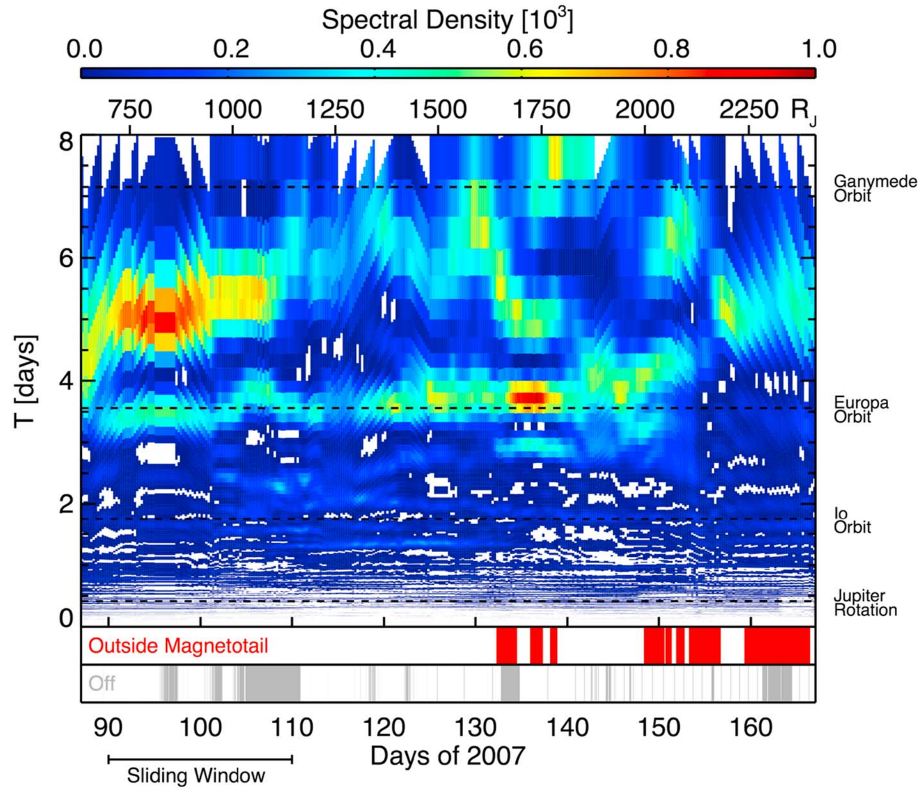

Figure 8. Color-coded spectrogram of spectral density as a function of period (T) and time as New Horizons moved back through the Jovian magnetotail. The width of the sliding window used for this analysis is shown in the bottom left. A persistent peak at ~3.5 days is clear at essentially all distances back in the tail.

R_J all the way back to over 2500 R_J was primarily composed of light ions, which are mostly protons. The dominance of light over heavy ions is in fact so great that with our S/P mass composition technique, we are unable to detect the presence of any heavy plasma ions, at least up to ~4 keV/q (above that, the technique does not discriminate heavy and light ions), at any point in the tail.

It would be tempting to simply assume that the heavy ions were all at energies above a few keV/q. One might even imagine some sort of mass-dependent acceleration mechanism that would preferentially energize the heavier ions. However, if relatively cold S^{++} and/or O^+ were cotraveling with protons down the tail, they would have 16 times greater E/q than the protons, and at least for times of slower down-tail flows (see many examples in Figure 4), they would be observable in the SWAP energy range. Alternately, if they were hot ion populations, they could all be above SWAP's energy range, but then we would expect that the PEPSSI instrument should have routinely seen them instead of only observing appreciable quantities of heavy ions in a limited number of dispersion events. In addition, we have shown here that even for several of their larger dispersion events, the apparent extension down into the SWAP energy range does not appear to contain heavy ions.

How else might one explain the relative dearth of heavy ions observed by SWAP? Possible explanations include the following: (1) that New Horizons passed above an equatorial plasma sheet where the heavy ions are tightly confined, (2) perhaps the Jovian source of light ions and/or entry of light ions from the solar wind are actually significantly greater than Io's source of heavy ions into the Jovian magnetosphere, or (3) maybe the vast majority of heavy ions transit down the dawn flank of the tail and not the dusk one where New Horizons sampled.

Based on Voyager and Galileo observations, the plasma sheet (comprising ~90% heavy ions) has a density scale height of about 4–10 R_J observed out to about 50 R_J [*Bagenal and Delamere*, 2011; *Bagenal et al.*, 2016]. This is consistent with heavy ions having temperatures of ~1 keV. Farther from Jupiter the plasma heats up and it is the 20 keV to 50 MeV particles, particularly sulfur ions, that dominate (by about a factor of 10) the pressure in the Jovian plasma sheet [e.g., *Mauk et al*., 2004]. This suggests that the typical thickness of the plasma sheet extending into the tail to be 10–20 R_J. How the shape of plasmoids evolve down the Jovian magnetotail is unknown. If we take plasmoids in the Earth's tail as a possible guide, then plasmoids and their traveling compression regions [*Slavin et al*., 1993] suggest occurrence across the entire cross section of the tail and a roughly spherical expansion with some vertical compression. New Horizons crossed the equator about 200 R_J downtail, moving northward to $Z_{JSO} \sim 20$ R_J by 600 R_J. While SWAP did not see essentially any heavy ions in the tail, even when it was quite close in on the planet's nightside, it is possible that if the plasma sheet remains tightly confined to the equator and if any ejected plasmoids remain severely compressed vertically, then New Horizons might have moved far enough above the equator before a plasmoid containing heavy ions passed by.

The second possibility is that the overall ion density in the tail is simply dominated by light ions. Ionospheric outflow from Jupiter introduces significant quantities of H^+ and to a lesser extent, H_3^+ into the Jovian magnetosphere. *Nagy et al*. [1986] used a Voyager-based model of Jupiter's ionosphere to estimate the source of light ions from Jupiter's ionosphere to be ~2×10^{28} s^{-1}, which is ~8 times more (by number) than the fraction of the matter released by Io that is expected to escape down the Jovian magnetotail. Of course, owing to the large masses of these heavy ions (primarily 16 and 32), even such a small fraction would be the dominant mass flux down the tail. Interestingly, *Felici et al*. [2016] recently similarly argued that ionospheric losses were sometimes dominant at Saturn.

The problem with this large of an ionospheric source is that the observed composition in the plasma disk closer to the planet shows roughly 10 times more heavy ions than light ions [*Belcher*, 1983]. In order to account for both the observations of mostly heavy ions in the plasma disk and mostly light ions in the tail, the light ions would need to be "hiding" somewhere else in the inner magnetosphere. Perhaps, the light ions preferentially populate the higher-latitude portions of the flux tubes that connect through the plasma disk. This seems likely because the centrifugal force driving the ions outward would preferentially concentrate the heavy ions toward the rotational equator, while the light ions would preferentially migrate to higher magnetic latitudes both to maintain charge balance (electrons freely move along the magnetic field and cause ambipolar diffusion) and as a way to redistribute the pressure along each flux tube [e.g., *Bagenal and Sullivan*, 1981]. On average then, if the whole flux tube is evacuated, with both plasma disk and higher-latitude populations, released down the tail, then the dominant ions traveling down the magnetotail might be light.

Another possibility is the addition of light ions from the solar wind. While the importance of solar wind plasma (H^+ and He^{++}) entry into the Jovian magnetosphere has been called into question, especially the analog of an Earth-like "Dungey Cycle" [*McComas and Bagenal*, 2007; *Delamere and Bagenal*, 2010], any such entry would add additional light ions to the magnetosphere. Typical solar wind plasma fluxes scale from 1 AU to Jupiter at ~5 AU are ~ (400 km s^{-1})(5 cm^{-3})/5^2. In contrast, typical plasma parameters in the tail (see Figure 4) are ~ (200 km s^{-1})(2×10^{-3} cm^{-3}), which is a factor of ~200 times smaller than the solar wind flux. Thus, independent of the size of the magnetosphere and tail, if even only half a percent of the solar wind flux were to enter the Jovian magnetosphere and tail via reconnection and/or boundary mixing, it could account for the light ion fluxes observed by SWAP.

In addition, mixing along the magnetopause boundary either in larger-scale Kelvin-Hemholtz eddies [e.g., *Delamere and Bagenal*, 2010] or smaller-scale turbulence could also provide a method for heavy ions escaping from inside the tail while simultaneously adding light ones. *McComas et al*. [2007] in fact identified a boundary layer with a mixture of solar wind and tail plasma populations on a significant fraction of the deep tail magnetopause crossings (also see *Ebert et al*. [2010a] and *Nicolaou et al*. [2015b]). While *Haggerty et al*. [2009] reported some general increase in He compared to H energetic ions with increasing distance down the tail, we found no evidence for substantial solar wind plasma entering the tail, which would have produced enhancements in the S/P ratio above ~0.7 keV owing to the addition He^{++}, just as we observed in the magnetosheath intervals. Further, in this study we have shown that the peak energy of the structures does not increase on average with distance down the tail from ~600 to 2500 R_J, indicating that large amounts of solar wind flow energy are not being coupled into the tail over this large range of distance.

Another, perhaps more promising, possibility is that the heavy ion-dominated plasma disk material is lost primarily on the dawnside of the tail. This may be possible given Jupiter's unusual magnetospheric structure and asymmetry of the expected X-line predominantly on the dawnside of the near-Jupiter magnetotail [*Vasyliūnas*, 1983]. We can imagine a scenario where the magnetic field in the plasma disk is generally able to contain the heavy ions as they rotate across the dusk and midnight sectors of the near tail, until the flux tubes reached the dawn flank. At that point, this material would either need to be pulled back in toward the planet as the flux tube continued to rotates sunward or reconnect and release plasmoids of heavy ions down the dawn tail flank.

There is, in fact, evidence for the preferential release of plasma disk material on the dawnside of the magnetotail. *Vogt et al*. [2014] examined 43 plasmoid signatures in the Galileo magnetometer data. They found all but one of these on the dawn half of the magnetotail, with a large fraction of them occurring on a particular orbit that passed especially close to the dawn flank of the tail (see their Figure 6). There is also support for this concept from the magnetometer observations and general magnetic field model of the current sheet in Jupiter's plasma disk [*Khurana*, 2001; *Khurana and Schwarzl*, 2005]. For example, Figure 8 of *Khurana* [2001] shows that the flux tubes crossing the equatorial current sheet start relatively radial on the dayside and are increasingly bent back as they cross the tail, reaching maximum stress as they approach the dawn flank of the tail. These flux tubes rapidly become more radial again in the dawn quadrant as they are pulled back inward to fit inside the magnetopause around dawn. This appears to be additional direct proof that the plasma disk heavy ions must be being preferentially released down the dawnside of the tail, which allows the flux tubes to snap back inward and become less bent back. This situation is sketched in Figure 4 of *Kivelson and Southwood* [2005].

Another line of evidence that may support this explanation comes from the timescale for radial transport of plasma ions closer in to Jupiter. *Bagenal and Delamere* [2011] compared the Io plasma production rate and observed radial ion density profiles. For steady state conditions these authors found that the radial transport increases significantly with distance and reaches radial speeds of 50–200 km s^{-1} at ~50 R_J. Beyond this distance, according to steady state calculations of *Delamere and Bagenal* [2010], the plasma makes less than one complete rotation before being lost down the tail. This suggests that there may be some location where material is lost instead of continuing to rotate past. If so, it seems most likely that this would be where the material that rotates through the near tail reaches the dawn magnetopause and gets released in order for the flux tubes to contract and continue to rotate sunward.

Because New Horizons passed down the dusk flank, preferential release of plasma disk heavy ions down the dawnside and flank of the tail could well have caused the lack of heavy ions as observed by SWAP. In fact, because the light ions are, well, lighter, they are more mobile and tend to travel more quickly along magnetic field structures. Since electrons are free to run out along the expanding flux tubes, they create an ambipolar electric field and thus diffusion that preferentially moves the lighter ions into the expanded regions on the duskside of the tail. Pressure gradients can further drive a redistribution of particles, and plasma thermal pressure, along the field. We can imagine that as the heavy ions move tailward on the dawnside of the near tail ($<$600 R_J), the light ions largely move duskward as the newly detached magnetic structures expand inside the tail in order to try to maintain pressure balance within the overall solar wind, which defines the overall shape of the magnetosphere and tail in balance with the solar wind dynamic pressure. Beyond this distance, the tail boundary can simply act as a conduit that the already expanded structures simply pass down, as indicated in this study by the lack of additional expansion or energy loss or gain on average for ~600–2500 R_J in the tail. Figure 9 schematically summarizes this scenario.

In spite of the fact that we did not find compositional variations and structure in the Jovian tail data, the plasma is still highly spatially structured. We quantified these structures, borrowing a standard technique from another field that allowed us to select structures based simultaneously on the measured variations of the ion distributions in the two-dimensional space of time and *E/q*. This analysis showed that both peak energies (a combination of speed and temperature) and width remain roughly constant on average in the tail from ~600 to 2500 R_J. This provides two key findings: (1) constant widths mean that by ~600 R_J plasmoids (blobs) have mostly stopped expanding and the tail acts more as a conduit for structures to flow back through from there and (2) constant peak energy indicates that significant external energy is neither being added (e.g., from coupling at the magnetopause boundary) nor lost (e.g., from further expansion and cooling).

Independently, we did a simple time series analysis of peak energies. This analysis showed that there were at least two periods that were statistically significant at 3.53 (0.18 FWHM) and 5.35 (0.38 FWHM) days. We also

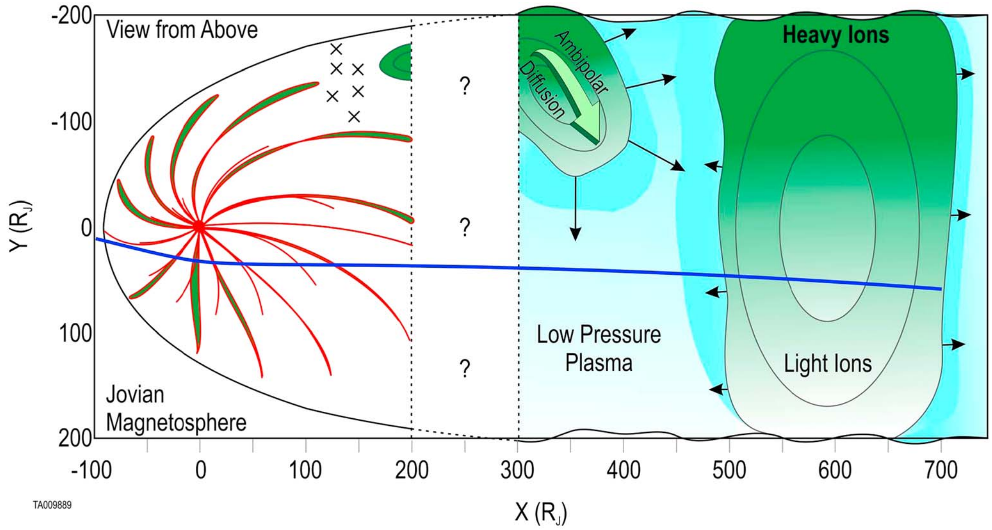

Figure 9. Schematic diagram of possible scenario to explain the SWAP observation of only light plasma ions over New Horizon's transit down the dusk flank of the Jovian magnetotail (blue trajectory). The red lines show the calculated shape and bend back of flux tubes for the *Khurana* [2001] magnetic field model. In the sketched scenario, when the distended flux tubes approach the dawn magnetopause, a significant quantity of heavy ions must be released as plasmoids in order for the magnetic flux tubes to snap back in far enough to continue rotating inward inside the magnetopause boundary. The release occurs through magnetic reconnection in the region of the magnetosphere where it has been primarily observed (X marks). The plasmoids expand into the much lower pressure surrounding tail plasma as they seek to establish pressure balance within a tail, the shape of which is set by the external solar wind forces. As the plasmoids expand, the electrons are free to run out along the expanding magnetic field lines and create ambipolar diffusion, which preferentially moves the light ions to the duskside of the tail, where New Horizons sampled them.

found a beat period between these two of 10.3 days; beating would not occur if either or both of these periods was simply statistical noise, so finding a peak at their beat period further demonstrates the physical reality of the two primary periods.

We turn now to the remarkable coincidence of the dominant periodicity in the Jovian magnetotail that we find to be 3.53 days—identical to Europa's orbital period of 3.55 days within the uncertainty of our observations. Of course, it seems problematic that the location (or orbital phase) of Europa, all the way in at ~9.5 R_J, could have any effect on the period of plasma structures observed deep in the Jovian magnetotail. Because of our concerns with this coincidence, we further wanted to see if some specific orbital phase (local time) of Europa could be associated with the timing of the peak energy per charge observed in the tail. To test this, we took Europa's orbital phase angle and propagated the time for average tailward speeds from 100 to 300 km s^{-1} in 5 km s^{-1} steps to the actual location of SWAP as it moved down the tail. In the resulting plots, we looked for alignment of the observed peak energies at some average speed but found no clear evidence that such a delay organized the data. Because we did not see a similar periodicity in the peak counts, we conclude that the structures are perhaps not best thought of as blobs but rather as recurrent plasma pulses driven by the release of structures in the near tail. Presumably, the evolution of the plasma structures has responded to both the varying speed and pressure inputs and the need to seek pressure balance (including all component, both particle and field) and equilibrium between the various structures as they propagate down tail. We note that analogous plasma structure persists and retains its periodicity in corotating interaction regions in the solar wind.

While we do not claim to explain the coincidence of these periods, we ponder whether the field-aligned currents along the flux tubes connected to Europa might somehow "pluck" over full flux tubes and initiate the release of material as Europa orbits past. Perhaps, this occurs on the dawnside of the tail, where flux tubes need to either move all of their plasma back in toward Jupiter or shed some of this material along the dawn flank of the tail prior to pulling back and making the turn back inside the dawn magnetopause. If so, this would connect nicely with one of the possible explanations given above for why heavy plasma ions are not observed all the back along the duskside of the tail.

Finally, we note that the Juno spacecraft will arrive at Jupiter and be inserted into an initial dawn-flank orbit on 4 July 2016. That spacecraft is well instrumented to make a broad range of particles and field measurements of the Jovian magnetosphere [*Bagenal et al*., 2014]. In particular, the Jovian Auroral Distributions Experiment (JADE) instrument [*McComas et al*., 2013] will observe the plasma ion and electron distributions in great detail, including the separation of the various ion species. With these new observations we will finally be able to discover the auroral processes and populations, which is the primary job of this instrument. In addition, observations from JADE and the other particle and fields instruments, including over other parts of Juno's orbits, should more globally resolve the overall workings of Jupiter's magnetosphere for the first time. The work in this study has been carried out in part in preparation for those critical new plasma observations.

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