Study of the Average Ion Mass of the Dayside Magnetospheric Plasma

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Abstract The investigation of heavy ions dynamics and properties in the Earth's magnetosphere is still an important field of research as they play an important role in several space weather aspects. We present a statistical survey of the average ion mass in the dayside magnetosphere made comparing plasma mass density with electron number density measurements and focusing on both spatial and geomagnetic activity dependence. Field line resonance frequency observations across the European quasi-Meridional Magnetometer Array, are used to infer the equatorial plasma mass density in the range of magnetic L-shells 1.6–6.2. The electron number density is derived from local electric field measurements made on Van Allen Probes using the Neural-network-based Upper-hybrid Resonance Determination algorithm. The analysis is conducted separately for the plasmasphere and the plasmatrough during favorable periods for which both the plasma parameters are observed simultaneously. We found that throughout the plasmasphere the average ion mass is ≈1 amu for a wide range of geomagnetic activity conditions, suggesting that the plasma mainly consist of hydrogen ions, without regard to the level of geomagnetic activity. Conversely, the plasmatrough is characterized by a variable composition, highlighting a heavy ion mass loading that increases with increasing levels of geomagnetic disturbance. During the most disturbed conditions, the average radial structure shows a broad maximum around 3–4 Earth radii, probably correlated with the accumulation of oxygen ions near the plasmapause. Those ions are mostly observed in the post-dawn and pre-dusk longitudinal sectors.

Plain Language Summary The space surrounding the Earth is permeated by plasma whose composition could affect the space weather conditions. The near Earth region, the plasmasphere, roughly co-rotates with our planet, while the external part, the plasmatrough, streams toward the Sun direction. The solar wind conditions determine the level of the geomagnetic activity and eventually the radial position of the layer separating the plasmasphere from the plasmatrough. We investigate the average ion mass in the dayside region between 1.6 and 6 Earth Radii, using ground based magnetic field observations recorded at the European quasi-Meridional Magnetometer Array and plasma waves measurements made on Van Allen Probes spacecrafts. The analysis shows that the plasmasphere is practically insensitive to the level of geomagnetic activity being composed predominantly by hydrogen ions. Contrarily, the contribution of oxygen ions in the plasmatrough increases with increasing geomagnetic activity and maximizes between 3 and 4 Earth radii and in the dawn and dusk longitudinal sectors.

1. Introduction

The Earth's inner magnetosphere is home to many different particle populations in a wide range of energies, which overlap and interact also by means of a multitude of plasma waves (Thorne, 2010). In terms of mass density the main population is the plasmasphere, a torus of cold and dense plasma (100–1,000s cm−3) that roughly co-rotates with the Earth. It is limited by a sharp decrease in the electron number density, known as plasmapause or plasmasphere boundary layer (PBL, Carpenter & Lemaire, 2004). After a prolonged period of quiet geomagnetic conditions, the sharp PBL is replaced by a smoothly decreasing density (Tu et al., 2007). The PBL may also be smooth or even absent if observed on the total mass density, a behavior which reflects the different radial distribution of the various ion species (Fraser et al., 2005). Outside the PBL, in the plasmatrough, the low density...
(1–100 cm\(^{-3}\)) plasma motion is primarily influenced by the convection electric field which dominates that region, and determines a stream of plasma toward the dayside magnetopause. During geomagnetically active periods the convection electric field intensifies, causing an erosion of the plasmasphere and contributing to the formation of plumes, notches, and shoulders that alter the shape of the PBL drastically (e.g., Sandel et al., 2003).

The plasma that populates the plasmasphere is primarily composed of light ions (H\(^+\), He\(^+\)) of ionospheric origin flowing outward along closed geomagnetic field lines. It is well known, however, that also heavy ions (O\(^+\), O\(^{++}\), N\(^+\)) are present and that beyond the PBL the O\(^+\) density can be comparable to or exceed the H\(^+\) density, forming what is known in literature as the oxygen torus (e.g., Chappell, 1982).

Several works confirmed the variable composition of the magnetospheric ions during different geomagnetic conditions (Comport et al., 1988; Denton et al., 2011, 2014; Fraser et al., 2005; Horwitz et al., 1984; Nosé et al., 2011, 2015; Roberts et al., 1987; Takahashi et al., 2006, 2008; Vellante et al., 2021). ULF hydromagnetic and ion cyclotron wave propagation as well as resonance features are influenced by the presence of heavy ions. Also these ions primarily flow out from the polar ionosphere (Yau & André, 1997), and inevitably affect the plasma properties and dynamics. The oxygen torus may also play an important role in the generation of an O\(^+\)-rich ring current (Nosé et al., 2011; Yue et al., 2019) during disturbed periods.

In this work we study the magnetospheric average ion mass as derived by the combined use of ground-based and satellite measurements. Indeed, the contribution of heavy ions to plasma mass density can be quantified by comparing the plasma mass density with the electron number density. The average ion mass \( M \) is by definition

\[
M = \frac{\sum n_i m_i}{\sum n_i} = \frac{\sum n_i m_i}{n_e},
\]

where \( n_i \) is the electron number density, \( n_i \) and \( m_i \) are the number density and the mass of the \( i \)th ion species. The last equality follows from the charge neutrality which implies \( \sum n_i = n_e \) in case of singly-ionized plasma.

On the other hand, the plasma mass density \( \rho \) can be written as (see e.g., Takahashi et al., 2006)

\[
\rho = n_e m_e + \sum n_i m_i \geq \sum n_i m_i = n_e M,
\]

where \( m_i \ll m_e \) is the mass of the electron. The above relationship provides a simple but effective tool to study the contribution of heavy ions in magnetosphere. For a plasma dominated by H\(^+\) ions \( M \sim 1 \) amu, while for a plasma composed principally by O\(^+\) ions \( M \sim 16 \) amu. It is expected that \( M \) lies between these two physical limits.

Most part of the ions contributing to the mass density have energies below a few eV (Liemohn, 2006) and direct observations are limited because the spacecraft charging prevents cold ions from reaching the detectors. A notable exception is the retarding ion mass spectrometer (RIMS, Chappell et al., 1981) on the Dynamics Explorer 1 (DE-1) which was negatively biased and could partially compensate for the positive potential generated by spacecraft charging. The mission was operative from October 1981 to March 1991. Another example is the LANL Magnetospheric Plasma Analyzer (MPA, Bame et al., 1993) on board the GOES satellites, that can measure fluxes of ions at energy/charge as low as 1 eV/e, although limited to the geosynchronous orbit and therefore mostly located in the plasmatrough. Recently Goldstein et al. (2019) found that the fractional concentration of H\(^+\) and He\(^+\) in the range 0.3–3 eV is weakly affected by the temperature, so that measurements of light ions above 1 eV are valuable estimates of colder ones. They also proposed a new technique to estimate O\(^+\) concentration from ion temperature information, extrapolating fractional concentration of O\(^+\) above several eV to colder temperatures. This technique provides at least the chance to estimate the order of magnitude of the main ion populations even on satellites without spacecraft charging compensation.

It is also possible to indirectly determine the total plasma mass density and the electron number density from in situ or remote observations of plasma waves. The equatorial plasma mass density can be estimated by analyzing Ultra Low Frequency (ULF) signals simultaneously detected by pairs of magnetic stations aligned along the same magnetic meridian. In this work we use the data set created by Del Corpo et al. (2019) which provides mass density estimates for approximately 6 months of data collected by the European quasi-Meridional Magnetometer Array (EMMA, Lichtenberger et al., 2013). EMMA consists of 27 magnetic stations extending from central Italy to Finland.
Electron number density can be inferred from satellites plasma wave measurements. For this study we use the electron number densities derived from the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS, Kletzing et al., 2013) experiment onboard the Van Allen Probes (Mauk et al., 2013). Combined with the EMMA estimates we created a data set of conjunction events in which the location of the satellite matches the location of the estimated plasma mass density for a given pair of stations. This technique has been also applied by Maeda et al. (2009) comparing observations of a magnetic station pair of the Circum-pan Pacific Magnetometer Network (CPMN, Yumoto & CPMN Group, 2001) and local electron number densities from Waves of High frequency Sounder for Probing the Electron density by Relaxation (WHISPER, Décréau et al., 1997) instrument onboard the CLUSTER satellites to investigate the dependence of the average ion mass on the geomagnetic activity. The use of a single station pair however limited the analysis to only 19 conjunction events over 5 years of data. By contrast, the extension of EMMA not only allows to considerably increase the probability to detect conjunction events, but also to perform an analysis on the spatial variation of the average ion mass, and to monitor the dynamics of the ion composition during prolonged favorable periods. An example of the potential of extended magnetometer networks for this kind of analysis was recently presented by Vellante et al. (2021) who compared the average ion mass determined using both ground based and in situ observations with different techniques for a geomagnetic storm.

The remainder of the article is organized as follows. Section 2 describes the data set of conjunction events created from the plasma mass density and the electron number density estimations and the procedure adopted in deriving it. A statistical study of the spatial and geomagnetic activity dependence of the average ion mass is presented in Section 3. Section 4 presents discussion and comparison with previous studies. Section 5 summarizes the main results of the analysis.

2. Data and Method

2.1. Plasma Mass Density

The data set presented by Del Corpo et al. (2019) provides a great opportunity to investigate the ion composition of the magnetospheric plasma through comparison with electron number density measurements. It consists of equatorial plasma mass densities inferred from field line resonance (FLR) frequencies observed by EMMA.

Using the technique originally introduced by Baransky et al. (1985) and further improved by Waters et al. (1991), FLR frequencies were derived performing Fourier cross-spectral analysis of magnetic signals simultaneously recorded at EMMA station pairs during 165 days in the year interval 2012–2017. Each FLR frequency refers to the field line whose footprint is halfway between the stations, and the spectral analysis was performed using a 2 hr sliding window with half-hour step. For any given frequency, the density ($\rho_{eq}$) at the equatorial crossing point ($r_{eq}$) was then derived by numerically solving the Singer et al. (1981) equation, and assuming that its variation along the field line can be modeled by a power law of the form

$$\rho = \rho_{eq} \left( \frac{r_{eq}}{r} \right)^{m},$$

where $r$ is the geocentric distance and $m$ is the power law index. Following previous investigations (Denton, Takahashi, et al., 2006; Takahashi et al., 2004; Vellante & Förster, 2006), the value $m = 1$ was assumed for the analysis. The procedure needs also a realistic description of the geomagnetic field, and the TS05 model (Tsyganenko & Sitnov, 2005) was used to accomplish this requirement.

Since station pairs at different latitudes provide estimates of the equatorial plasma mass density at different geocentric distances, the latitudinal extension of EMMA allows to get information on the radial distribution of the plasma for $L$-shells ranging from 1.6 to 6.2. In summary, the data set provides radial profiles of the equatorial plasma mass density in the magnetic local time sector identified by EMMA ($\approx UT + 2$), with a time resolution of half an hour. The data set comprises a wide range of geomagnetic activity conditions, including 13 storms, so it is particularly suitable to investigate the behavior of the average ion mass in response to the activity level. The complete list of period analyzed is reported in Table 1. On the average, the mass density uncertainty is about 35%, but can vary from 10% to over 50% depending on the $L$-parameter of the station pair and also from the geomagnetic conditions at the time of the observation.
Table 1

| Year     | Period                  | doy range |
|----------|-------------------------|-----------|
| 2012     | 22 September – 1 December | 266–336   |
| 2013     | 13 March – 27 March      | 72–86     |
| 2013     | 25 May – 11 June         | 145–162   |
| 2014     | 14 February – 9 March    | 45–68     |
| 2015     | 13 March – 31 March      | 72–90     |
| 2015     | 18 June – 27 June        | 169–178   |
| 2017     | 26 May – 2 June          | 146–153   |

2.2. Electron Number Density

The Van Allen Probes, formerly known as Radiation Belt Storm Probes (RBSP), is a mission composed by two twin satellites (RBSP-A, RBSP-B) orbiting in the Earth's equatorial plane with a period of 9 hr. Due to their eccentric orbits the probes have a spatial coverage that approximately extends from 1.1 to 5.8 Earth radii ($R_E$), providing high probability to cross the area sounded by EMMA. Moreover, the mission was active from 2012 to 2019 which perfectly overlaps with the EMMA data set.

The probes carried the EMFISIS experiment which makes possible an accurate estimation of the electron density by detection of the upper hybrid band radio emissions (Mosier et al., 1973). The electron number density is indeed linked to the upper frequency edge ($f_{\text{uh}}$) of the upper hybrid band and can be indirectly determined from it (e.g., Benson et al., 2004). During this procedure, the ambient magnetic field strength is also necessary, and is provided by the instruments on board the spacecraft.

Recently, Zhelavskaya et al. (2016) presented the Neural-network-based Upper-hybrid Resonance Determination (NURD) algorithm which automatically determines $f_{\text{uh}}$ from the spectrograms of the EMFISIS electric power spectral density and eventually provide the electron plasma density. The electron number density is sampled at a resolution of $\delta t = 6$ s and has a variable uncertainty ranging from 10% to 14%, the highest values being reached in the plasmatrough.

To remove random fluctuations, the density data were smoothed using a boxcar kernel with variable smooth width $w$. The last choice was made to overcome inconsistencies due to the high variability of the probes velocity, which would inevitably introduce, in some part of the orbit, an insufficient spatial resolution if a fixed time window were adopted. We rather imposed spatial constraints and chose $w$ accordingly, as a function of the McIlwain parameter ($L$). In particular, we required that in the smoothing time window $\Delta T = w \delta t$ the probe position varied for at most $\Delta \text{MLT} = 10$ min and $\Delta L = 0.1$, where MLT is the magnetic local time. Figure 1 illustrates the procedure adopted to determine $w(L)$. Top panel shows, for each orbit leg in the periods listed in Table 1, the absolute variation of the McIlwain parameter between two adjacent samples, as a function of $L$. The yellow solid curve is the fourth order polynomial fit:

$$\delta L = (-0.0088 L^4 + 0.11 L^3 - 0.50 L^2 + 0.31 L + 4.7) \times 10^{-3}. \quad (2)$$

The middle panel shows the absolute variation of the magnetic local time for the same periods. A linear combination of exponential functions (cyan curve) is used to model the $L$ dependence:

$$\delta \text{MLT} \equiv \left(4.53 e^{-1.2 L} + 0.39 e^{-0.28 L}\right). \quad (3)$$

By imposing the aforementioned constraints one can obtain the typical smooth width as a function of $L$. More specifically, the maximum smooth width related to the $L$ variation is $w_L = 0.1/\delta L$, which assumes a minimum value of 23 at $L = 1.7$, but diverges to infinity as $L$ approaches the apogee. The curve is reported as a green dashed line in the bottom panel. Similarly the maximum smooth width related to the MLT variations is $w_{\text{MLT}} = 10/\delta \text{MLT}$, where $\delta \text{MLT}$ is expressed in minutes, and varies from 12 at $L = 1.7$ to 145 at $L = 6.2$. It is represented as a blue dashed curve in the bottom panel. Considering both the constraints, the final choice for $w$ is the minimum values: $w = w_{\text{MLT}} = 10/\delta \text{MLT}$.
between \( w_L \) and \( w_{MLT} \), and is represented as a red solid line. The red curve actually represents the nearest odd integer, so that the smooth operation is symmetrically balanced around the central point. The resulting smooth width corresponds to a time window that varies between 78 s when the satellites are near the Earth and 14.5 min at the apogee. Accordingly, the uncertainty \( \Delta n_o \) associated with each smoothed value is the standard deviation of the same \( w \) samples used to evaluate \( n_o \).

An example of this adaptive smoothing procedure is shown as a black solid curve in Figure 2 where gray dots are electron number density values from RBSP-B in the time interval 15:50–19:00 UT on 13 October 2012.

### Figure 2.
Top panel shows the results of the selection procedure applied to the inbound orbit of RBSP-B on 13 October 2012, in the interval 15:50–19:00 UT corresponding to 15:45–21:45 MLT. Red open circles are selected RBSP points and blue open circles are associated EMMA points. Gray points represent the electron number density in the entire temporal range and the black solid line is the smoothed profile used in the selection procedure. Bottom panel shows the average ion mass evaluated at the selected points. The points across the PBL (inside the green circles) are excluded.

2.3. **Conjunction Events Selection Procedure**

To evaluate the average ion mass, the two plasma densities described above must refer to measurements taken simultaneously in the same region of space. In practical terms, we must impose some constraints on both space and time to identify the two measures as a conjunction event.

The position of the spacecraft and the position of the plasma mass density measurements (the last ones estimated using the TS05 model), were converted to Solar Magnetic (SM) coordinates. In this reference frame the EMMA-derived measurements \( \rho \) are in the \( X-Y \) plane, while RBSP-derived measurements \( n_o \) can depart from the magnetic equator due to the orbit inclination. However, we can derive the electron number density \( n_o \) in the equatorial plane using some assumptions. In the analyzed periods, the RBSP never exceeded an absolute magnetic latitude of 16°, with a median value of about –8°. Under these conditions, a dipole field approximation
can be used to describe the portion of the field line from the satellite to the equatorial crossing point and a reasonable decrease of $r^{-1}$ can be assumed for the electron number density along that portion (e.g., Denton, Takahashi, et al., 2006). The equatorial values are then evaluated using the relation:

$$n = n_o \left( \frac{r_{RBSP}}{L_{RBSP}R_E} \right),$$  

where $r_{RBSP}$ is the geocentric distance of the satellite and $L_{RBSP}$ is the McIlwain parameter of the field line passing through it. The associated uncertainty can be derived by error propagation of Equation 4:

$$\Delta n = \Delta n_o \left( \frac{r_{RBSP}}{L_{RBSP}R_E} \right),$$

where $\Delta n_o$ is the uncertainty determined in the smoothed procedure, and the uncertainty on the satellite position is neglected.

The conjunction events were identified as follows.

1. For each EMMA radial profile taken at universal time $t$ (center of the 2-hr spectral window), the portion of orbit covered from $t - \Delta t$ to $t + \Delta t$ was considered for each satellite, where $\Delta t = 1$ hr.
2. Each equatorial position derived for an EMMA station pair at time $t$ was compared with the nearest RBSP-derived equatorial position of the segment selected at point 1.
3. Only EMMA–RBSP data pairs that satisfy the following conditions were considered conjunction events:
   (a) $|r_{EMMA} - L_{RBSP}R_E|/r_{EMMA} < 0.05$,
   (b) $|\text{MLT}_{EMMA} - \text{MLT}_{RBSP}| < 0.5$ h,
   where $r_{EMMA}$ and $\text{MLT}_{EMMA}$ are the geocentric distance and the magnetic local time of the equatorial EMMA-derived measurements.
4. More than one EMMA-RBSP data pair, referring to the same RBSP data point, could be selected applying only conditions 1 to 3. In this case, only the EMMA-RBSP data pair with the lowest radial distance separation has been retained.
5. Conjunctions selected across the PBL were excluded. The PBL is highly dynamic and conditions 1 to 4 can select pairs having one point belonging to the PBL and the other to the plasmasphere or the plasmatrough, giving incorrect values for the average ion mass.

Summarizing, to identify a conjunction event the plasma mass density measure and the electron number density measure must differ in UT by at most 1 hr and must refer to positions that differ at most by $\Delta r/r = 0.05$ and $\Delta \text{MLT} = 0.5$ hr.

The choice $\Delta t = 1$ hr somewhat reduces the simultaneity between $n$ and $\rho$, but it is a reasonable compromise since the RBSP measurements are inside the 2-hr window used to estimate the plasma mass density. Rapid density variations in time cannot be efficiently resolved in the EMMA-derived data. They could however be well represented in the electron number density, and this could occasionally lead to an overestimation or underestimation of $M$. The MLT constraint was set to 0.5 hr which is the longitudinal separation between two EMMA radial profiles. It is worth noting, however that two contiguous $\rho$ estimates from the same station pair are not independent since they share most part of the time interval used to derive them. This could also lead to occasional overestimation or underestimation of $M$. The variable constraint on the radial density variation reflects the separation of the EMMA points in the equatorial plane which increases as the geocentric distance increases. The choice made gives a maximum absolute separation ranging from 0.1 to 0.4 $R_E$ as we move from 2 to 8 $R_E$.

The technique used to detect FLRs treats the field lines as vibrating strings, assuming that the footprints are fixed at ionospheric height. This approximation is generally valid during daytime when the electric conductivity in the ionosphere is high, but it is questionable during nighttime when the conductivity is relatively low. Accordingly, observations show a drastic reduction of the FLR occurrences after sunset (Chi et al., 2013; Del Corpo et al., 2019). For this reason we adopted the same criteria of Del Corpo et al. (2020) limiting our analysis only to measurements for which the footprints of the field lines were both sunlit. The sunrise and sunset times were evaluated at 120 km of altitude, which is approximately the height at which the wave reflection occurs (Denton,
Goldstein, et al., 2006). The analysis was also limited in geocentric distance by the apogee of the spacecraft orbits, that is at \( \sim 6 R_E \).

Applied to the entire database, the above procedure selected 774 conjunction events. Another 28 conjunctions, not included in the counting above, were excluded due to the proximity to the PBL. We found at least one conjunction event for 109 different RBSP orbits, belonging to 13 different storm events (8 of which with minimum \( Dst \) less than \( -100 \) nT) occurred in the year interval 2012–2017 (see Table 1). The data set is therefore heterogeneous enough to be used for general conclusions on the typical properties of the average ion mass around the maximum of the solar cycle 24. As an example, the top panel of Figure 2 shows the seven EMMA-RBSP data pairs selected in the time interval 15:50–19:00 UT on 13 October 2012, for the inbound orbit of RBSP-B. EMMA selected points are represented as blue open circles and RBSP ones as red open circles. The electron number density measurements for the entire interval are indicated as gray dots to give information about the plasmasphere status in the analyzed period. Black solid line is the resulting curve obtained applying the smoothing procedure described in Section 2.2. The bottom panel shows the average ion mass evaluated for the EMMA-RBSP selected pairs. Dashed lines indicates the physical limits \( M = 1 \) amu (bottom line) and \( M = 16 \) amu (top line). As can be seen, both \( \rho \) and \( n \) profiles suggest the presence of a PBL near 2.6 \( R_E \). In the plasmasphere, \( \rho \) and \( n \) have similar numerical values suggesting that the plasma is dominated by \( H^+ \) ions. By contrast, in the plasmatrough, \( \rho \) takes values higher than the \( n \) counterpart. As a result, the average ion mass increases by a factor of four or more passing from the plasmasphere to the plasmatrough, suggesting the presence of heavy ions. This scenario is consistent with some studies made in the past on this topic. For example, Nosé et al. (2011) examined four events and found a typical value of \( M \approx 3 \) amu in the plasmatrough, but with an enhancement of >7 amu in the proximity of the plasmapause, interpreted as the presence of an oxygen torus. The top panel of Figure 2 shows also an example of data points excluded due to their vicinity to the PBL (highlighted by a green circle). The corresponding value of \( M \) is highlighted by a green circle in the bottom panel and is well below the physical limit of 1 amu.

3. Results

The data set constructed applying the procedure described in Section 2.3 is composed of data obtained in a large variety of positions and geomagnetic conditions. The statistical properties of the data set are examined in this section.

In many cases, as in the example presented in Figure 2, we found a different ion composition between the plasmasphere and the plasmatrough region. Therefore, we first separate the data into two subsets referring to the two plasma regimes. The selection was performed by visually inspecting the single orbit plots such as that described in Figure 2. For orbit legs in which a PBL was clearly visible in the electron number density the selection was straightforward. An example is shown in Figure 3a, where EMMA points are in blue, RBSP points are in red, circles are plasmasphere points and crosses are plasmatrough points. The gray curve is the smoothed electron number density and clearly shows a PBL crossing around 3.5–4.1 \( R_E \), which helps to classify the conjunctions as plasmasphere or plasmatrough points. For cases with no PBL crossing, we compared the electron density with the equation empirically derived by Sheeley et al. (2001) roughly representing the border \( n_b \) between the plasmasphere-like and the trough-like typical density values. The equation is of the form \( n_b = 10(6.6/L)^4 \) and is represented as a dashed line in Figure 3. Panels b and c show typical passages of the RBSP

![Figure 3](image-url)

**Figure 3.** Examples of conjunction events for three RBSP orbit legs related to different configurations of the magnetospheric plasma. EMMA points are in blue. RBSP points are in red, open circles are plasmasphere points, crosses are plasmatrough points. Gray curves are the smoothed electron number density profiles during the orbit legs. Black dashed curves represent the boundary between plasmaspheric-like and plasmatrough-like typical densities as empirically derived by Sheeley et al. (2001). From top to bottom are shown a PBL crossing (a), an RBSP passage inside the plasmasphere (b) and an orbit leg entirely inside the plasmatrough (c).
probes in plasmasphere and plasmatrough, respectively, for which the attribution to either of the two plasma regimes would have been difficult without the reference curve. After the classification, the two subsets consist of 614 samples in the plasmasphere and 160 samples in the plasmatrough.

Figure 4 shows the locations of the data selected in a $r_{eq}$-MLT coordinate system. Plasmasphere and plasmatrough samples are represented as blue and red open circles, respectively. Although there are samples in all dayside MLT sectors and geocentric distances, the spatial coverage is not uniform. The best covered regions are the 07:00–11:00 and the 13:00–16:00 MLT sectors from 2 to $5 R_E$.

### 3.1. Spatial Variation of the Average Ion Mass

Figure 5 shows the plasma mass density as a function of the electron number density. The geocentric distance is represented in color scale as indicated in the color bar on the right. As expected, lower densities are generally found at higher geocentric distances. Plasmasphere samples are marked as open circles, while plasmatrough samples are marked as crosses. Thin dashed lines represent the physical limits within which the average ion mass is expected to lie. The bottom line corresponds to $M = 1$ amu while the top line corresponds to $M = 16$ amu. Pink shadowed area represents the typical mass density value at the inner edge of the PBL as determined by the Del Corpo et al. (2020) model for highly disturbed geomagnetic conditions. The model is limited to the 06:00-18:00 local time sector and provides an estimate of the plasma mass density distribution in the inner magnetosphere between 2.3 and $8 R_E$. It is LT dependent and uses the maximum $Kp$ index in the preceding 24 hr ($Kp^{*}$) as indicator of the geomagnetic activity to estimate the PBL inner edge position. The strip reported in Figure 5 is evaluated at LT = 12 using a variable $Kp^{*}$ ranging from 4.5 to 7, and roughly represents the limit above which no plasmatrough samples should be found. Figure 5 effectively shows that this strip approximately separates two distinct regimes. Above that limit the data points are only from the plasmasphere region and are distributed along the 1 amu line. Below the strip both plasmasphere and plasmatrough samples are present. The former are distributed along the 1 amu line; the latter are distributed toward the 16 amu line. If we consider also the uncertainty, 65 samples (8.4%) are outside the physical range. More specifically, they are all plasmaspheric samples distributed below the 1 amu line, and the corresponding circles are filled in magenta in Figure 5. Empty circles below 1 amu line have uncertainties such that $M + \Delta M \geq 1$.

Figure 6a shows the histogram of $M$ from the entire data set using a bin size of 0.1 amu. The median value of the distribution is $\bar{M} = 1.0$ amu, and the first and third quartile are 0.9 and 1.4 amu. If we consider separately the plasmasphere and plasmatrough subsets, the median values are 1.0 and 2.6 amu, respectively. The upper and lower quartiles for the plasmasphere distribution are 0.8 and 1.1 amu, while for the plasmatrough distribution are 1.8 and 3.8 amu. Histograms of $M$ for the two subsets are shown in Figures 6b and 6c. The pronounced peak at 1 amu for the plasmasphere subset suggests an overall dominance of H$^+$ ions. The symmetry of the counting distribution around this value is possibly due to an over- and underestimation of $M$ because of the not perfect conjunction between $ρ$ and $n$ measurements, rather than a real variation of the ion composition. The uncertainty of the density measurements can also determine a spread around the median value. Both causes could explain the presence of 65 samples out of the physical range. Since the aim of this work is to statistically characterize the variation of $M$ we kept also this values in the analysis, trying to avoid any bias. The counting distribution for the plasmatrough subset is highly irregular, suggesting a more variable composition, with important contribution of heavy ions.

Figure 7 describes more in detail the spatial distribution of the average ion mass. Red and blue open circles represents the plasmatrough and plasmasphere samples, respectively. Figure 7a shows the $M$ radial distribution. The samples are clustered due to the separation between EMMA station pairs. Dividing each subset in bins with variable size, the radial dependence can be described in terms of median values in each bin, using the first and third quartiles of the bin distribution to quantify the uncertainty (error bars). The bin limits in crescent order are 1.5, 2.0, 2.3, 2.5, 2.8, 3.1, 3.5, 4.1, 4.9, 5.5, 6.0, 6.5, and median values are shown as open squares, but only for those
bins that contain at least five points. The occurrence in each bin is reported in the top panel. The plasmasphere profile shows a typical value of 1 amu for all geocentric distances, with the exception of the first bin in which $\tilde{A}M$ reach a value of 1.5 amu. A similar behavior was also found by Chi et al. (2013) analyzing $L$-shells in the range 1.6–3.3 and is possibly related to the shorter scale heights of He$^+$ and O$^+$ ions with respect to those of H$^+$ ions (e.g., Horwitz et al., 1990). The proximity of magnetic shells with $L < 2$ to the ionosphere could explain the higher concentration of heavy ions. An alternative explanation could be an overestimation of $\rho$ due to the wrong power law coefficient used in Equation 1. As pointed out by Vellante and Förster (2006) a value greater than $m = 1$ should be adopted for $L < 2$. The plasmatrough profile, on the contrary, presents variations from $M \sim 2$ amu to $M \sim 7$ amu, with an enhancement at $r_{eq} \sim 3–3.5$ Re. Figure 7b shows the MLT distribution of $M$. Median values were obtained dividing each subset in 2 hr MLT bins. The results confirm that in plasmasphere $M \approx 1$ amu, without any clear dependence on the magnetic local time. Conversely, in the plasmatrough, the median points vary between $\sim 2$ and 5 amu reaching the highest values in the 07:00–09:00 MLT sector.

### 3.2. Effects of the Geomagnetic Activity

In this section, we investigate the statistical behavior of $M$ for different magnetospheric conditions, using the maximum $Kp$ in the preceding 24 hr ($Kp^*$) as an indicator of the geomagnetic activity level. Figure 8 shows the average ion mass as a function of $Kp^*$. The markers have the same meaning as in Figure 7 except the median...
results are evaluated for each value of the $Kp$ discrete scale. The $M$ plasmasphere profile does not show any variation on the geomagnetic activity, being $\sim 1$ amu for all but the last bin, for which $\tilde{M} = 1.6$ amu. This would suggest the presence of heavy ions also inside the plasmasphere during very strong geomagnetic conditions. However, for that particular bin, the points come from the same event (17–18 March 2015) so the above conclusion should not be intended in a statistical sense. The plasmatrough profile shows a pronounced dependence on $Kp^*$, with $M$ increasing from 1.5 to 6.3 amu. The bin $Kp^* = 7$ has a median value of 2.5, which is remarkably lower than the value one could expect following the increasing trend visible for $Kp^* < 7$. As for the case cited above, the points in that particular bin come from the same RBSP-A orbit (an outbound passage on 28 May 2017) so the median value is representative of that passage only.

Figure 6. Histograms of the average ion mass $M$ using (a) the whole data set, (b) only plasmasphere data, (c) only plasmatrough data. Total number of points and number of points out of the physical range are reported at the top right corner of each panel. Red dashed lines are the median values $\tilde{M}$, blue dashed lines are the first ($q_1$) and third ($q_3$) quartiles.
Following the criteria adopted by Del Corpo et al. (2019, 2020), we can extract further information arranging the data in three broad levels of geomagnetic activity:

1. $Kp^* \leq 2^+$, quiet magnetosphere;
2. $3^- \leq Kp^* \leq 4^+$, moderately disturbed magnetosphere;
3. $Kp^* \geq 5^-$, highly disturbed magnetosphere.

Figure 9 shows the radial dependence of $M$ for the three levels. The geomagnetic activity increases moving from top to bottom. Light green areas indicate the range of the PBL inner edge position, as derived by the Del Corpo et al. (2020) model. Since the model depends on $Kp^*$, a given range of $Kp^*$ values determine a corresponding range of PBL inner edge. In panel (a) the position is determined for $Kp^*$ varying from its minimum value in the data set to $2^+$. In panel (b) from $3^-$ to $4^+$. In panel (c) from $5^-$ to the maximum value occurring in the data set. The same limits are used to determine the average position of the O\(^+\) density enhancements as determined by the Roberts et al. (1987) model (area between magenta dashed lines), that will be discussed in the next section. The PBL inner edge position moves earthward as the geomagnetic activity increases. Concurrently, the relative number of plasmatrough samples increases and the higher the activity level the larger the radial distance range over which the samples are observed. This is the direct effect of the plasmasphere erosion, that intensifies...
during highly disturbed geomagnetic conditions and allows the appearance of plasmatrough samples at low radial distances, preventing at the same time plasmasphere observations at higher distances. The radial limit below which no plasmatrough points are found is well represented by the modeled PBL inner edge. However, there are plasmasphere points also beyond the estimated PBL. Besides the intrinsic error associated to the model in estimating the PBL position, some of those points might be related to plumes or co-rotating structures that are not predictable by the Del Corpo et al. (2020) model. The model provides the average inner edge position of the PBL for a particular geomagnetic activity condition, but is not able to reconstruct dynamical structures like plumes. The result is that typical plasmasphere density values are observed also beyond the average PBL position estimated by the model. Pezzopane et al. (2019) and Vellante et al. (2021) identified the presence of such structures for two events used also in this analysis.

Although the number of samples in each bin does not always allow a rigorous statistical description, this analysis confirms the overall picture that the plasmasphere ion composition does not depend on geomagnetic activity, maintaining the value of ∼1 amu for all the geocentric distances considered. As already mentioned commenting Figure 7, the only exception is the first bin of panel c. Points below $L = 2$ appear mostly for high geomagnetic activity conditions because a high ULF power is needed to reach the inner shells and drive FLRs (Menk et al., 2000; Vellante et al., 2007).

On the contrary, the plasmatrough is characterized by an increase of the average ion mass with increasing geomagnetic activity. For quiet geomagnetic conditions the median value is ∼1.5 amu, while for moderately disturbed geomagnetic conditions is between 2 and 3 amu. In both conditions no evident radial dependence is observed. For highly disturbed geomagnetic conditions $M$ shows a more complex behavior. A broad maximum ($M \sim 6–7$ amu) appears in the range 3–4 $R_E$, suggesting a more significant contribution of heavy ions.

Figure 10 shows the MLT dependence of $M$ for the three levels of geomagnetic activity. Markers have the same meaning as in Figure 7b. Again, the plasmasphere appears dominated by H$^+$ ions for all geomagnetic conditions and in all the MLT sectors considered. As observed in the previous analysis, the average ion mass in plasmatrough generally increases with geomagnetic activity. For quiet geomagnetic conditions only the MLT sector around noon is covered, with a median value of ∼1.5 amu. For moderately disturbed geomagnetic conditions the MLT interval over which the points are observable increases. The median value is ∼2 amu in the 9–15 MLT sector while is ∼5 amu in the 7–9 MLT sector. For highly disturbed conditions the magnetic local time sector for which $M$ reaches 5 amu extends to 7–11 MLT suggesting an expansion of the morning region with preferred heavy ion mass loading.

Following a reviewer suggestion, we repeated the analysis presented in this section using a weighted average of the $Kp$ in the preceding 24 hr as indicator of the geomagnetic activity. In particular, we followed the idea
Figure 9. Radial profiles of the average ion mass $M$ for three levels of geomagnetic activity: (a) quiet, (b) moderately disturbed, and (c) highly disturbed magnetosphere. The meaning of the markers is the same as in Figure 7a. Light green areas are the average positions of PBL inner edge as deduced from the Del Corpo et al. (2020) model. The area between magenta dashed lines represents the average position of the oxygen density enhancements as determined by the Roberts et al. (1987) model.
Figure 10. Longitudinal profiles of the average ion mass $M$ for three levels of geomagnetic activity: (a) quiet, (b) moderately disturbed, and (c) highly disturbed magnetosphere. The meaning of the markers is the same as in Figure 7b.
suggested by Gallagher et al. (1988), evaluating the average \( Kp \) over a period \( \tau \) preceding the current time \( t_0 \), weighting with an exponential function of the form \( w(t) = \exp[-(t - t_0)/\tau] \). Similar indicators were also used in other works (e.g., Takahashi et al., 2006). The main results shown in Figures 8–10 are basically unchanged.

4. Discussion

The results of this work clearly show that, on the average, the dayside plasmasphere is dominated by \( H^+ \) ions regardless of the position and the geomagnetic activity. As shown in Figure 6b the plasmaspheric points are well distributed around \( M = 1 \) amu with an interquartile range of 0.3 amu, and this tendency is confirmed by the subsequent analysis presented in Figures 7–10.

About 8% of the conjunctions points in the plasmasphere provide \( M \) estimates which are unrealistically low. If the presence of those points is due to the not simultaneity of mass and electron densities or to their uncertainties, it is reasonable to assume that a similar proportion of \( M \) estimates might be higher, but the statistical description should not be affected by any bias. We cannot rule out, however, the presence of any bias due to systematic errors that could arise from the techniques and the approximations used to infer \( \rho \) and \( n \). In particular, the tracing of the field line could be a major source of error, but it is not considered in the determination of the uncertainty of \( \rho \) (Del Corpo et al., 2019). A critical review of all the major sources of error that can affect the final estimation of \( \rho \) is still missing and definitively deserves further investigations.

Past experiments clearly show that the \( \mathrm{He}^+ \) density in the plasmasphere is not zero. For example, the Extreme Ultraviolet Imager instrument (EUV, Sandel et al., 2000) on board the IMAGE spacecraft uses images of \( \mathrm{He}^+ \) concentration to map the plasmasphere. Combining EUV images with electron number densities and plasma mass density estimations, Menk et al. (2012) studied the plasmaspheric ion composition at \( L \sim 2.5 \) for the 2001 solar maximum (cycle 23). They found an \( \mathrm{He}^+ \) concentration of about 5% by number, and a variable \( O^+ \) concentration in the range 0.5%–6%, corresponding to an average ion mass loading in the range 1.3–2.1 amu. A similar study by Grew et al. (2007) for the 30 September–8 October 2002 geomagnetic storm suggested a typical plasmaspheric \( \mathrm{He}^+ \) concentration of the order of 15% of the total number density, and an \( O^+ \) concentration of 3%. This would imply an average ion mass of \( \sim 1.9 \) amu, that is well above the typical values found in our analysis: \( M \pm \Delta M = 0.98 \pm 0.15 \) amu, where \( \Delta M \) is one-half of the interquartile distance that for symmetric distributions is a good estimator of the dispersion (see Huber, 1981).

This discrepancy may be related to the difference in the solar activity levels during the analyzed time intervals. Indeed the ratio \( R = n_{\mathrm{He}^+}/n_{\mathrm{He}^2+} \) can increase by a factor of 5 passing from the minimum to the maximum of the solar cycle (Craven et al., 1997). Both our analysis and the ones cited above refer to the maximum of a solar cycle, but the cycle studied in the present work was atypical and weaker than the preceding ones (e.g., Jiang et al., 2015). An extensive characterization of the \( \mathrm{He}^+ \) plasmaspheric concentration was made by Craven et al. (1997) who used DE-1/RIMS measurements collected during the declining phase of the solar cycle 21 (1981–1984). They realized that \( R \) varies mostly with the radial distance \( r \) and the solar activity, and very weakly with season, local time and geomagnetic activity, the last two dependencies confirmed also by our analysis. Using the index proposed by Richards et al. (1994) \( P = (F10.7 + F10.7A)/2 \) as a proxy for the solar activity, where \( F10.7 \) is the daily measure of the 10.7 cm solar flux and \( F10.7A \) is its 81-day average centered on the day of interest, they modeled the ratio \( R \) with the function:

\[
\log_{10} R(r, P) = -1.541 - 0.176 r + 8.557 \times 10^{-3} P - 1.458 \times 10^{-5} P^2.
\]  

We used Equation 6 to evaluate the modeled average ion mass for each plasmasphere conjunction assuming that only light ions were present. The median points for the same radial bins of Figure 7a decrease from 1.2 amu at 1.9 \( R_E \) to less than 1.1 amu at 5.9 \( R_E \). Adding an \( O^+ \) concentration of 1% (e.g., Gallagher et al., 2021; Goldstein et al., 2019), the above quantities change to 1.4 amu at 1.9 \( R_E \) to 1.2 amu at 5.9 \( R_E \). The decreasing trend predicted by the model is loosely reproduced by our observations, which on the average vary from 1.1 amu at 2 \( R_E \) to 0.9 amu at 3.7 \( R_E \). This comparison makes us confident that if any bias affects the distribution of \( M \) it is of the order of \( \Delta M \) and, consequently, the physical interpretations discussed in this section should be considered reliable within this uncertainty. Vellante et al. (2021) made a comparison similar to the one adopted in this paper and found median values very close to 1 in the range 2.5–5 \( R_E \), pretty much consistent with our results.
A decreasing trend was found also in other studies. Chi et al. (2013) found an average ion mass decreasing from 1.3 at $L = 1.9$ to 1 at $L = 3.1$, comparing mass density observations inferred using FLRs detected by the Mid-continent MAgnetoseismic Chain (McMAC) with the electron number density empirical model by Ozhogin et al. (2012). Similarly, Del Corpo et al. (2020) compared their local time dependent model of the plasmaspheric plasma mass density with the Ozhogin et al. (2012) and Carpenter and Anderson (1992) charge density models. In the morning sector, they found a typical value of 1 amu in the $L$ range 3–4 with an increasing trend toward lower $L$, up to a value of 1.2 amu at $L = 2.3$. In the afternoon sector, they found the same trend, although with higher values for $M$ (1.3–1.4 amu in the $L$ range 3–4, 1.8 amu at $L = 2.3$).

Focusing on Figure 9 we can see that the decreasing trend stops inside or soon after the predicted position of the PBL inner edge, where an increase of $M$ is visible for all the geomagnetic activity conditions. During quiet times we estimated an average ion mass enhancement of 30% comparing the median points at 3.7 and 4.2 $R_E$. For moderately disturbed conditions, $M$ increases of about 24% comparing the points at 3.3 and 3.8 $R_E$. For highly disturbed conditions we estimated a negligible increase of 4% comparing the points at 2.4 and 2.6 $R_E$.

Although these variations are inside the statistical dispersion of the individual points, such increase is expected as well documented by DE-1/RIMS observations of heavy ions concentration enhancements across the PBL (e.g., Chappell, 1982; Fraser et al., 2005; Horwitz et al., 1984, 1986; Roberts et al., 1987).

Also the plasmatrough ion concentration could be strongly influenced by the solar activity. An analysis by Denton et al. (2011) at the geosynchronous orbit in the interval 1990–2007 (i.e., across solar cycles 22 and 23), showed that $M$ is typically $\sim$3.8 amu at solar maximum and near unity at solar minimum. Extrapolating to 6.6 $R_E$ the red dotted curve in Figure 7a we find a median value of $\sim$1.8 amu, which can be assumed as representative of the solar cycle 24 maximum. This comparison confirm that the low solar activity of the last solar cycle strongly influenced the average magnetospheric ion composition.

In general, the plasmatrough analysis suggests a significant dependence of the heavy ion composition on both position and geomagnetic activity. Figure 8 highlights a pronounced dependence on $Kp^s$. Takahashi et al. (2006) found a similar behavior for the plasmatrough in the afternoon MLT sector using, as geomagnetic activity indicator, $Kp$ weighted averages over 1.5 and 3.0 days previous to the time of the observation. They found no evident radial dependence of the average ion mass, but their analysis extended from 4 $R_E$ to 8 $R_E$, so it is not in contrast with our results which confirm a very slow decrease beyond 4.5 $R_E$ (see Figures 7a and 9). Takahashi et al. (2006) observed $M$ values varying from $\sim$2.5 amu during quiet geomagnetic conditions to $\sim$6 amu for highly disturbed geomagnetic conditions, in line with our results.

An interesting outcome revealed by our analysis, is a broad maximum ($M \sim 6–7$ amu) in the range 3–4 $R_E$ for highly disturbed geomagnetic conditions (Figure 9c), suggesting a more significant contribution of heavy ions, compatible with the formation of an oxygen torus in the proximity of the plasmapause. The $O^+$ increase across the PBL is well documented and has been observed in many works (e.g., Chappell, 1982; Fraser et al., 2005; Horwitz et al., 1984; Nosé et al., 2011, 2015), but the only attempt to statistically describe the phenomenon is the work of Roberts et al. (1987), who characterized the heavy ion enhancements using the DE-1/RIMS database. They found that the oxygen density enhancements occurrence peaks between $L = 2$ and $L = 5$ and tried to model the dependence on the $Kp$ index of the enhancement position with the linear function $L_o = -0.20 Kp + 4.50$. The values of $L_o$ for the extrema of the three magnetic activity levels used in our analysis are reported as magenta dashed lines in Figure 9. Because of its definition, we expect that the predicted oxygen peak lies beyond the PBL inner edge position that we determined using the Del Corpo et al. (2020) model (light green areas), and coincide with a peak in the average ion mass observed. This is strictly true only for highly disturbed periods, as we do not observe significant $M$ enhancements for quiet and moderately disturbed periods. A small enhancement is barely visible for moderate conditions around 4.3 $R_E$ but is outside the predicted $O^+$ peak position. During quiet times there is no peak observed. Anyway, $L_o$ seems too small if compared with the modeled PBL inner edge and the first trough points observed.

Del Corpo et al. (2020) compared their plasmatrough mass density model with several charge density models. In particular, the comparison with the Carpenter and Anderson (1992) model in the 06–15 LT sector suggested values between 2.0 and 4.7 amu at 4 $R_E$ which is in line with our results (see Figure 7a), and from 2.4 to 3.9 amu at 7 $R_E$, which are somewhat larger than the present findings. Their analysis showed an $M$ increase throughout the daytime hours, an effect much larger at 4 $R_E$ than 7 $R_E$. Such behavior seems in contrast with the longitudinal...
dependence shown in Figure 7b. However, a comparison of electron and mass density models for deriving the average ion mass is quite questionable because the two models may correspond to measurements made under different phases of the solar cycle, or they may be based on a different relative weight of high and quiet geomagnetic activity periods. We believe that a reliable estimate of the average ion mass can only be derived from a direct comparison of simultaneous measurements of mass and electron density as in the present paper.

Besides the work by Roberts et al. (1987), very few studies have been focused on the longitudinal structure of the ion composition. Denton et al. (2014) investigated the O\(^+\) concentration at the geosynchronous orbit during two events, one active and one more quiet. During the active event, they observed an oscillation in the plasma composition with low concentration on the dayside and high concentration near midnight. They interpreted this asymmetry as a change of observation of plasma streaming on closed and open drift paths. The drift boundary was common encountered between dusk and midnight, separating a region more influenced by ionospheric plasma from relatively empty flux tubes convecting from the tail and, thus, having more plasma sheet-like characteristics. During prolonged quiet periods they observed a gradual change of the ion composition from low-density and high-M to high-density and low-M, interpreting this behavior as the manifestation of long-term refilling. Roberts et al. (1987) found that the O\(^+\) enhancement occurrence tends to peak in the dawn and pre-midnight sectors, while the enhancements magnitude broadly peaks at dawn and in the pre-dusk MLT sector. The coverage of our observations (limited to daily hours) does not allow a detailed description of the dawn sector, but we observe an enhancement of \(M\) around 7–9 MLT and 15–17 MLT (Figure 7b) which is generally consistent with the results by Roberts et al. (1987). Analyzing more in detail the dependence on the geomagnetic activity (Figure 10), we argue that the heavy ion mass loading is more intense during disturbed conditions, particularly in the dawn sector. Although \(M\) slightly increases also in the noon sector, the study suggests that the presence of heavy ions in that particular MLT sector is moderate also during severe geomagnetic activity conditions. As pointed out by Nosé et al. (2020), despite the name, there is no evidence that the oxygen torus symmetrically extends over all longitudes. They also presented a case study suggesting that it could be skewed toward the dawn. Considering that a similar conclusion was already reported for another event (Nosé et al., 2018), they proposed that a crescent shape torus centered around dawn could be a general feature of the O\(^+\) enhancements. Our results are consistent with this scenario, but we have to call attention on the possibility that this variation could also be attributed to the non-uniform distribution of the samples. Indeed, a comparison with the spatial distribution shown in Figure 4 suggests that the MLT sectors with higher \(M\) values mostly have points closer to the Earth, where, as highlighted during the discussion of Figure 7a, the average ion mass assumes the highest values.

It is worthwhile to mention that the spatial distribution of \(M\) observed in this work is also compatible with the warm plasma cloak, a plasma population with energies of 10 eV to 3 keV originally introduced by Chappell et al. (2008). The plasma cloak consists of ions flowing out from the polar ionosphere, subsequently energized in the polar cap and the magnetotail. After this energization, the ions convect sunward and drift eastward around the Earth under the combined effect of the convection and co-rotation electric fields, eventually being lost into the magnetosheath. For this reason, the plasma cloak ions are observed more often in the morning sector than the afternoon sector. Nosé et al. (2015) performed a numerical calculation in the attempt to interpret the formation and evolution of the oxygen torus observed by the RBSPs during the 15 November 2012 event. The morphology of the simulated oxygen torus was identical to the warm plasma cloak presented by Chappell et al. (2008), with the main difference that the former can be located also inside the plasmasphere and pertain to a limited set of \(L\)-shells. The techniques used to determine \(\rho\) and \(n\) do not allow to make considerations on the energy of the plasma, so we cannot exclude or confirm the contribution of the cloak to the general pattern described in this section. A possible extension to the analysis presented here could be the systematic comparison of the average ion mass derived for each conjunction with the partial ion densities measured by the Energetic Particle, Composition, and Thermal Plasma (ECT) suite on board the Van Allen Probes. The Helium Oxygen Proton Electron (HOPE, Funsten et al., 2013) mass spectrometer instrument, which is part of the suite, is able to measure ion densities with energies from 30 eV to 45 keV, and would be able to clarify the warm plasma cloak contribution to the average ion mass observed. We plan to dedicate a separate work to this comparison.
5. Conclusions

We investigated the statistical dependence of the magnetospheric average ion mass on the position and the geomagnetic activity. The analysis was conducted comparing plasma mass density inferred from FLRs detected at the European quasi-Meridional Magnetometer Array with electron number density derived from local electric field measurements made on the Van Allen Probes. Plasma mass density measurements was limited to daytime hours so the statistic is limited to the dayside magnetosphere. Moreover, the apogee of the spacecraft orbits limited the analysis to geocentric distances below 6 $R_E$. The study refers to several periods in the year interval 2012–2017 for about six months of observations, focusing on conjunction events in which both mass and charge densities were simultaneously available approximately at the same position. The analysis was conducted independently for the plasmasphere and the plasmatrough finding 614 conjunction events for the former and 160 for the latter.

We found that in the plasmasphere the average ion mass is $\approx 1$ amu, with no clear dependence on the position or the geomagnetic activity conditions. This result suggests that the plasma mainly consists of $H^+$ ions.

On the other hand, in the plasmatrough, the average ion mass can increase considerably with the geomagnetic activity, ranging from 1.5 to 6 amu, with a median value of 2.6 amu. The contribution of heavy ions varies also with the position. An analysis of the radial distribution of the plasma revealed that during the most disturbed conditions, a broad maximum appears around 3–4 $R_E$, just near the position usually occupied by the plasmapause. This could be the consequence of the accumulation of oxygen ions in that region. Focusing on the longitudinal structure of the ion composition, we found that the greatest heavy ions enhancements are more likely to be observed in the 7–9 and 15–17 MLT sectors.

The limited number of selected points does not always allow a rigorous description, and an extension of the data set is necessary to improve the reliability of the results presented. It is important to note, however, that the data set presented here is the largest collection of average ion mass estimates obtained from simultaneous observations of mass and electron density, and encompassing a vast region of the dayside magnetosphere and a wide range of geomagnetic conditions. We plan to extend the analysis to all available EMMA data in the RBSP era, once a fully reliable automated procedure for the identification of FLRs will be developed.

Data Availability Statement

NURD electron density data (Zhelavskaya et al., 2020, https://doi.org/10.5880/GFZ.2.8.2020.002) are available from GFZ Data Services. EMMA data (Vellante & Heilig, 2019, https://doi.org/10.5281/zenodo.3387216) used to infer the plasma mass density and the conjunctions data set produced in this study (Del Corpo & Vellante, 2022, https://doi.org/10.5281/zenodo.6928712) are available from Zenodo. Solar wind parameters as well as geomagnetic and solar indices from OMNI data set are available at https://cdaweb.gsfc.nasa.gov. The software to evaluate the magnetospheric model by Tsyganenko and Sitnov (2005) and the GEOPACK 2008 library are openly available at https://geo.phys.spbu.ru/~tsyganenko/empirical-models/.

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