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Jupiter's deep magnetotail boundary layer

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ABSTRACT

In 2007 the New Horizons (NH) spacecraft flew by Jupiter for a gravity assist en route to Pluto. After closest approach on day of year (DOY) 58, 2007, NH followed a tailward trajectory that provided a unique opportunity to explore the deep jovian magnetotail and the surrounding magnetosheath. After DOY 132, 16 magnetopause crossings were observed between 1654 and 2429 Jupiter radii (R_j) along the dusk flank tailward of the planet. In some cases the crossings were identified as rapid transitions from the magnetotail to the magnetosheath and vice versa. In other cases a boundary layer was observed just inside the magnetopause. Solar Wind Around Pluto (SWAP) is an instrument on board NH that obtained spectra of low energy ions during the flyby period. We use a forward model including the SWAP instrument response to derive plasma parameters (density, temperature and velocity) which best reproduce the observations. We also vary the plasma parameters in our model in order to fit the observations more accurately on occasions where the measurements exhibit significant variability. We compare the properties of the plasma in the boundary layer with those of the magnetosheath plasma derived in our earlier work. We attempt to estimate the magnetic field in the boundary layer assuming pressure balance between it and the magnetosheath. Finally, we investigate several possible scenarios to assess if magnetopause movement and structure could cause the variations seen in the data.

1. Introduction

The New Horizons (NH) spacecraft (Fountain et al., 2008) was launched on day of year (DOY) 19, 2006 on a nearly 10 year journey to Pluto (Stern, 2008). In 2007 NH flew past Jupiter for a gravity assist, crossing the Jupiter's dayside magnetopause on DOY 56. After the closest approach on DOY 58, the spacecraft began a trajectory that provided the first opportunity to study the previously unexplored jovian magnetotail between ~100 and 2550R_j ($1R_j$=71,492 km) (McComas et al., 2007; McNutt et al., 2007). Plasma observations onboard NH were provided by the Solar Wind Around Pluto (SWAP) instrument (McComas et al., 2007, 2008).

After the Jupiter flyby, NH crossed the distant jovian magnetopause ~16 times (McComas et al., 2007; Ebert et al., 2010a). The first crossing of the distant magnetopause occurred on DOY 132, 2007 with NH entering Jupiter's magnetosheath at ~1654R_j along the dusk flank. These crossings were identified as transitions between regions of significantly different plasma flux. Ebert et al. (2010a) studied the 16 magnetopause crossings and compared the observed magnetopause locations with those predicted by semi-empirical models. They suggested that these multiple crossings resulted from the deflection and contraction/expansion of the magnetotail during the passage of co-rotating interaction regions (CIRs) and high-speed streams in the near Jupiter solar wind. Nicolaou et al. (2014) derived the fluid properties of plasma ions in the deep jovian magnetosheath. The flow direction of the plasma in this region implied that flapping of the magnetotail occurred in both the meridional and equatorial planes deflecting the magnetopause by roughly 5°. This observation supported the interpretation of Ebert et al. (2010a).

During some of the magnetopause crossings, NH observed a region between the tail and magnetosheath with flux characteristics distinct from both of these plasmas. This region was identified as a magnetospheric boundary layer (McComas et al., 2007). This boundary layer plasma was slower and less dense than the adjacent magnetosheath and composed primarily of light ions, likely hydrogen, in the SWAP energy range. The mechanisms leading to the formation of this region and the source of particles that populate it have important implications for the solar wind–magnetotail interaction at these distances (e.g. Delamere and Bagenal, 2010).

Prior to NH, the jovian magnetosphere was studied using observations that were mostly confined to within 100R_j of the

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planet (see reviews by Khurana et al. (2004) and Krupp et al. (2004) and references therein). The boundary layer was a prominent feature on the dayside and near-tail region of the magnetopause. Sonnerup et al. (1981) identified a boundary layer inside of and adjacent to the dayside magnetopause from observations made during crossings of Pioneer 10 and 11. The thickness of the magnetopause was a few ion gyroradii. Electron data from Ulysses implied that the spacecraft made several incursions into the dawnside low latitude boundary layer (Bame et al., 1992). Galvin et al. (1993) studied the ion composition of the plasma within the boundary layer and identified ion species of magnetospheric and magnetosheath origin. They showed evidence of particles crossing the magnetopause boundary. During the Cassini Jupiter flyby, a boundary layer was observed inside the dusk magnetopause, on the tailward side of Jupiter (Svenes et al., 2004).

These boundary layer observations yield important clues regarding the nature of solar wind–magnetosphere interactions that occur on the dayside. McComas and Bagenal (2007) argued that an Earth-like Dungey cycle cannot work at Jupiter because of the size of the jovian magnetosphere and its strong internal plasma sources. Instead, they suggested that magnetic reconnection on the magnetopause could both open and re-close magnetic flux between the solar wind and Jupiter. The concept described in their paper allows for the mixing of solar wind and magnetospheric plasma across the magnetopause and thus the formation of a boundary layer. Delamere and Bagenal (2010) suggested a viscous, Kelvin–Helmholtz type interaction between the solar wind and magnetospheric plasma that would result in momentum transfer across the magnetopause boundary and mixing of the solar wind and magnetospheric plasma composition. Either of these types of interactions would also likely extend down the magnetotail boundary along the extended jovian magnetopause.

In this study, we extend our analysis techniques described by Nicolaou et al. (2014) in order to derive the fluid properties in the distant boundary layer of the jovian magnetosphere. Our results are used to study the solar wind–magnetotail interaction and investigate whether viscous interactions could act as possible sources of mixed magnetosheath and magnetotail plasma. In Section 2 we briefly describe the SWAP instrument and our data. In Section 3 we describe our methodology. The results are presented in Section 4. In Section 5 we discuss the results. Finally, in Section 6, we summarize this study.

2. SWAP instrument and observations

The Solar Wind Around Pluto (SWAP) plasma instrument on the NH spacecraft combines an electrostatic analyzer (ESA) with coincidence detection (2 channel electron multipliers and 1 carbon foil) to measure low energy ions in the energy per charge (E/q) range of ~21 eV/q–7.8 keV/q (McComas et al., 2008). The field of view (FOV) of the SWAP instrument is 276° × 10° centered on the instrument's spin axis (which is parallel to the spacecraft y-axis and points towards Earth throughout the jovian magnetotail observations). The entire energy range is covered in 64 logarithmically-spaced voltage steps over each 32 s sweep. Owing to the very tight telemetry limitations for the Jupiter encounter, two consecutive scans of the energy range are sampled (64 s) and followed by a gap of 256 s. The integration time of each measurement is 0.39 s. After DOY 82, 2007, NH was spinning at the rate of ~5 rpm.

We used level 2 data files which provide time-labeled coincidence (COIN) counts as a function of E/q and time, as well as orbital and attitude information calculated in the spacecraft's coordinate system. For every measurement, we use the instantaneous rotation phase of the instrument, which we define as the angle between the Z_{sc} and the projection of Jupiter's spin axis (north) onto the X_{sc}–Z_{sc} plane. We note that in this study (as in Nicolaou et al., 2014), we define the spacecraft's frame to be identical to the instrument's frame. In level 2 data the instrument's reference frame is rotated by 180° about the Y_{sc}. Thus, we shifted the angles given in the level 2 data by 180°.

In prior work, we analyzed SWAP spectrograms to derive the fluid properties of ions in the distant jovian magnetosheath. In this study, we extend this technique to derive the ion fluid properties of the deep jovian boundary layer. The time periods that NH spent in the boundary layer (~65 h in total) around the 16 MP crossings were identified by Ebert et al. (2010a) (for more information see their Figure 4).

3. Methodology

3.1. Ion fluid properties to counts

We have developed a method to derive the fluid properties of plasma ions that are measured by the SWAP instrument. Our method is based on forward modeling the response of the instrument to an assumed flowing Maxwellian distribution and produces simulated energy–time spectrograms and spin–angle spectrograms for specified ion bulk parameters. We then compare the simulated results with the actual spectrograms observed by SWAP and iterate the forward model until the two closely coincide. The model allows for the calculation of the density, bulk flow velocity and temperature of the measured ions at a given time, assuming a Maxwellian distribution. Initially, we group the observed spectrograms into subintervals with duration of ~1–3 h. Bulk properties of the plasma observed during each subinterval are determined by the best fit between the simulated and measured spectrograms. Subintervals are chosen to be long enough (> 1 h) to have data coverage over many spacecraft rotation angles (at least one observation for every 30°) and for all the 64-energy steps. On the other hand, we try to select the minimum possible duration, in order to avoid including plasma with different fluid properties in the same subinterval.

Nicolaou et al. (2014) developed a method to derive the fluid properties of plasma ions in the deep jovian magnetosheath. In this study we follow the same method. For our calculations, we define the phase space density of the plasma in a non-spinning reference frame that is identical to the instrument's reference frame at the rotation phase angle (which we define as the angle between the Z_{sc} and the projection of Jupiter's spin axis (north) onto the X_{sc}–Z_{sc} plane) of 0°. The y-axis of this frame points towards Earth (throughout the jovian magnetotail observations), the z-axis is aligned with the projection of Jupiter's spin axis (north) onto the $y=0$ plane, and x-axis is in the y cross z direction (Fig. 1). This frame is moving with the spacecraft's velocity. In this frame the direction of the plasma flow is determined by the angles θ and φ (Fig. 1) where θ, is the angle between the plasma flow vector and the z-axis (from 0° to 180°) and φ is the angle between the flow vector projection in the x–y plane and the negative x-axis (from 0° to 360° counterclockwise about the z-axis). For example, the downtail flow is along the negative y-axis for $\theta=\varphi=90°$.

The formula used to calculate the expected counts for each energy step for a single species with mass m is

$$C(E) = \frac{2}{m^2}\Delta t A_{\text{eff}} \int_{\theta_{\text{in}1}}^{\theta_{\text{in}2}} \int_{\phi_{\text{in}1}}^{\phi_{\text{in}2}} E(\theta_{\text{in}})^2 R (E, \theta_{\text{in}}) f(E, \theta_{\text{in}}, \varphi_{\text{in}})) \frac{\Delta E}{E}(E, \theta_{\text{in}}) \sin\theta_{\text{in}} \, d\theta_{\text{in}} d\varphi_{\text{in}} \tag{1}$$

where the modeled number of counts is obtained during the integration time $\Delta t=0.39$ s, A_{eff} is the effective area of the