The cold ion population at geosynchronous orbit and transport to the dayside magnetopause: September 2015 to February 2016.

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ABSTRACT

During intervals of enhanced magnetospheric convection, a high-density plume of cold ions is eroded from the plasmasphere and can flow toward the dayside magnetopause where it has the potential to reduce the rate of magnetic reconnection. In any interval of long-duration enhanced convection, tons of ions may follow such a trajectory. The study here concerns cold ion observations from geosynchronous orbit (GEO) during both calm and active periods. Probability distributions of the cold ion density and cold ion flow speed are determined during the six-month period from September 2015 to February 2016, inclusive. During low geomagnetic activity the cold, dense ions are in co-rotation with the Earth and flow speeds rarely exceed 10 km s^{-1}. During elevated geomagnetic activity, the cold ions between 12-18 MLT are observed to flow towards the dayside magnetosphere with a speed >10 km s^{-1} ~50% of the time. The *Shue et al.* [1998] model of the magnetopause location is used to derive the distribution of approximate *minimum* times for the cold ions to be transported from GEO to the dayside magnetopause. On average, during enhanced convection periods (Kp>3) ions will take a mean time of ~4.5 hours to travel from GEO to the dayside magnetopause.

1. Introduction

Cold ions (<1 eV to ~tens eV) in the Earth's plasmasphere are the primary constituent contributing to the mass density in the Earth's magnetosphere with a total mass ~10^2-10^3 metric tons [*Borovsky and Denton*, 2008; *Goldstein et al.*, 2018]. These ions are predominately H^+, but there is a relatively large concentration of He^+ in the plasmasphere. Previous work has revealed the importance of this population in terms of its role in: (i) mass-loading of the dayside reconnection site [*Borovsky and Denton*, 2006, 2008; *Walsh et al.*, 2013; *Borovsky et al.*, 2013; *Fuselier et al.*, 2017, 2018]; contributing to wave-growth and wave-particle interactions in general [*MacDonald et al.*, 2008, 2010; *Posch et al.*, 2010; *Blum et al.*, 2012; *Borovsky et al.*, 2014]; refilling of the plasmasphere and warm plasma cloak following intervals of enhanced magnetospheric convection [*Chappell et al.*, 1971; *Carpenter and Lemaire*, 1997; *Su et al.*, 2001; *Denton and Borovsky*, 2014]; and (iv) the total inertia in the magnetospheric system [*Denton et al.*, 2014; *Goldstein et al.*, 2018].

During times of enhanced convection the dense cold ions co-rotating in the Earth's plasmasphere can transition to drift paths that transport the plasma to the dayside reconnection site in the form of a plasmaspheric drainage plume (e.g. *Borovsky and Denton* [2006]; *Darrouzet et al.* [2008]; *Walsh et al.* [2013]; *Cassak and Fuselier* [2016]). At the reconnection site itself, the plasma can directly modulate the rate of magnetic reconnection [*Borovsky and Denton*, 2006; *Cassak and Shay*, 2007; *Borovsky*, 2013; *Birn et al.*, 2008; *Walsh et al.*, 2014a; 2014b; *Cassak and Fuselier*, 2016; *Fuselier et al.*, 2017]. Other physical effects of cold ions at the dayside magnetopause have also been investigated including modification of Hall physics by the cold ions [*André et al.*, 2016] and cold ion demagnetization near the reconnection site [*Toledo-Redondo et al.*, 2016].. During long-duration enhanced-convection events (e.g. high-speed solar-wind streams) a total mass of ~tens of tons of ions can flow to the dayside

[*Borovsky and Denton*, 2008].

Geosynchronous orbit (GEO) at 6.6 Earth radii (R_E) is an ideal location at which to survey the plasma transitioning from the co-rotating plasmasphere towards the dayside reconnection site. At this distance from the Earth, orbiting satellites co-rotate with the Earth and suitable instrumentation can measure the in-situ plasma as it also co-rotates, or as it moves radially outwards towards the dayside during periods of enhanced convection in a plasmaspheric drainage plume [*Borovsky and Denton*; 2006; 2008]. Los Alamos National Laboratory (LANL) satellites orbiting at GEO have the necessary instrumentation to sample the cold (and hot) plasma [*Bame et al.*, 1993; *Thomsen et al.*, 1999] and have been used in numerous studies to determine the characteristics of this plasma under a range of different conditions (e.g. *Denton et al.* [2005;2017]; *Borovsky and Denton* [2006; 2008]; *Denton and Borovsky* [2008; 2014]).

The primary objective of the current study is to survey cold ions during the interval September 2015 to February 2016 (inclusive). These specific dates are chosen since during this period the four satellites that form the Magnetosphere MultiScale (MMS) mission [*Fuselier et al.*, 2016] are orbiting close to the dayside magnetopause and sample cold plasma [*Young et al.*, 2014] that has been delivered to the region during periods of enhanced convection. These measurements include ion composition, wave measurements of the total plasma density, and, at times, active reduction of the spacecraft potential in order to better observe the low-energy ions. During the same period, the twin Van Allen Probes satellites are orbiting in the inner magnetosphere inwards of GEO and also provide cold ion measurements including the ion composition [*Funsten et al.*, 2013], the erosion flux [*Foster et al.*, 2014], and electromagnetic wave properties of the plasma. Thus, there is the potential for three independent data-sets to provide a capability to track cold ions as they transition from the inner magnetosphere, via GEO, out towards the dayside reconnection site. There are >100 conjunctions of the LANL, MMS, and Van Allen Probes satellites in this period (with a conjunction being defined as one satellite from each constellation being aligned on the dayside radially outwards from inner magnetosphere to magnetopause). In this current study the probability distribution statistics of the cold ions (density and flow-speed) between September 2015 and February 2016 are determined as a function of geomagnetic activity at GEO. Using these probability distributions, combined with a model of the magnetopause stand-off distance [*Shue et al.*, 1998], allows the distribution of cold-ion transport times from GEO to the magnetopause to be estimated in a statistical manner. Such analyses of the statistical distribution of the cold ions at GEO are intended to enable follow-on studies that compare and contrast the statistics of the cold plasma observed by LANL satellites at GEO with the same plasma observed in the inner magnetosphere with Van Allen Probes and at the dayside magnetopause with MMS.

2. Data

The main data set used in the current study is that provided from LANL satellites orbiting at GEO. The Magnetospheric Plasma Analyzer (MPA) instruments onboard LANL satellites sample the plasma (electrons and ions) at GEO in the energy range ~1 eV to ~40 keV. MPA is a spherical sector electro-static analyzer comprising six detectors measuring forty logarithmically-spaced energy channels. Situated on a spinning spacecraft MPA is able to provide full three-dimensional particle distributions for the ions and electrons once every 86 seconds. A full description of the instrument and the analysis software can be found in *Bame et al.* [1993] and *Thomsen et al.* [1999]. Since LANL spacecraft usually charge in a negative sense, all positively charged ions are detected at all times by MPA. Two particle populations can be present at GEO and the ion density and the ion velocity are calculated directly from the moments of the distribution for both the cold (plasmasphere) and hot (plasma sheet) populations [*Thomsen et al.*, 1999]. When calculating the moments, all ions are assumed to be protons. Data from all available LANL satellites are used in the analysis in this study. Furthermore, LANL satellites are located close to the geographic equator, with each orbiting at a slightly different inclination. Effects due to orbital differences between satellites are not considered during this study with all data assumed to originate from the geographic equator.

Figure 1 shows examples of MPA ion observations from a single satellite (01A) at GEO during calm geomagnetic conditions (Kp < 1 with the plasmasphere in quasi-co-rotation with the Earth) and during an interval of enhanced convection (plasma moving radially outwards from GEO towards the dayside) (cf. Figure 12 of *Borovsky and Denton* [2008]). The number density of the magnetospheric ions is indicated by the color bar and the line vectors indicate the flow direction in the geographic xy-plane as a function of magnetic local time (MLT) and position. Here, MLT is calculated as follows: firstly we find the anti-sunward direction in geomagnetic coordinates (ϕ), secondly, we locate the spacecraft longitudinal position (ϕ_{SC}) also in geomagnetic coordinates, and thirdly we define MLT = UT + (ϕ_{SC}-ϕ)/15. Thus, here MLT is the coordinate that specifies the longitudinal location of the satellite around geosynchronous orbit: local noon is the sub-solar point and local midnight is anti-sunward. For the 24 hour periods plotted, each 5th available data point is plotted for clarity. Additionally, to emphasize the highest density plasma likely to have the greatest effect on the reconnection rate at the dayside, data are only plotted if the plasma number density >10 cm^{-3}. The top panel shows data from a calm day in 2014. The high-density plasma during this day is in quasi-corotation with Earth (flow speed ~few $km\ s^{-1}$) i.e. the satellite is sampling the outer plasmasphere with no major sunward flows on the dayside. In contrast, the bottom panel shows data from a disturbed day in 2015 when magnetospheric convection was enhanced due to the passage of a high-speed solar-wind stream (HSS). There are substantial sunward flows during this period (>20 km s^{-1}) - the satellite is likely sampling plasma within a drainage plume where plasma originally co-rotating in the Earth's plasmasphere is now transported to the dayside due to the enhanced convection. The plasma flowing towards the dayside magnetopause is the main subject of interest in this study.

3. Analysis and Results

3.1 The cold ion distribution at GEO

Analysis of the LANL/MPA data is carried out in order to reveal the characteristic density and flow-speed of the plasma at GEO and the plasma that is transported towards the dayside. However, the cold ion flux at a particular energy is also variable. As a first step, the mean ion flux at two energies is calculated for all available observations from the LANL/MPA data set in the period 1990 to 2008. This period is chosen since it is the same period used in many previous statistical studies concerning the cold ion population (e.g. *Borovsky and Denton* [2008, 2009, 2010]; *Denton and Borovsky* [2008, 2009, 2012]). In the current study data are binned into one of 24 magnetic local time bins, and one of 28 discrete bins based on the Kp index [*Bartels et al.*, 1939]. The Kp index correlates very well with large-scale magnetospheric convection [*Thomsen*, 2004]. Magnetosheath intervals are filtered out of the analysis. The mean ion flux in each bin is then calculated at ~11 eV and ~1 keV and plotted in Figure 2. There are over 10 million unique data points contributing to each panel in Figure 2 and this figure very clearly highlights the different statistical behaviour of ions sampled at GEO based on their energy. Low energy ions (top panel) with energies of a few eV are part of the plasmasphere and plasmaspheric drainage plume population. This population is detected at all magnetic local times during low activity (plasmasphere - Kp < ~2). During enhanced convection (Kp > ~2) the outer regions of the plasmasphere are transported to the dayside magnetosphere in the form of a plasmasphere drainage plume that is clearly visible as the elevated fluxes in the noon to dusk sector (~12-18 MLT). The flux peak is shifted from ~18 MLT toward 12 MLT and the peak flux tends to decrease slightly as Kp increases.

Higher energy ions (bottom panel) with energies of a few keV are part of the ion plasma sheet population. The measured flux of these ions is enhanced during elevated convection intervals as new dense plasma enters the inner magnetosphere from the magnetotail. Previous work has clearly demonstrated that the different drift paths that each population follows, and the general behaviour of each population, are largely determined by the particle energy [*Korth et al.*, 1999; *Fernandes et al.*, 2017] and lead to the enhancement in ion flux observed for very high Kp values. While there are occasions where both populations low-energy and high-energy ions are observed in the same spatial location by MPA, it is clear from Figure 2 that statistically the two populations do not overlap to any significant degree - the two populations (hot and cold) are following different drift paths. Recent work by *Denton et al.* [2016] does explore one occasion when high-energy and low-energy plasma are co-located. That study demonstrated that low energy ions don't necessarily originate directly from the outer regions of the plasmasphere in the form of a plasmaspheric drainage plume in the post-noon sector. An alternative transport path, from the nightside region, carries low energy ions towards the dayside reconnection site via the dawn sector, rather than from dusk. Such ions arrive on the dayside and abut the plasmaspheric drainage plume, although they have taken very different drift paths to arrive there (see Figure 4 and Supp. Mat. of *Denton et al.* [2016]). However, the main population of interest in the current study is low energy ions that form the plasmasphere and drainage plume (top panel).

3.2 Cold ions and their variation with activity

The period of interest in the current study is the six-month interval from September 2015 to February 2016 (when >100 conjunctions with the MMS spacecraft orbiting near the dayside magnetopause occur). For this period all data are analyzed for all conditions (active and calm), as a function of magnetic local time and activity proxied by the Kp index.

Figure 3 contains scatter plots of all cold ion number density (N) and xy-flow speed (V) observations made by MPA, and plotted here as a function of magnetic local time and the Kp index (again, magnetosheath intervals are filtered out). As can be seen in the top panel of the figure, the cold ions are to be found at all magnetic local times around GEO, with a typical number density >1 cm^{-3}. The highest densities observed are >100 cm^{-3} and occur in the post-noon sector (12-18 MLT) where the plasmaspheric drainage plume is typically located during enhanced convection intervals. As found in previous studies, the density and the flow-speed of the plume (and the plume density structure itself) are correlated with Kp, and with the age of each plume [cf. Figures 10 and 11 of *Borovsky and Denton*, 2008], although it should be noted that geomagnetic activity during the six-month period under study here was quite low with less frequent intervals of Kp>3 than those used in the previous work referenced above. The mean Kp for the period under investigation is ~2^+.

The bottom panel of Figure 3 shows the flow speed in the spacecraft xy (geographic) plane (see *Thomsen et al.* [1999]). A flow speed greater than ~10 km s^{-1} indicates a large deviation from co-rotation and in the post-noon region where a plasmaspheric plume is expected, the dense cold ions are generally moving rapidly to the dayside magnetopause with the flow speed in this region being well-correlated with Kp - the highest speeds are typically observed during elevated Kp intervals, again in line with previous observations (e.g. Figure 3 of *Denton and Borovsky* [2012]).

In order to quantify the probability distributions of the density and velocity of the cold ions during quiet and disturbed intervals, we calculate the probability distributions for all data plotted in Figure 3, but now separated into calm (Kp $<1^+$) and disturbed (Kp >3) intervals. The Kp cut-offs used in these definitions were derived based on the expected statistical location of the plasmasphere and plume with reference to Figure 2. Since we are particularly interested in ions that may be moving to the dayside magnetopause (and thus the dayside reconnection site) we restrict the magnetic local times of the observations to the post-noon sector values between 12 and 18 MLT. Figure 4 contains the probability distributions for these calm and disturbed intervals for both N and V, along with statistical information on each distribution. The left column in this figure shows the cold ion density and cold ion velocity for Kp$<1^+$. It is clear that during calm intervals, the cold ions are usually co-rotating with the Earth at GEO with flow speeds <10 km s^{-1}, and have a typical density ~10 cm^{-3}. The right column of the figure shows the cold ion density and cold ion velocity for Kp>3. During such active intervals the cold plasma density is very slightly higher than during calm periods but in contrast, the flow speed of this plasma is certainly greatly increased (cf. Figure 3). Given that speeds in excess of ~10 km s^{-1} indicate a strong deviation from (quasi) co-rotation, and that the flow-vectors of this plasma are typically directed sunwards (cf. Figure 1 and Figure 12 of *Borovsky and Denton*, 2008), it can be readily concluded that this plasma is moving towards the dayside magnetopause. During the period studied here, dayside directed flows at GEO exceed ~10 km s^{-1} roughly 50% of the time when Kp>3.

3.3 Cold ions transport times to the dayside magnetosphere

The flow-speed of the ions is directly related to their transit time to the dayside magnetopause (and hence to the dayside reconnection site). While more complex calculations are certainly possible, a simple estimate of the *minimum* time taken for these ions to reach the dayside magnetopause from GEO requires an estimate of how distant the magnetopause might be. This estimate is obtained: (i) by utilizing the *Shue et al.* [1998] model for magnetopause standoff distance, (ii) by assuming the flow is directed from GEO in a straight line to the dayside magnetopause, and (iii) by assuming the speed of the plasma measured at GEO remains constant from GEO to this location. Hence, while more sophisticated estimates of the ion transport time can be carried out in future (particularly for individual spacecraft conjunction studies), the results of the current analysis provide a valuable estimate of the *minimum* transport time from GEO to the magnetopause.

Figure 5 contains the probability distribution for the transport time (in hours) from GEO to the estimated magnetopause location for the same data as is plotted in the right column of Figure 4 (Kp >3, 12-18 MLT). Each transport time contributing to this distribution is calculated based on the instantaneous solar wind conditions that drive the *Shue et al.* [1998] model, and on the instantaneous flow-speed at GEO. Such analysis relates the plasma characteristics at GEO with those that may be subsequently detected at the dayside reconnection site (e.g. by MMS satellites). It is clear from Figure 5 that transit times of a few hours are typical, with a mean transport time of ~4.5 hours for ions arriving at the magnetopause from GEO

4. Discussion

The effects of cold ions on the rate of magnetic reconnection at the dayside magnetopause are still being evaluated. Our current understanding is that the dayside reconnection rate is likely to be reduced in the presence of dense, cold ions at the magnetopause, since these ions create conditions that favor asymmetric reconnection [*Cassak and Shay*, 2007; *Birn et al.*, 2008]. *Borovsky and Denton* [2008] calculated that tons of ions (protons) were likely being transported to the dayside magnetopause during long-duration enhanced convection conditions such as those found during HSSs. Should there be a substantial presence of heavy ions then the total mass density of ions will be greater still. *Borovsky and Denton* [2008] also provided estimates of correction factors to be applied to the observations in the case of a plasma with substantial heavy ion composition. For a plasma with 70% H+ , 20% He+ and 10% O+ then the total overall density would be multiplied by 1.21. At a reconnection site, a higher mass density on the magnetospheric side would certainly cause changes in the rate of magnetic reconnection, potentially reducing the reconnection rate still further [*Cassak and Shay*, 2007; *Birn et al.*, 2008].

Observational studies have provided statistical and case-study evidence for a reduction in the reconnection rate due to the presence of dense, cold ions at the dayside magnetopause [*Borovsky and Denton*, 2006; *McPhadden et al.*, 2008; *Borovsky et al.*, 2013; *Walsh et al.,* 2013; 2014a; 2014b; *Fuselier et al.*, 2017]. However, there is a debate as to whether the local or global reconnection rate is affected. *Borovsky and Birn* [2014] argue that the local conditions at the reconnection site (by necessity including the cold ion density) control the magnetic reconnection rate at the dayside magnetopause. In contrast, *Lopez* [2016] suggests that the solar wind itself is the primary factor controlling the total integrated reconnection rate on the dayside, and that localized density changes on the magnetospheric side of the reconnection site merely affect the local reconnection rate, rather than the integrated total.

This study is a first step in more-fully determining the role of cold ions affecting the rate of magnetic reconnection at the dayside, in both a local and global sense. We have quantified the flow-speed and density of the ions transported towards the dayside from GEO during enhanced convection and provided estimates of the timescales for such transport to occur over. These values are intended to provide modelers with quantitative estimates of how much cold plasma is moving to the dayside via GEO and the timescales such transport occurs over. Future work will couple the full capabilities of the Van Allen Probes satellites in the inner magnetosphere, the LANL satellites at GEO, and the MMS satellites near the dayside reconnection site to provide a detailed description of: (a) the low-energy ion transport to the dayside, (b) the electro-magnetic wave characteristics within the plasma, (c) the potential evolution of the ions due to wave-particle interactions occurring as they drift, (d) the composition of the ions and the total mass density that travels from the inner magnetosphere to the dayside magnetopause, and (e) the subsequent role of the low-energy ions in modulating the rate of dayside magnetic reconnection.

5. Summary

1. Cold ion data from LANL/MPA satellites are analyzed during the interval September 2015 to February 2016 in order to understand the characteristics of plasma that is transported to the dayside magnetopause from GEO. Probability distributions of the cold ion flow speed and cold ion density during this period are determined. These indicate densities of ~10 cm^{-3} and flow speeds in excess of 10 km s^{-1} during enhanced convection (Kp>3) compared to calm intervals ($Kp<1^{+}$).

2. Plasma flows are directed to the dayside magnetopause ~50% of the time for Kp>3. Plasma is in quasi-corotation during intervals when $Kp<1^+$.

3. The distribution of expected *minimum* transport times for the ion plasma from GEO to the magnetopause indicates that ions arrive at the dayside magnetopause within a few hours (mean transport time ~4.5 hours). Such quantification of cold ion flows enable estimates of the effect of cold ions on dayside reconnection to be made in future studies.

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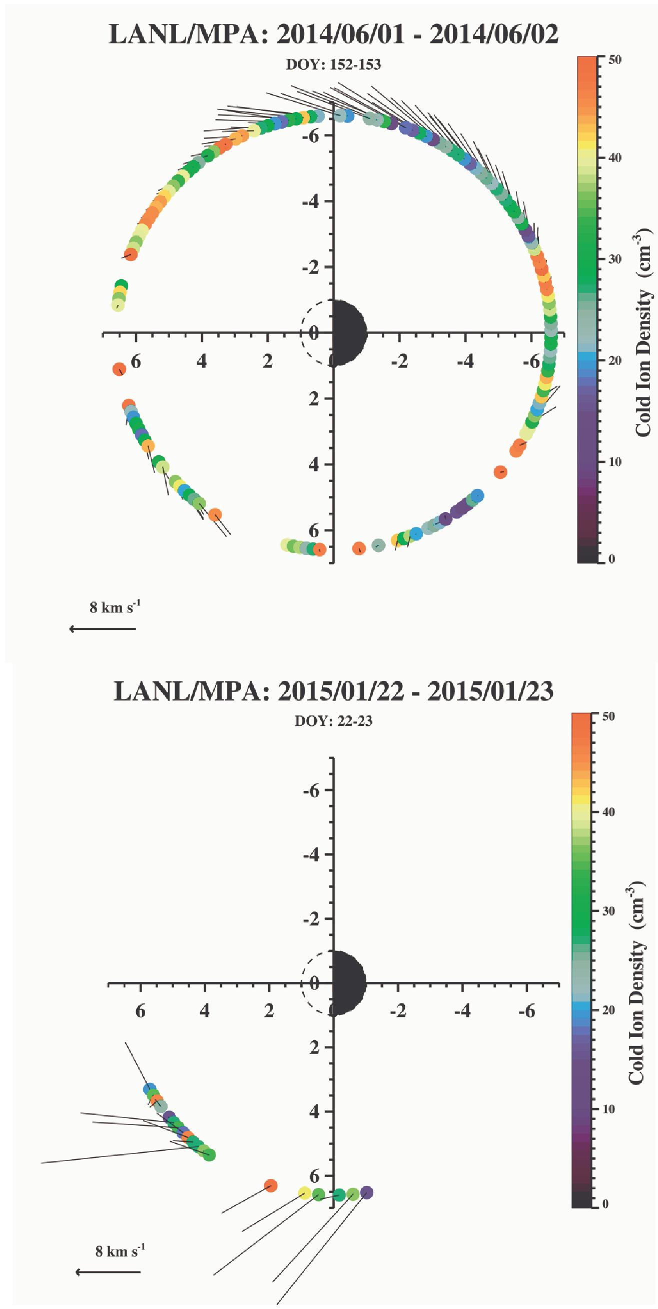

Figure 1. Example ion density and flow vectors measured by a single LANL satellite (01A) during a calm period in 2014 when co-rotation dominates (top) and a disturbed period in 2015 when flow to the dayside occurs (bottom).

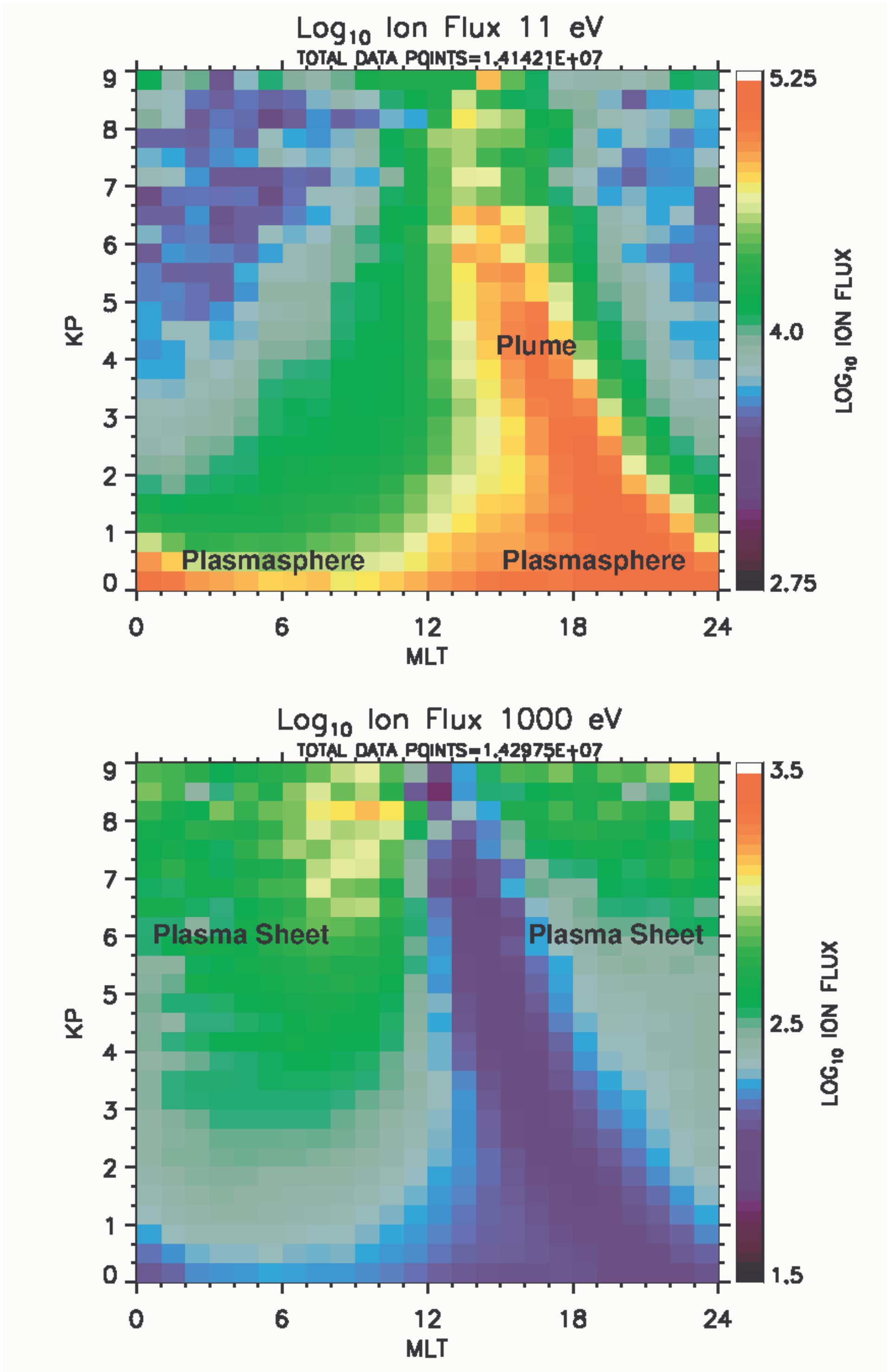

Figure 2. The mean ion flux calculated from MPA observations at GEO at two energies, and as a function of magnetic local time and the Kp index (1990-2008 inclusive). The low energy ions (top panel) comprise the plasmasphere and drainage plume population (few eV) whereas the higher energy ions (~ keV) are the population of plasma sheet. All ions are assumed to be protons. It is clear that these two populations vary significantly with Kp, but do not generally overlap as they are typically on different drift trajectories.

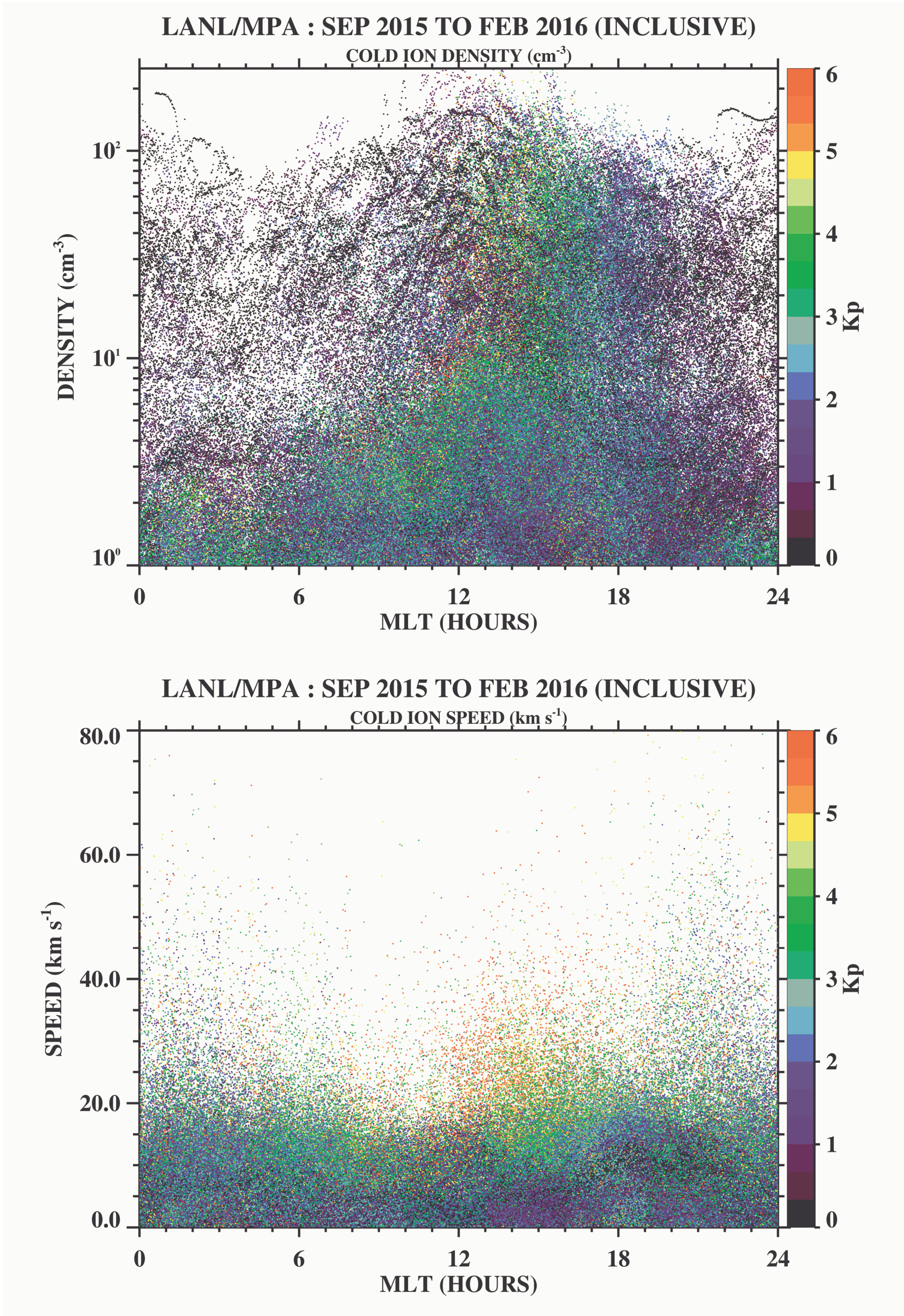

Figure 3. Scatter plots of density (top panel) and flow speed (bottom panel) of all cold ions sampled by MPA between September 2015 and February 2016 as a function of MLT and Kp (magnetosheath intervals are excluded).

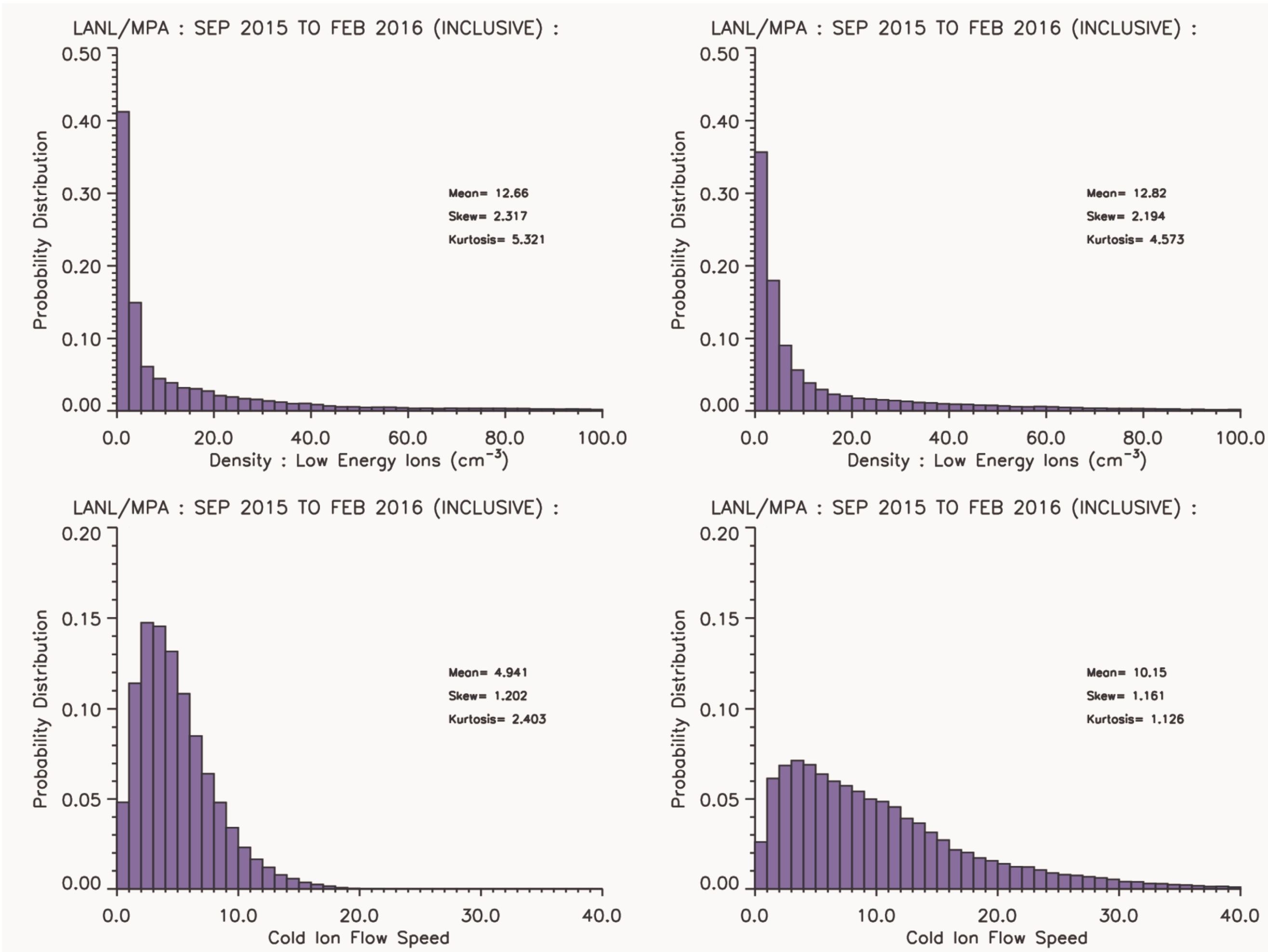

Figure 4. Probability distributions plots of density and flow speed for calm intervals (left column : $Kp<1^+$) and disturbed intervals (right column : Kp>3). All available data Sept. 2015 to Feb 2016 are plotted for the magnetic local time region between 12 and 18 MLT.

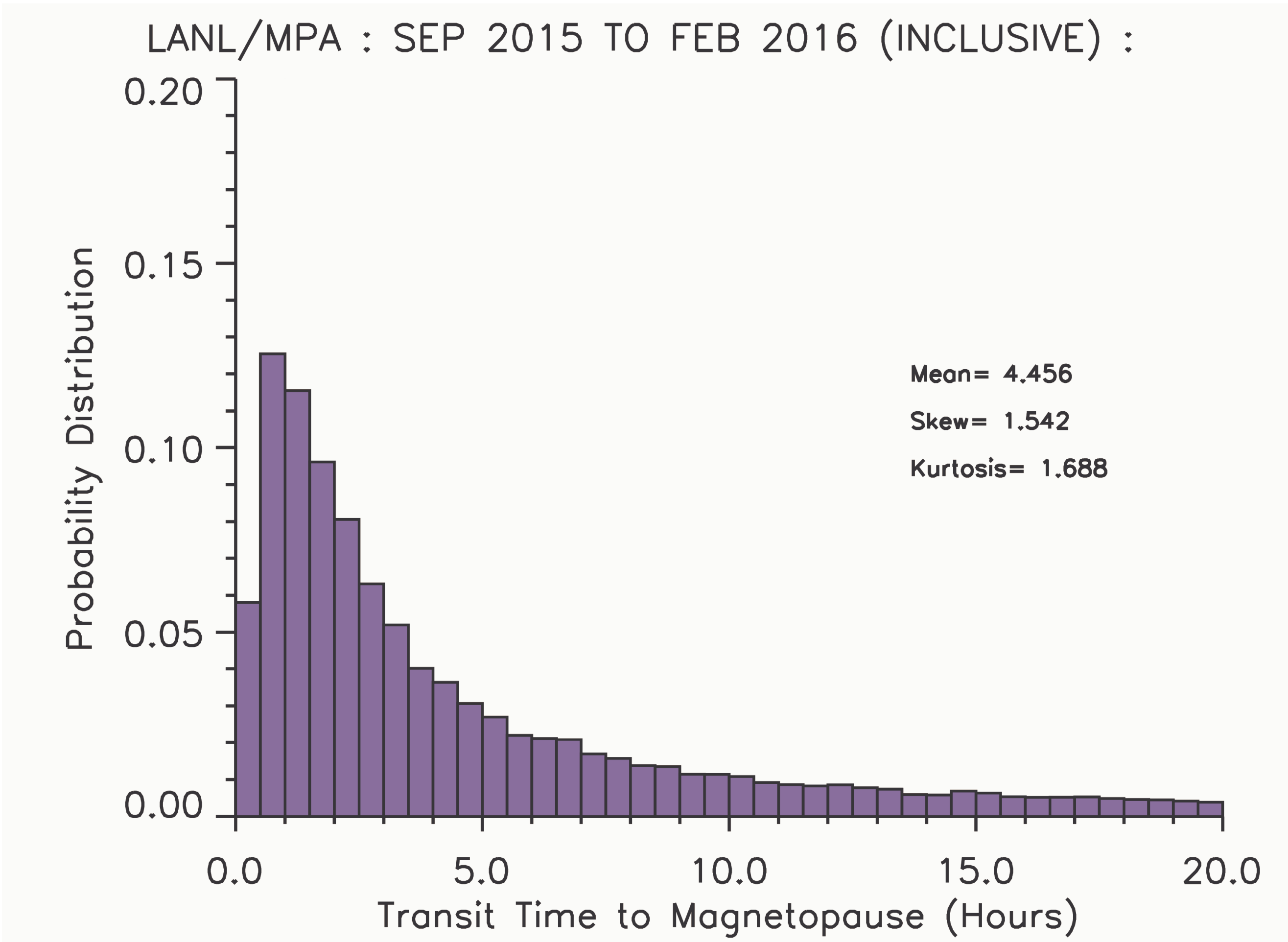

Figure 5. The probability distribution of (minimum) transport times from GEO to the estimated magnetopause location based on the *Shue et al.* [1998] model. All available data from 12-18 MLT and Kp>3 are plotted.