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Plasma properties in the deep jovian magnetotail

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ABSTRACT

New Horizons observed consistently and continuously the jovian magnetotail at distances up to ~2500 Jupiter Radii (R_j) during its Jupiter flyby in 2007. The Solar Wind Around Pluto (SWAP) plasma instrument on New Horizons made in situ observations of plasma ions in the energy per charge range of ~21 eV to 7.8 keV. We analyze the SWAP plasma observations and derive the bulk properties of the plasma ions in the deep jovian magnetotail for 64 intervals from ~500 to 1700 R_j, just before the spacecraft start crossing the jovian magnetopause. There is no clear evolution of the plasma parameters over this distance range and we show that the plasma is very diverse over this entire range. There are significant changes in the plasma parameters and the flow direction over times as short as a few hours, showing evidence that boundaries between different plasma structures pass over the spacecraft rapidly. We discuss in detail a few subintervals where two species are observed within the instrument's energy per charge range and a set of subintervals where the plasma flow rotates ~20° over just six hours. We finally discuss the mass flux during the subintervals we study and the scenario of expanding plasmoids that propagate tailward and expand and interact to fill the magnetotail. This scenario is supported by the observed plasma diversity and flow characteristics.

1. Introduction

The near planet jovian magnetotail ($r < 200\,R_j$) has been explored by several spacecraft. However, even with these near-planet observations, it remains unclear how similar or different this magnetosphere's global structure is to that of the Earth's. Jupiter's (1) very large size scale, (2) fast rotation, and (3) large amounts of internal volcanic plasma released by its satellite Io all have important roles to play in the dynamics of Jupiter's magnetosphere.

The jovian magnetosphere is rich in oxygen and sulfur ions of iogenic origin. Io's neutral sulfur dioxide gas is ionized and then picked up and trapped by Jupiter's strong magnetic field forming the Io torus. The ionization rate is estimated to be around 1000 kg s^{-1} (Thomas et al., 2004 and references therein). Delamere and Bagenal (2003) estimated that roughly half of the Io torus plasma is lost via charge exchange and the other half, eventually, flows radially outwards and escapes down the tail. Bursts of tailward flow were observed by Voyager 2 at the dawn flank at distances ~150 R_j (Krimigis et al., 1979, 1981). The authors noted that the observed plasma was from the Io torus.

Besides the heavy ions from Io, there is a significant quantity of light plasma ions, mostly H^+ and $H_3{}^+$ in the jovian magnetosphere (Hamilton et al., 1981; Krimigis et al., 1981; Nagy et al., 1986; Yelle and Miller 2004). The outflow of ionospheric H^+ was estimated to be $\sim 2 \times 10^{28}$ ions/s (Nagy et al., 1986) indicating that the light ions, which come from the jovian ionosphere, are comparable with the amount of the heavy ions from Io's volcanoes. This mixture of light and heavy ions co-rotates with the planet at small radial distances, forming a rapidly rotating disk that extends in the equatorial plane. Observations at larger distances in the magnetotail are crucial to understand how this plasma eventually leaves the jovian magnetosphere down the tail.

Various theoretical models have been developed in order to try and explain jovian magnetospheric dynamics. The rotationally driven dynamics model of Vasyliūnas and Dessler (1983) explains how flux tubes are stretched and eventually pinch off forming plasmoids that can escape down the tail. Using in situ plasma and magnetic field measurements, studies provided evidence for plasmoids being ejected in the Jovian magnetotail (Russell et al., 2000; Woch et al., 2002; Kronberg et al., 2005; Vogt et al., 2010; Ge et al., 2010). These plasmoids seemed to be ejected every 4 h to 3 days, mostly from the post-midnight sector at distances ~70 to 120 R_j. Ejected plasmoids are on the scale of ~25 Rj at those distances. In addition to the in situ measurements, Grodent et al.

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(2003, 2004) reported on aurora flashes that are probably coupled to a magnetotail regions located further than 100 R_j back in the magnetotail with scale sizes of ~5 to 50 R_j (Grodent et al., 2004; Radioti et al., 2010, 2011).

Cowley et al. (2003) suggest that magnetic flux in Jupiter's magnetosphere follows an Earth-like Dungey cycle (Dungey, 1961), where the dynamics are mainly driven by the solar wind and the magnetic flux that opens via solar wind driven reconnection in the dayside closes via reconnection down the tail. McComas and Bagenal (2007) proposed a different scenario for opening and closing the magnetic flux. In their model, the opened magnetic flux closes via reconnection tailward of the cusps and not down the center of the tail. They argued that reconnection in the deep tail cannot close magnetic flux like that in the Earth's lobes due to the huge size of the jovian magnetosphere, strong internal plasma sources, and the planet's fast rotation. Observations of the deep jovian tail will help us to understand the global processes and dynamics of Jupiter's magnetosphere.

Voyager 2 had several encounters with the distant jovian magnetotail at distances greater than 700 R_j (mostly > 7000 R_j) and in a wide range of locations (Scarf et al., 1981; Kurth et al., 1982; Lepping et al. 1982, 1983). Observations of the continuum radiation and the magnetic field (up to 9000 R_j) during some of the encounters could be interpreted as observations of filaments, even though in overall, the tail does not seem to consist of fine-scale filamentary structures (Lepping et al., 1982, 1983). Evidence for tail reconnection or tail detachments, like comet tail disconnection events, are discussed in Kurth et al. (1982).

The nearly tailward trajectory of New Horizons right after its closest approach gave the opportunity to study continuously the deep jovian magnetospheric plasma back to ~2500 R_j. The Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) (McNutt et al., 2008) instrument onboard New Horizons measured the energetic plasma particles in the energy range from 10 keV to 1 MeV. McNutt et al. (2007) analyzed six dispersion events observed by PEPSSI. Their analysis indicated that those events are probably related to reconnection events which resulted in energetic particle flows in the tail. The onset times of those events is consistent with the periodicity observed by Galileo Energetic Particle Detector (EPD) near the planet (80–115 R_j). Hill et al. (2009) studied numerous dispersion events observed by PEPSSI and they provided evidence for magnetic filaments in the tail.

The Solar Wind Around Pluto (SWAP) (McComas et al., 2008) instrument onboard New Horizons took in-situ measurements of the magnetotail plasma ions in the energy per charge (E/q) range of ~21 eV/q to ~7.8 keV/q. SWAP observed a diverse range of the plasma populations (McComas et al., 2007). The plasma in many intervals is highly variable and in some cases there are discontinuities between the plasma regimes. Expanding plasmoids that propagate tailward could result in the observed gradual E/q variations. In addition, those authors found a 10 h and a 2–3 days periodicities in some intervals of the SWAP observations inside the magnetotail. The authors concluded that in general, the SWAP observations are consistent with the Vasiliunas model. The plasmoids that are observed by previous studies to be ejected at ~70 to 120 R_j could expand as they move tailwards. As a result the distant tail could be filled with plasmoids of many different size scales that expand and interact with each other as they move down the tail.

Nicolaou et al. (2014, 2015) modeled the response of the SWAP instrument in order to simulate the spin-angle spectrograms for given parameters of the plasma. The free parameters in the model are the phase space density of the plasma ions, the ion bulk parameters (density, temperature and velocity), and the kappa index in cases where kappa distributions were tried. The simulated spin spectrograms were then compared to the observations over ranges of assumed plasma parameters, allowing us to estimate which bulk plasma parameters give the best fit to the data. Using this forward model we estimated the bulk properties of the plasma ions in the deep jovian magnetosheath and boundary layer.

In this study we analyze the SWAP magnetotail observations taken after DOY 81 of 2007, when the spacecraft started spinning at 5 rotations per minute. We exclude observations of the magnetotail boundary layer and the deep magnetosheath, since those observations were examined in (Nicolaou et al., 2014, 2015). This paper is organized as follows: In Section 2 we briefly describe the instrument and in Section 3 we explain the methodology we use to derive the plasma parameters in the deep magnetotail. In Section 4 we present our results, while in Section 5 we discuss our findings. We summarize our conclusion is Section 6.

2. Instrument description-data

SWAP is a plasma instrument on board New Horizons which observes plasma ions in the energy per charge range of ~21 eV/q to ~7.8 keV/q (for details see the SWAP instrument paper (McComas et al., 2008)). For the observations analyzed in this study, the energy range is covered in 64 logarithmically spaced steps. The coincidence detection system of SWAP consists of one carbon foil and two channel electron multipliers. The Field of View (FOV) is $10° \times 276°$ centered on the spacecraft's spin axis which points nearly towards Earth (within 5°) for the times analyzed here, thus, when spinning the instrument observes ~87% of the full 4π steradians (McComas et al., 2007, 2008). New Horizons started spinning at DOY 81 of 2007 during the Jupiter encounter. For every measurement, we use the instantaneous rotation phase of the instrument, which is defined as the angle between the Z_{sc} and the projection of Jupiter's spin axis (north) onto the X_{sc}–Z_{sc} plane. Orbital information and observations of the SWAP instrument during the flyby are recorded as level 2 data, which we use in this study.

For simplicity, we define a coordinate system that moves (but does not spin) with our instrument. The y-axis points nearly towards Earth. During the time period we examine in this work, the angle within the y-axis and the sun-spacecraft direction ranges from ~4° to ~10°. We set the z-axis in the direction for which Jupiter's spin axis is in the y–z plane, and the x-axis completes the orthogonal Cartesian (right hand) system (Fig. 1). This coordinate system is the same as the instrument's reference frame when spin phase angle is 0°. We note that the spin phase angle used in this study is shifted by 180° from the spin phase angle provided by level 2 data. We define the plasma flow using the cone angle (ω) and the clock angle (α). The ω angle is between the plasma flow and the negative y-axis and ranges from 0° to 180°. α is the angle between the flow vector projected onto the y–z plane and x-axis and ranges from 0° to 360° (see also Fig. 1b).

3. Methodology

In our previous studies we estimated the bulk properties of the ions in the deep jovian magnetosheath (Nicolaou et al., 2014) and magnetospheric boundary layer (Nicolaou et al., 2015). The plasma flux in those regions is high (a few thousand counts per second for the magnetosheath and a few hundred in the boundary layer) and is often relatively stable over periods of a few hours. Thus, we used a model distribution function to fit the spin angle spectrograms of selected subintervals. However, the plasma flux inside the deep jovian magnetosphere is much lower and highly variable; which makes fitting of spectrograms difficult. For this study, we extend