Investigation of Small-Scale Density Electron Irregularities Observed by the Arase and Van Allen Probes Satellites Inside and Outside the Plasmasphere

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Abstract In situ electron density profiles obtained from Arase in the night magnetic local time (MLT) sector and from RBSP-B covering all MLTs are used to study the small-scale density irregularities present in the plasmasphere and near the plasmapause. Electron density perturbations with amplitudes >10% from background density and with time-scales less than 30-min are investigated here as the small-scale density irregularities. The statistical survey of the density irregularities is carried out using nearly 2 years of density data obtained from RBSP-B and 4 months of data from Arase satellites. The results show that density irregularities are present globally at all MLT sectors and L-shells both inside and outside the plasmapause, with a higher occurrence at L > 4. The occurrence of density irregularities is found to be higher during disturbed geomagnetic and interplanetary conditions. The case studies presented here revealed: (1) The plasmaspheric density irregularities observed during both quiet and disturbed conditions are found to coexist with the hot plasma sheet population. (2) During quiet periods, the plasma waves in the whistler-mode frequency range are found to be modulated by the small-scale density irregularities, with density depletions coinciding well with the decrease in whistler intensity. Our observations suggest that different source mechanisms are responsible for the generation of density structures at different MLTs and geomagnetic conditions.

1. Introduction

The plasmasphere is the innermost region of the Earth’s magnetosphere, which is filled with cold (low energy ∼1–10 electron volt (eV) and dense (10–10⁴ cm⁻³)) plasma of ionospheric origin trapped to the Earth’s magnetic field, forming a thermal plasma cloud encircling the Earth (Darrouzet et al., 2009b; Lemaire et al., 1998). Outside the plasmasphere, the plasma characteristics change abruptly to tenuous (1 cm⁻³), hot (high energy ∼100 eV) plasma. The boundary that separates this outer region of the highly energized, low-density plasma from the plasmasphere, is called plasmapause.

The plasma motions in the inner magnetosphere are dominated by large scale electric fields. The corotation electric field enhances the corotation of cold plasma near the Earth, and the magnetospheric convection electric field (generated by the interaction between the solar wind and the magnetosphere) causes the loss of cold plasma outside the plasmasphere. The convection electric field, being a key factor for the formation of the plasmapause (Pierrard et al., 2008), the location and sharpness of the plasmapause vary with...
geomagnetic activity, with plasmapause located closer to the Earth and sharper during times of high geomagnetic activity (Carpenter & Anderson, 1992; Chappell et al., 1970; Goldstein, 2006).

Apart from this simple picture of clear, sharp density variations, the satellite and ground observations have revealed that the plasmasphere and its boundary are often complicated by density structures of various scale sizes (Carpenter & Lemaire, 1997; Darrouzet et al., 2009a). The large scale structures like plumes, which are enhanced plasma elements attached to the main plasmasphere body, are routinely observed in the afternoon to dusk sector by extreme ultra violet (EUV) instrument onboard IMAGE (Sandel et al., 2003) and Waves of High frequency and Sounder for Probing Electron density by Relaxation (WHISPER) onboard Cluster satellites (Darrouzet et al., 2008). In addition to the large scale structures, the observations from satellite (Darrouzet et al., 2004; Higel, 1978; LeDocq et al., 1994; Moldwin et al., 1995) and ground platforms (Smith, 1961) have also revealed the occurrence of small-scale density irregularities both inside and outside the plasmapause.

The plasmaspheric density irregularities were mostly probed using indirect methods by exploiting their transmission properties as waveguides or ducts (Carpenter & Anderson, 1992; Carpenter & Park, 1973; Ganguli et al., 2000; Singh et al., 1998). The whistler-mode waves in the magnetosphere are known to be effectively guided by field-aligned ducts. Satellite-borne observations have shown that the intensity of the whistler-mode chorus and hiss emissions are modulated by enhanced and depleted plasma structures often observed near the plasmapause between \( L = 4 \) and \( L = 6 \) (Angerami, 1970; Koons, 1989; Moullard et al., 2002; Scarf & Chappell, 1973). Li et al. (2011) using THEMIS data have reported a remarkable correlation of density irregularities in the plasmasphere with modulated chorus wave intensity in the dawn sector. In a recent study using RBSP-B observations, Yue et al. (2020) have reported an event which shows the modulation of particle fluxes and the plasma waves by the background electron density irregularities. They have shown that the density irregularities create preferential conditions for wave generations, which in turn accelerate electrons and ions through wave-particle interaction. These observations point out the significant impact of the density variations on different plasma waves and, hence, on the energization and loss processes of energetic charged particles in the inner magnetosphere (Adrian et al., 2015).

The fluctuations in the electron density were observed since the beginning of the in situ observations. One of the earliest in situ observations of the cold plasma density was made by OGO 5 (Chappell et al., 1970), EXOS-B (Oya & Ono, 1987), CRRES (LeDocq et al., 1994), and Los Alamos National Laboratory (Moldwin et al., 1995) satellite missions. These observations revealed the existence of density irregularities near the plasmapause and the outer regions of the plasmasphere. The multi-point in situ observations from four Cluster satellites and the global imaging capabilities of IMAGE satellite have brought valuable insights into the dynamics of the plasmasphere and the density irregularities near the plasmapause (see review by Darrouzet et al. [2009a]). These novel missions, with their unprecedented time and spatial resolution, could reveal the finer structures in the plasmasphere and its outer boundaries. With the capability to receive the echoes of the long-range electromagnetic sounder waves, reflected from remote plasmasphere locations, the Radio Plasma Imager (RPI) onboard the IMAGE satellite can yield the plasma parameters and the characteristic scale sizes of the irregularities present in these regions (Fung et al., 2000). Carpenter et al. (2002) have observed the range spreading in the plasmasphere echoes obtained from RPI and have attributed them to be caused by the interactions with the field-aligned electron density irregularities having cross-field scale size ranging between \(~200\) m and \(10\) km.

The in situ observations from Cluster satellites have confirmed the occurrence of small-scale density irregularities inside the plasmasphere (Darrouzet et al., 2004) and in the plasmapause boundary layer (Décréau et al., 2005). The density gradients obtained using the four-point Cluster observations also suggest the field-aligned nature of the plasma elements, with cross field scale size ranging between tens to hundreds of kilometers (Darrouzet et al., 2006). The velocities of the plasma structures deduced by this multi-satellite mission showed that the density irregularities have azimuthal velocities comparable to the corotation of the plasmasphere, indicating the corotation motion of these plasma elements with the Earth. Darrouzet et al. (2004) performed the first statistical study of the small-scale density structures using the electron density observations from 33 plasmapause crossings of four Cluster satellites. Their study indicates a higher occurrence of the density irregularities during disturbed geomagnetic conditions (Kp > 2) and asymmetry...
in its magnetic local time (MLT) distribution. However, this statistical study was based on a limited number of satellite passes and less global coverage.

Based on the various observation and plasmaspheric modeling studies, different mechanisms have been proposed to address these density irregularities. However, the causative mechanisms responsible for the generation of these density irregularities remain unsolved yet. The association of the density irregularities with disturbed geomagnetic conditions suggests changes in plasma convection caused by the variations in the direction and strength of the interplanetary magnetic field (IMF) as a source mechanism for the formation of density irregularities (Goldstein et al., 2002). Moldwin et al. (1995) attributed the increased occurrence of the fine-scale density structures in the outer plasmasphere during substorm intervals to the penetrating substorm electric fields. Moldwin et al. (1995) attributed the increased occurrence of the fine-scale density structures in the outer plasmasphere during substorm intervals to the penetrating substorm electric fields.

Morioka and Oya (1996) have reported sudden plasma density depletions observed by the Akebono satellite during the plasmapause crossings. These plasma depletions showed one to one correspondence with the UHR wave enhancement and also with the auroral kilometric radiations (a proxy of substorm onset), propagating from the remote sources in the auroral regions. The observed plasma density irregularities are suggested to be caused by the fast plasma injections into the plasmapause region in association with substorm activity.

The plasma instabilities are also reported to have a significant role in the generation of these density irregularities. The interchange motion of the flux tubes is considered to be one of the main factors which control the radial plasma transport in the magnetosphere (Ferriere et al., 1999). During enhanced convection, the quasi-interchange mode driven by gravitational and centrifugal effects will have a dominant impact on the outer plasmasphere (Ferriere et al., 2001; Lemaire, 2001). In this scenario, the increased flux tube interchange can cause the plasma density distribution to become convectively unstable, thereby leading to the growth of small-scale density irregularities in the plasmasphere. Kelvin-Helmholtz (KH) instability ( Chandrasekhar, 1961) excited by the velocity shear of the plasma (Liu et al., 2018 and references therein), can also be a triggering factor for generating these small-scale density undulations near the plasmapause boundary.

The previous studies of density irregularities were mainly based on case studies or a limited number of density profiles restricted to particular local time sectors. Hence, a global picture of the occurrence of density irregularities, its distribution in L, MLT, and Mlat has never been derived. The availability of large samples of density profiles from two inner magnetospheric satellite missions, Van Allen Probes and Arase, has provided an excellent opportunity to obtain the global features of the density irregularities. This paper presents the statistical survey of small-scale density irregularities in the plasmasphere and near the plasmapause by investigating the electron density profiles from Van Allen Probes and Arase satellites in the equatorial and off-equatorial latitudes, respectively. The study derives the global features of the density irregularities and also the dependence of density irregularities on various geomagnetic and solar wind conditions. We have investigated 2 years of data from Van Allen Probes covering all local time sectors and 4 months of data from Arase in the night sector. To the best of the authors’ knowledge, this is the first statistical study of density irregularities carried out by examining an extensive data set obtained from in situ measurements. In addition to the statistical analysis, the paper also presents case studies comparing density observations with the simultaneous plasma waves, the electric/magnetic field measurements onboard satellites. Through case studies, we have also investigated the energy—time distribution of the ion/electron flux (in the energy range 100s of eV to a few MeV) when density irregularities were observed.

The paper is organized as follows. Section 2 describes the data set used in this study. Sections 3 and 4 discuss the case studies of electron density irregularities observed by Van Allen Probes and Arase satellites, respectively. The statistical results of density variations combining observations from both satellite missions are presented in Section 5. The findings of the study are discussed and summarized in Section 6.

2. Data

The present study investigates the density irregularities inside and outside the plasmasphere using data from two inner magnetospheric satellite missions, Exploration of energization and Radiation in Geospace (ERG, also known as Arase; Miyoshi et al., 2018c) and Van Allen Probes (Mauk et al., 2012; henceforth
RBSP) satellites. Arase and RBSP move in elliptical orbits with altitudes of ∼460 and ∼600 km at perigee and 5\(R_E\) and 4.8\(R_E\) at apogee, respectively. Both satellites probe the plasmasphere and its outer regions (inner plasma sheet) at different inclinations. Arase covers larger L shells with a higher inclination of ∼31°, whereas RBSP orbits in the near-equatorial plane (inclination ∼10°).

In this study, the in situ electron density observations from Arase averaged to 1 min time interval and from RBSP-B with 11 s sampling are investigated to study the plasmaspheric density structures. The electron density data from Arase is inferred by the visual inspection of the upper hybrid resonance (UHR) frequency of the plasma obtained from the High Frequency Analyzer (HFA) and Onboard Frequency Analyzer (OFA) on Plasma Wave Experiment (PWE) instrument (Y. Kasahara et al., 2018; Kumamoto et al., 2018). Using the observed UHR frequency and the local cyclotron frequency data derived from the magnetic field experiment (MGF) instrument (Matsuoka et al., 2018), the plasma frequency, that is, the total electron density can be derived. It has to be noted that the original HFA sampling rate is 8 or 1 s, and the Level-3 HFA electron density data used in this study is provided as 1 min averaged values. The density data from RBSP-B is obtained from the electric field and wave (EFW; Wygant et al., 2013) instrument. EFW gives the density measurements inferred from the spacecraft potential and calibrated using the UHR line from Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS; Kletzing et al., 2013). We have investigated 4 months of Arase data from April to July 2017, which are currently available, and nearly 2 years of RBSP-B density data from August 2016 to May 2018. Note that, the present study utilizes only the RBSP-B satellite of Van Allen Probes mission due to the unequal availability of density data from RBSP-A and RBSP-B satellites.

In the considered study period, the apogee of Arase spans pre- to post-midnight local time sectors. The larger data set from RBSP-B enabled us to get observations covering all MLT sectors. Using this combined data set from Arase and RBSP-B, we have performed a statistical survey of the density irregularities to understand their characteristic features.

In addition to the density, we have also used data from plasma instruments onboard both Arase and RBSP-B and electric and magnetic field instruments onboard RBSP-B. The density structures observed are compared with the plasma and electric and magnetic field data and are presented as case studies.

The plasma data from Arase is obtained from medium-energy particle experiments—electron analyzer (MEP-e; S. Kasahara et al., 2018a, 2018b), medium-energy particle experiments—ion mass analyzer (MEP-i; Yokota et al., 2017, 2018), low-energy particle experiments—electron analyzer (LEP-e; Kazama et al., 2017; Wang et al., 2018), and low-energy particle experiments—ion mass analyzer (LEP-i; Asamura et al., 2018a, 2018b). Plasma data from RBSP-B comprise electron and proton flux from Helium Oxygen Proton Electron (HOPE; Funsten et al., 2013) plasma spectrometer instrument, and Magnetic Electron Ion Spectrometer (MagEIS; Blake et al., 2013) instrument and ion fluxes from Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE; Mitchell et al., 2013).

Electric and magnetic field data used in the study are obtained from EFW and EMFISIS instruments onboard RBSP-B satellite. In the present study, we have used the plasma wave observations recorded by waveform receiver (WFR) on EMFISIS, which gives the power spectral densities of the oscillating electric and magnetic fields in the frequency range from 10 to 12 kHz at 6 s sampling and static magnetic field recorded by fluxgate magnetometer with a 1 s sampling on EMFISIS. The DC electric field used here is the spin-fit electric field in the modified GSE (mGSE) coordinate system with 11 s (spin period) sampling obtained from EFW instrument. Note that the mGSE coordinate system is a near geocentric solar elliptic (GSE) system for RBSP. If the spin axis of the satellite points toward the sun, then the mGSE system is exactly the same as the GSE system. Generally, the mGSE system for RBSP will be about 20° off the GSE system.

### 3. Event Study: RBSP Observations on August 16, 2017

Figure 1 presents the case study of electron density irregularities observed by RBSP-B on August 16, 2017 during quiet geomagnetic conditions (Kp < 2). Extreme quiet geomagnetic condition was also prevailing in the previous 24 h with Kp ≤ 1. During this event, the RBSP-B satellite was located in the dayside, with MLT around 13:00 h near the apogee location. Figure 1a shows the total electron density profiles obtained from the EFW instrument during the three successive orbits of RBSP-B. The observations show density depletions of ∼90 (/cc) near the apogee location at L shell of ∼5.9 in all the three orbits. The presence of nearly
identical density depletions near the apogee at ∼2, 11, and 20 UT may indicate the persistence of these structures in the dayside over 24 h interval. The density depletions are also evident at the lower L values in both inbound and outbound legs. However, these structures are found to vary from orbit to orbit. Figures 1b and 1c show the energy-time spectrogram of the spin averaged differential proton flux in the energy range 150 keV–1 MeV from MagEIS and (c) low energy range from HOPE instruments. Similarly, panels (d and e) shows that for the differential electron flux. In panels (b–e), the electron density profile are overplotted and are marked on the right hand scale. Please note that the vertical lines in panel (e) are caused by data gaps.

Figures 1b and 1c show the energy-time spectrogram of the spin averaged differential proton flux in the energy range 150 keV–1 MeV from MagEIS and 300 eV–50 keV from HOPE instruments. The proton flux in the energy range 200 keV–1 MeV (Figure 1b) does not show any significant variations when the density irregularities were observed. However, in Figure 1c, the discrete band-like structures of the proton flux can be noticed close to apogee. These structures indicate the energy dispersion (i.e., higher energy ions penetrating more into the low L shells) of the plasma sheet ions, with the energy of the order of ∼tens of keV. These observations suggest the adiabatic acceleration by the Earthward injection and duskward drift of the plasma sheet ions.

Figures 1d and 1e (similar to Figures 1c and 1d) show the energy-time spectra of the spin averaged differential electron fluxes in the energy range 30 keV–3 MeV from MagEIS and 300 eV–50 keV from HOPE instruments respectively. Figure 1d shows enhancement in the electron flux in the energy range ∼30 keV–1 MeV, indicating the presence of ring current electrons (energy range: 10–100s of keV) and outer radiation-belt electrons (energy range: 100s of keV to few MeV). The lower energy electron flux with energies below
∼10 keV, shown in Figure 1e is found to be rather homogeneous, indicating the plasma sheet populations. Please note that the vertical lines in panel (e) are caused by data gaps.

The comparison of the density and flux observations presented in Figure 1 clearly indicates that RBSP-B observed the density depletions in the dayside inner magnetosphere at $L > \sim 4$, when the ions and electrons originating from the plasma sheet and outer radiation belt were coexisting with the cold plasma population. However, no correspondence between the density depletion and the variations of ions and electrons with energy above 1 keV is observed.

Figure 2 compares the density observations presented in Figure 1 with static (DC) electric and magnetic fields at the satellite together with the plasma waves in the frequency-time spectrogram of oscillating (d) electric and (e) magnetic field. Total electron density is overplotted in panels (d and e), and the values are marked on the right-hand scale.
ues and also subtracting a 20 min running average. The magnetic fields in all three components are found to be different from that of density.

Figures 2d and 2e show the frequency-time spectra of the oscillating electric and magnetic fields, respectively. Both electric and magnetic field spectra indicate the presence of whistler-mode plasma waves below the local electron cyclotron frequency (shown as solid red curves). The discrete band of the waves observed in the frequency range between ~ 50 and 2,000 Hz may indicate whistler-mode hiss emissions (Bortnik et al., 2008; Hayakawa & Sazhin, 1992; Meredith et al., 2006; Shi et al., 2018; Thorne et al., 1973). The comparison of the plasma waves with the density profiles reveals that the hiss emissions in the frequency between 55 Hz and 1.5 kHz have modulations matching the density irregularities. The density depletions are found to coincide remarkably well with the decrease of wave intensity or even the wave absence. The observations suggest the excellent correlation between the density irregularities and the whistler-mode wave intensity.

4. Event Study: Arase Observations on July 16, 2017

Figure 3 presents a case study of electron density irregularities observed in the night side by the Arase satellite on July 16, 2017 during a magnetic storm with a minimum Dst (real time) of −72 nT at 16:00 UT. During the event, the apogee of the Arase was located in the pre-midnight hours at ~22 h. Figure 3, in the same format as Figure 1, compares the electron density with the differential proton and electron flux observations in the low to medium energy range from LEP-i(e) and MEP-i(e) instruments onboard Arase. Figure 3a depicts the total electron density profile obtained from the UHR frequency of the plasma recorded by Arase in its two consecutive orbits. The electron density profile is shown as a thin white curve, and the values are indicated on the right-hand scale. The HFA electric field spectrum depicting the UHR frequency of the plasma is shown in the background for comparison. The UHR curve can be seen in the spectrum as a faint blue curve.

The large density gradients in the outbound passes are the locations of plasmapause and are marked by red arrows in Figure 3a. In both passes, significant density perturbations are observed near the apogee locations at 07:00–11:00 UT and around 16:00 UT. In contrast to Figure 1, these density perturbations are not only the depletions, but also include small density enhancements. The clear plasmapause crossings in both orbits indicate that Arase observed these density structures outside the plasmasphere. However, it should be noted that the density variations with small amplitudes are also evident inside the plasmasphere in the outbound leg of Arase at 04:00–06:00 UT.

Figures 3b and 3c show the energy-time spectra of the proton flux from MEP-i in the energy range 10–200 keV and LEP-i in the energy range 100 eV/q to 25 keV/q. Similarly, Figures 3d and 3e present the electron flux spectra from MEP-e in the energy range 7–90 keV/q and LEP-e in the energy range 100 eV to 20 keV. These figures clearly show the plasma sheet ion and electron population (energies of the order of 10 keV) near the apogee, when the density irregularities are observed. Plasma sheet ion and electron fluxes are found to be modulated in time and have some similarity with the density irregularities. However, a clear one to one correspondence is not evident.

The observations reveal that the density irregularities are observed by Arase in the night side plasma sheet. Similar to quiet time observations (Figure 1), the density irregularities observed by Arase during disturbed period are also found to coexist with the hot plasma sheet particles. The presence of plasma sheet particles along with the cold plasmaspheric plasma may indicate the fast plasma injections from night side in association with substorm activity.

5. Statistical Study

In this section, we present the statistical results of the density irregularities comprising 4 months (April–July 2017) of observations from Arase and nearly 2 years of data (August 2016–May 2018) from RBSP-B satellites. The density irregularities, which deviate more than 10% from background plasma density along the satellite orbit, are considered in the statistical analysis presented in this section. Please note that our
analysis also includes large scale structures like plumes in addition to small-scale density undulations. The steps involved in the analysis are as follows.

Step 1. Identification of plasmapause: For each satellite orbit, we have looked for the plasmapause crossings in the outbound, and inbound satellite passes separately. The criteria for identifying the plasmapause is as follows. A gradient in the density (decrease for an outbound pass and increase for an inbound pass) by a factor of 5 in an $L$ shell range of 0.5 (Malaspina et al., 2016) is identified as the plasmapause. If more than one density gradient is satisfying this criterion, the one identified closest to Earth is considered as the plasmapause crossing. Once the plasmapause is identified in the inbound/outbound pass, we have removed it from the density data. If the above criterion is not satisfied in the inbound/outbound pass, we have categorized it as no plasmapause identified.

Step 2. Estimating the density deviation: After removing the plasmapause (if identified), a 30-min running average is fitted to the density profile to derive the background plasma density. We have chosen this 30 min window after trying different window lengths such as 10 and 20 min. It was found that 30 min window opti-

**Figure 3.** Case study of density irregularity observed by Arase on July 16, 2017 comparing the electron density profile with the differential proton and electron flux. Panel (a) shows the total electron density profile (thin white curve) obtained from the UHR frequency of the plasma. The HFA electric field spectrum depicting the UHR curve (faint blue curve) is shown in the background. The total electron density values are marked on the right-hand scale, and the HFA frequency is denoted on the left-hand scale. Panels (b–e) in the same format as Figure 1, show the energy—time spectrogram of the differential proton/electron flux from (b) MEP-i, (c) LEP-i, (d) MEP-e, and (e) LEP-e instruments.
mally represents the background density values. The density irregularities are then identified by estimating the deviation in the density from the background values. The density deviation is defined as

\[ \frac{N_{\text{obs}} - N_{\text{avg}}}{N_{\text{avg}}} \]

where \( N_{\text{obs}} \) and \( N_{\text{avg}} \) are the observed and average density values.

It is to be noted that, for the orbits with clear plasmapause identified in Step 1, the 30-min running average is fitted after removing the plasmapause crossings. This is to avoid density variations artificially caused by the plasmapause.

Step 3. Depending on the location with respect to the plasmapause, the density irregularities identified are classified into three categories, namely the ones observed (1) inside plasmapause, (2) outside plasmapause, and when (3) no plasmapause was identified.

The methodology described above is depicted in Figure 4. Figures 4a and 4b respectively show the electron density profiles (black solid curve) observed by RBSP-B on August 16, 2017 and by Arase on July 16, 2017 along with the 30-min running averages (red solid curve). The locations of the density structure with respect to plasmapause are marked in Figures 4a and 4b as (1), (2), and (3). It can be noticed that no plasmapause is identified in the case of RBSP-B observations (Figure 4a). In the case of Arase, the plasmapause crossings are identified during the outbound passes and are indicated by the red arrows in the top panel of Figure 4b. The bottom panels of Figures 4a and 4b show the percentage deviation in the density from the average values. We have picked up electron density perturbations with percentage deviations more than 10% from background plasma density. Large density irregularities having amplitude >50% are evident when both RBSP-B and Arase were near their apogee locations.

5.1. Global Distribution of Density Irregularities

Figure 5 shows the distribution of the density irregularities in the L-MLT plane as observed by (left panels) Arase and (right panels) RBSP-B satellites. Figures 5a and 5c show the number of samples observed, where each sample indicates a data point. It is to be noted that the sampling of Arase electron density data is 1 min, and that of RBSP-B is 11 s. The bottom panels (Figures 5b and 5d) show the occurrence rate (i.e., the ratio between the number of samples having deviation greater than 10% and the total number of samples) of the density irregularities. The observations from both Arase and RBSP-B indicate that the density structures have higher occurrence at larger \( L \) shells (\( L > 4 \)). RBSP-B observations covering different MLT sectors clearly indicate that the density structures exist at all MLTs. A slightly higher occurrence rate is evident during dawn to noon and dusk hours. An unequal distribution of the density irregularities in different MLT regions was also reported by (Darrouzet et al., 2004) using the Cluster satellite observations. Their study has shown that the density irregularities have a higher occurrence in the dawn, afternoon and post-dusk sectors.

Figure 6 in the same format as Figure 5 shows the distribution of density irregularities in the L-MLAT plane. Arase (left panels) with higher inclination (31°) can reach higher Mlats compared to RBSP-B (right panels) which has a lower inclination of 10°. The difference in the inclination of the two satellites enables us to compare density observations from the near-equatorial plane and that from higher latitudes. The bottom panels of Figure 6 show the percentage occurrence of the density irregularities with amplitudes >10% for Arase (Figure 6b) and RBSP-B (Figure 6d). The occurrence of density irregularities are found to be higher when Arase was located in the high L-Mlat plane compared to the observations from low-equatorial latitudes at (\( L < 7 \)) for both Arase and RBSP-B. This may either indicate that the density irregularities have a higher occurrence in high L-Mlat region and/or at larger \( L \)-shells. However, with lack of observations at \( L > 7 \) in the low-equatorial latitudes, the latitudinal dependence of the irregularities is inconclusive. Please note that the asymmetry in Arase data in the L-MLAT plane is due to orbital configuration of the Arase satellite (Miyoshi et al., 2018c) and limited length of the analyzed interval.
5.2. Dependence of Density Irregularities on Geomagnetic and Interplanetary Conditions

The dependence of the geomagnetic and interplanetary conditions on the occurrence of the density irregularities (amplitudes > 10%) for RBSP-B and Arase are depicted in Figures 7 and 8, respectively. Depending on the location of the irregularities, the occurrence rates are classified into inside plasmapause, outside plasmapause, and when no plasmapause is identified. Note that the percentage occurrence is the ratio between the number of data samples having deviation greater than 10% and the total number of samples. These ratios are indicated on the top of the bar plots in Figures 7 and 8. Figure 7 presents the results obtained from RBSP-B for the night (18–6 h through midnight; indicated by blue shade) and day (6–18 h through noon; indicated by yellow shade) MLTs separately. As the plasmaspheric dynamics is largely as-

Figure 4. Methodology depicting the percentage deviations in the electron density derived from (a) RBSP-B and (b) Arase observations. In subplots (a and b), the top panels show the observed electron density profile (solid black curve) along with 30 min running average (solid red curve). Bottom panels show the percentage deviation in density from the average value. The dashed red line marks the 10% deviation in the amplitude of the density irregularities. The locations of the density irregularities are indicated as (1) inside plasmapause, (2) outside plasmapause, and (3) when no plasmapause was found. The red arrows indicate the plasmapause.
The dependence of the solar wind parameters such as IMF-Bz and solar wind velocity on the occurrence of the density structures are presented in the bottom panels of Figures 7 and 8. A steady increase in the occurrence rate during southward (negative) IMF-Bz and enhanced solar wind velocity is clearly evident in Arase (Figures 8b and 8d) data. RBSP-B observations also showed a systematic increase in the occurrence with solar wind velocity (Figure 7d), but a significant dependence is not evident in the case of IMF-Bz (Figure 7b). These observations indicate that the density irregularities have a preferential occurrence during the enhanced solar wind interaction with Earth's magnetosphere. From Figures 7 and 8, it is also evident that the highest occurrence of density irregularities is observed when the satellite was either outside the plasmasphere or when no plasmapause is identified. This shows that the density irregularities occur mostly in the plasma sheet or near the plasmapause. Also, this feature is found to be pronounced during more active
times (symH < −50 nT and AL < −600 nT, IMF-Bz < −5 and solar wind velocity > 600 km/sec), indicating the shrinking of the plasmasphere to lower L values during disturbed conditions. This result is consistent with the fact that density irregularities have a higher occurrence at larger L shells (as shown in Figures 5 and 6). It can be noticed that the percentage occurrence during no plasmapause identified is higher for RBSP-B compared to Arase. This may be because of the lower L shell (L < 7) of RBSP-B orbit compared to that of Arase (L < 9).

Figure 6. L-MLAT distribution of the density irregularities observed by Arase (left panels (a and b)) and RBSP-B (right panels (c and d)). Top panels (a and c) show the number of data samples used. Bottom panels (b and d) show the occurrence rate of density irregularities with amplitude > 10%.
6. Summary and Discussion

The present study investigates the density irregularities in the plasmasphere and its outer regions in detail by probing the electron density observations from Arase in the nightside and RBSP-B from all MLT sectors. The structures investigated in the present study include small-scale density undulations such as depletions and enhancements and also large scale structures like plumes. The Arase and RBSP-B observations reveal the frequent occurrence of the density irregularities, mainly near its apogee locations. The case studies clearly show that the density irregularities were observed when RBSP-B (Figure 1) and Arase (Figure 3) were located in the plasma sheet. The coexistence of the density irregularities with the hot plasma sheet particles supports the idea of fast plasma injections into the plasmapause region in association with substorm, as suggested by Morioka and Oya (1996). A higher occurrence of density irregularities is also observed during active geomagnetic conditions (Figures 7 and 8), which also supports the fact that the density irregularities are related to substorm.

In the case study presented, the magnetic field components did not show any matching variations with that of density (Figure 2c). The poor correlation between density and magnetic field indicates that the observed density irregularities are less likely to be caused by Ultra Low Frequency oscillations.

Another possible candidate responsible for the density irregularities is Rayleigh-Taylor (RT) instability. RT instability can be present near the plasmapause boundary due to the difference in the density of the...
different plasma populations coexisting in this region (Kelley, 1989; Treumann & Baumjohann, 1997). In the case of the Rayleigh-Taylor-like instability, the density irregularities are expected to be related to the plasma pressure variations. In order to check this possibility, we have investigated the partial plasma pressure ($P = nK_B T$, where $P$ = pressure in nPa, $n$ = ion density in cm$^{-3}$, $K_B T$ = thermal energy in eV) observations from the ion fluxes obtained from HOPE (energy range 1 eV–50 keV) and RBSPICE (energy range 50 keV–20 MeV) instruments onboard RBSP-B. Both HOPE and RBSPICE observations of partial pressure did not show any matching variations with the electron density irregularities. However, HOPE observations of ion density ($n$) and thermal energy ($K_B T$) are found to be often correlated with the total electron density. An example showing the relation between the partial plasma pressure and the density irregularity observed on August 16, 2017 is illustrated in Figure S1.

Our statistical study clearly demonstrates the occurrence of density irregularities in all MLT sectors (Figure 5). The result is consistent with the Cluster observations by Darrouzet et al. (2004). The presence of density irregularities in different MLTs may indicate that they are generated by different source mechanisms unique to different MLT sectors. A brief description of different possible scenarios for the generation of density irregularities are as follows.

In the post-midnight to dawn sector, the enhanced plasma convection resulted from the viscous interaction between the solar wind and the Earth’s magnetosphere during disturbed geomagnetic conditions is considered as one of the primary candidates for the generation of density irregularities in the plasmasphere. According to Lemaire (1975), Lemaire (1999), and André and Lemaire (2006), the gravitational and centrifugal effects can lead to the interchange motion of the plasma both along (quasi-interchange mode) and across...
the flux (interchange mode) tubes and therefore can result in the formation of small-scale density structures in the post-midnight to dawn sector.

The electric fields caused by the gradient and curvature drifts can result in self-induced small-scale convective motion of the plasma, where the flux tubes with larger particle pressure will be convected away from the Earth (Richmond, 1973). The low-frequency electrostatic waves excited by the particle drifts and the plasma currents associated with the external force are reported to have a significant role in the flux tube interchange and plasma transport processes (Hasegawa, 1971; Huang et al., 1990; Richmond, 1973). Huang et al. (1990) reported that the density structures near the plasmapause might be actively maintained by an external source, with solar-wind-induced convection being the most probable candidate. Our observation of higher density irregularities during the period of the southward IMF-Bz and enhanced solar wind velocity supports this idea of solar wind origin of the source mechanism (Figures 7 and 8). The density irregularities can be triggered by the external source either from the nightside associated with plasma-sheet particle injection or dayside solar wind dynamic variations.

Previous studies have also reported the occurrence of different fine structures in the aurora and its possible relation to the variations in the ambient plasma density. Shiokawa et al. (2010), Shiokawa et al. (2014), and Hashimoto et al. (2015) have reported auroral finger-like structures mainly in the post-midnight local times at the equatorward part of the auroral oval. These auroral finger-like structures are likely to be caused by the pressure-driven instability with the anti-phase variation of magnetic and plasma pressures (Nishi et al., 2017, 2018) and are possibly accompanied by ambient density structures. Ebihara et al. (2010) have reported highly structured thin auroras near the equatorward edge of the auroral oval. They found a significant increase in the electron plasma pressure prior to the structured aurora, which may be caused by the combined effect of the entry of plasma sheet electrons and the injection of hot electrons. Ebihara et al. (2010) suggest that these highly structured auroras can be a visual demonstration of the density structures in the cold plasma.

A detailed study quantifying the generation of the density irregularities at different local times is important to address the different possible candidate mechanisms. This will be addressed in the future by employing coordinate observations from satellite and ground.

Data Availability Statement

The authors would like to thank NASA’s Van Allen Probe team for the use of EFW LEVEL 3 data produced from (http://www.space.umn.edu/rbspew-data/), EMFISIS data from (https://emfisis.physics.uiowa.edu/data/index), the plasma data of HOPE and MagEIS instruments from (https://rbsp-ect.newmexicoconsortium.org/science/DataDirectories.php) and the plasma data of RBSPICE instrument from (http://rbspice.fitesc.com/Data.html). The geomagnetic and solar wind indices used in the study are downloaded from NASA’s OMNI data base in Coordinated Data Analysis web (https://cdaweb.gsfc.nasa.gov/index.html). This work is supported by JSPS KAKENHI (15H05815, 16H06286, 15H05747, 17H00728, and 20H01959).

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