

Energetic ion variations during substorm intervals using the Van Allen Probes data

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Abstract

The study investigates ion flux variations for the substorms in the inner magnetosphere. The effect of substorm-induced magnetic field dipolarization on the O^+ and H^+ ion flux is analysed for 22 events from the year 2018 using the Helium, Oxygen, Proton, and Electron (HOPE) Mass Spectrometer data on board the Van Allen Probes (VAP/RBSP) satellite. The clear dipolarization signatures are observed using the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) suite from the VAP. These observations provide evidence of the ion flux enhancement at 1–50 keV energy after the substorm onset, in particular, the energy range of 20–50 shows dominance. The typical characteristics of magnetic field dipolarization and its time scales are investigated. It is found that the O^+ ion flux enhances greater in magnitude than H^+ ion flux at energies 20–50 keV after the substorm onset. In addition to it, the correlation of these enhanced oxygen fluxes with the related interplanetary magnetic field (IMF) B_z , solar wind velocity (V_{sw}), and the auroral electrojet (AE) index are found good. The new results reports that the ion flux variation ratio shows the MLT dependence for different energy ranges and found that the peak of the O^+/H^+ ion flux ratio centred near midnight for the energy range of 8–20 keV, whereas the O^+/H^+ ion flux ratio of the energy 20–50 keV is high within the post-midnight. The possible mechanisms for the enhanced ion flux are discussed.

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1. Introduction

The magnetospheric substorm is a short-lived process that depends on the magnitude and direction of the Interplanetary Magnetic Field (IMF), and on the solar wind velocity (V_{sw}). The southward direction of the IMF is a

necessary prerequisite for substorm occurrence and magnetic reconnection in the dayside magnetosphere. Generally the average duration substorm is about 2–4 h (Partamies et al., 2013). During such process, a significant amount of energy ($\sim 10^{15}$ J) is extracted from the interaction between the solar wind and the magnetosphere (Forsyth et al., 2015). Through the course of time this energy is ultimately deposited in the inner magnetosphere ($< 8 R_E$) (Fernandes et al., 2017; Lakhina et al., 2006; Rostoker et al., 1980). The substorm onset is characterized by a rapid magnetic field dipolarization at the inner edge of the plasma sheet and an increase in the westward electrojet

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in the ionosphere. This westward electrojet reflects the ionospheric signature of the plasma sheet dynamics and is accompanied by a Pi2 pulsation burst (Rostoker et al., 1980). Eventually, the electrojet starts fading, and magnetic field topology becomes tail-like indicating the recovery phase of the substorm. The energy release in this electrojet is only a small portion of the total substorm energy release, and the maximum energy is released through the changes observed in the ring current, the cross-tail current, the plasma sheet magnetic field, the plasmoid formation and it is earthward, and tailward motion in the magnetosphere (Cheng et al., 2004).

The study of substorm-induced magnetic field fluctuations and their effects on the flux of energetic O^+ and H^+ ions in the inner magnetosphere is very important as they vary depending upon temporal scales. It is well known that the H^+ ion is the dominant species in the plasma sheet and ring current during quiet times (Gloeckler et al., 1985). Whereas, numerical simulations as well as data analysis prove that O^+ ion is one of the important species in the plasma sheet and ring current during disturbed times (Jordanova et al., 2001; Keika et al., 2013, references therein). The oxygen ion also acts as tracers of ionospheric contribution to the magnetosphere during geomagnetically active periods, as the outflow and heating of these ions alter the density, pressure, and ion composition in the inner magnetosphere. These ions can also reduce the reconnection rate by decreasing the Alfvén wave speed or reduce the convection strength by conserving the momentum (Fok et al., 2006; Winglee et al., 2002).

Several studies have focused on the effects of the O^+ ion population during substorm activity (Nosé et al., 2021, references therein). The main compositional change that takes place during the substorm is, the absolute and relative increase of the ionospheric oxygen component in the inner magnetosphere compared to the proton component (Daglis et al., 1998). During the substorm onset, the O^+ ion flux in the energy range of 10 eV to tens of keV enhances rapidly in the field-aligned direction. These O^+ ions are extracted from the ionosphere during substorm which in due course contribute to the formation of the warm plasma cloak (Nosé et al., 2016; Nosé et al., 2021). In near-Earth tail ($X \sim -16$ to $-6 R_E$) substorm enhances O^+ ions of 60 keV–3.6 MeV energies. Geotail spacecraft observed this strong increase of energetic oxygen ions and concluded that this increase is due to magnetic field reconfiguration (dipolarization) and not due to magnetotail reconnection (Nosé et al., 2000). Further, Fu et al., (2002) using CRRES observations proved a clear increase in the O^+ ion flux at energies > 50 keV which was identified in the nightside region associated with substorms. The enhancement of O^+ ions compared to H^+ ions is also studied by global oxygen energetic neutral atom (ENA) data from Imager for Magnetopause-to-Aurora Global Exploration/High Energy Neutral Atom (IMAGE/HENA) spacecraft. For a few events, this spacecraft noted the oxygen ENA emitted from energetic O^+ ions between 50 and 200 keV showed

sudden enhancement whereas hydrogen did not show an increase (Keika et al., 2010; Mitchell et al., 2003). The day side polar region also contributes to being the origin of the energetic O^+ ion observed in the plasma sheet during the substorm. These energetic ions from the dayside polar region accelerate in the plasma sheet and are injected into inner magnetosphere during substorm onset (Nakayama et al., 2017). The dipolarization fronts which are typically observed during substorm, also enhance the O^+ ions significantly inside the earthward propagating magnetic island (Wang et al., 2016).

The substorm associated magnetic field dipolarization in the inner magnetosphere is recently gaining a lot of attention with some single events and few statistical studies. The statistical study of 74 events during the solar cycle maximum from 2012 to 2013 using the data sets of VAP reveals that the magnetic field dipolarization causes ion flux enhancement at 20–50 keV more pronounced for the O^+ ions than for the H^+ ions (Nosé et al., 2016). Recently, a statistical study of low energy O^+ flux enhancement followed by magnetic field dipolarization using Arase spacecraft has been performed. The study reports energy-dispersed signatures with decreasing energy from a few keV down to 10 eV (Nosé et al., 2018; Nosé et al., 2021). Also, an event-based analysis using data from Magnetospheric Multiscale (MMS) spacecraft reveals two different parts of dipolarization, the initial laminar part and the latter irregular part (Matsui et al., 2016). In addition to it, there have been numerous studies proposing particle acceleration by magnetotail dipolarization fronts, which are thoroughly reviewed by Fu et al., 2020. Still the ion flux variations during substorm induced dipolarization is not understood and needs investigation with their temporal and spatial aspect in respect to related interplanetary parameters and the strength of substorm activity.

In this study, we present a statistical analysis of 22 substorm induced dipolarization events during the year 2018 using the data from Helium, Oxygen, Proton, and Electron (HOPE) Mass Spectrometer and Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument onboard the VAP spacecraft. We attempt to investigate the significant characteristics of magnetic field dipolarization, such as its time scale and associated enhancement in energetic O^+ and H^+ ions. In addition to it, we try to examine the dependence of these energetic ions on the IMF B_z , the V_{sw} , and the AE index and discuss the possible mechanisms for the observed enhancement. The paper is organized as follows: Section 2 deals with the description of the spacecraft data set and the event selection criteria. Section 3 gives the results, and in Section 4 we discuss the possible mechanisms for the energetic ion evolution during the substorm and summarize the conclusions.

2. Data set and event selection

To identify a substorm event we employ recently derived Wave and planetary (Wp) index data for the year 2018. It

uses the data from a longitudinal network of 11 ground stations located between 21° to 49° geomagnetic latitude. Wp is a global index that reflects low-latitude Pi2 pulsations (Nosé et al., 2012). When a substorm is commenced, auroral electrojets are developed and they eventually get enhanced (Nakamura et al., 2015). The AE index (Sugiura et al., 1964) and the ASY (ASYmmetric disturbance) index (Iyemori et al., 2010) are also used to identify the signatures of substorms for the mentioned period. Sym-H and the interplanetary parameters IMF B_z, the V_{sw}, and solar wind dynamic pressure (P_{sw}) were acquired from the OMNI database. OMNI data set consists of averaged ACE, WIND, IMP 8, and Geotail magnetic field and plasma data shifted to the bow shock nose location. The hourly Dst index and one-minute resolution of Symmetric data (Sym-H) are almost alike (Sugiura et al., 1964), they indicate magnetic storm activity. The only difference is the time resolution and set of stations taken into consideration (Iyemori et al., 2010).

2.1. VAP data

The Van Allen Probes (VAP) satellites also known as Radiation Belt Storm Probes (RBSP) were launched in August 2012 and deactivated in October 2019. To maintain consistency with other Van Allen Probes spacecraft papers, we use the RBSP acronym here. It consisted of two spacecraft, namely, RBSP-A and RBSP-B. They had a near-equatorial orbit with 10° inclination. The apogee altitude of the satellite was 30,050–31,250 km ($\sim 5.8 R_E$ from the center of the Earth), and the perigee altitude was 500–675 km ($\sim 0.09 R_E$) (Stratton et al., 2013). It had a ~ 9 h orbit period and ~ 12 s spin period, with its spin axis pointing nearly in the solar direction (Mauk et al., 2013). For this study, we employ the data sets from HOPE and EMFISIS instruments onboard the RBSP spacecraft (Funsten et al., 2013; Kletzing et al., 2013). The substorm events are selected for the year 2018 because, the study can be continued with the data from the recent launch of Arase satellite for the overlapping years.

To study the energetic particle flux evolution during the substorm interval the HOPE spectrometer data is used. HOPE is one of the three pairs of instruments of the Energetic Particle, Composition, and Thermal Plasma (ECT) suite (Spence et al., 2013). It measures fluxes of H⁺, He⁺, and O⁺ using foil-based time-of-flight mass spectroscopy with channel electron multiplier detectors. It comprises of 72 logarithmically spaced energy channels with measurements in five directions relative to the spin axis (Sarno-Smith et al., 2015). The H⁺ and O⁺ ion flux data are obtained at nearly 22 s as the HOPE instrument measures ions and electrons during alternate spins (Funsten et al., 2013).

To find the dipolarization signature associated with the substorm, the data from the EMFISIS instrument is used in the present study. The one-second resolution magnetic field vector data in geographic coordinates (GEO) mea-

sured by the EMFISIS instrument is used to calculate the deviation in the magnetic field from the modelled magnetic field. To observe only the time scale for which magnetic field dipolarization persists the Tsyganenko model (T89Q) magnetic field vector data is subtracted from the EMFISIS magnetic field data (Fu et al., 2014). The deviated magnetic field components thus obtained are denoted by ΔB_x and ΔB_z .

2.2. Event selection

The present study incorporates the data from the HOPE instrument for the year 2018 which corresponds to the period of low solar activity. The 22 substorms analysed in this study are selected upon applying the following criteria: (1) to find substorm onset: a) the standard deviation of the Wp index in a 30-min interval before t_0 (Substorm onset time) is ≤ 0.05 nT. b) the Wp index is enhanced to ≥ 0.2 nT within 10 min after t_0 , (2) either RBSP-A/ RBSP-B/ both spacecraft are located at 18:00–06:00 magnetic local time (MLT), (3) the L* value of the spacecraft is > 4 , and (4) magnetic field fluctuations appear in ΔB_x and ΔB_z . Fig. 1 depicts the orbit of the spacecraft (RBSP-A or RBSP-B) during the selected substorm events for the study. The black dot represents the position of the spacecraft during the substorm onset. The red and blue orbits represent the path of RBSP-A and RBSP-B spacecraft respectively in (a) x-y and (b) y-z planes in geocentric solar magnetospheric (GSM) coordinates.

3. Results

3.1. The O⁺ and H⁺ flux variations during the substorm: RBSP observations

The details of all the substorm events used in this study are summarized in Table 1. The energy time spectrogram analysis has been done for all the events. As an example, Fig. 2 presents the energy time spectra for the substorm event observed by RBSP-B on 05 May 2018. From top to bottom displayed are (a) the energy time spectrogram for O⁺ ions, (b) the energy time spectrogram for H⁺ ions, (c) the L* value, (d) the MLT, (e) the IMF B_z, (f) the solar wind pressure (P_{sw}), (g) the Wp index and, (h) the AE index.

A vertical line at 13:47 UT on 05 May 2018 corresponds to the substorm onset according to the event selection criteria. It reflects the onset of Pi2 pulsations at low geomagnetic latitudes. The corresponding MLT, L-value and MLAT of RBSP-B at the onset was 02.54, 6.0 and -5.68° respectively. During this substorm, the IMF B_z is directed southward and its average intensity is -7.8 nT (averaged for 2 min). Also, the substorm is accompanied by a strong increase in P_{sw}. The P_{sw} abruptly increases to 20 nPa after the substorm onset. The average V_{sw} during this substorm is 386 km/s, and the highest value of the AE index after the substorm onset is around 1100 nT. After the sub-

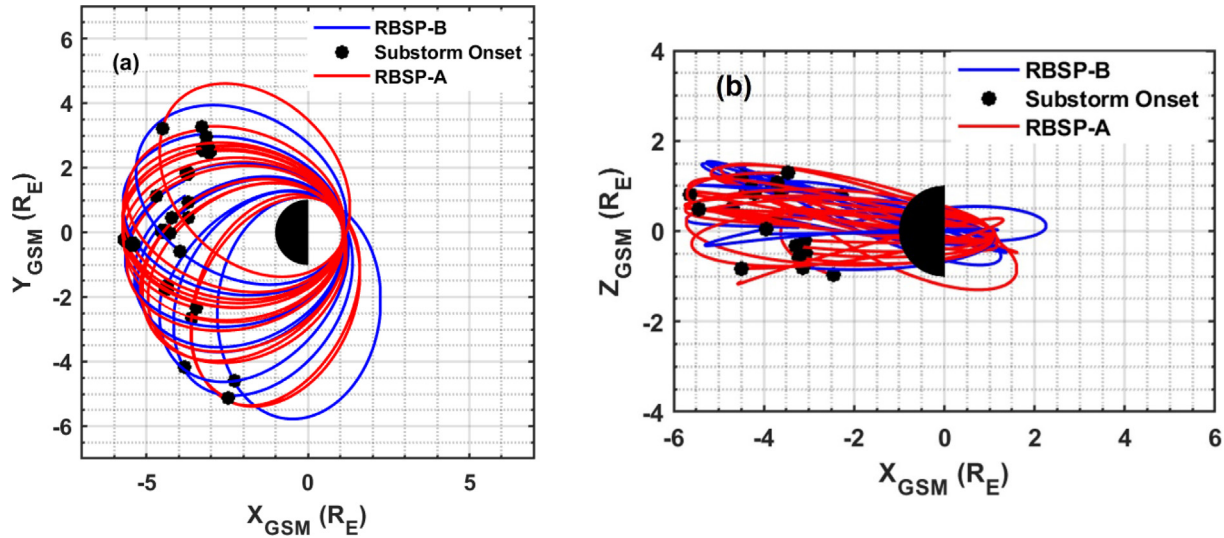


Fig. 1. Orbit of RBSP-A and RBSP-B spacecrafts during the selected Substorm events in the x-y (a) and y-z (b) planes in geocentric solar magnetospheric coordinates.

Table 1
Selected substorm events during the year 2018 for the study.

Sr. No	Event Date	RBSP (A/B)	Substorm Onset time (hh:mm) UT	Wp index at the onset (nT)	AE index (nT)	IMF B _z (nT)	Solar wind velocity V _{sw} (km/s)	MLT (hrs)
1	09/03/2018	B	13:49	0.030	77	−3.47	389.30	04.38
2	05/05/2018	A	13:47	0.075	264	−7.82	386.80	02.54
3	05/05/2018	B	13:47	0.075	264	−7.82	386.80	02.54
4	06/05/2018	A	01:09	0.152	1274	−8.50	638.80	04.20
5	22/05/2018	B	20:33	0.124	136	1.10	345.20	00.98
6	22/06/2018	B	18:39	0.059	137	−3.25	350.90	23.58
7	28/06/2018	A	15:04	0.205	214	−2.49	490.90	23.50
8	28/06/2018	B	18:56	0.096	263	−3.49	491.50	02.85
9	07/07/2018	A	23:16	0.091	81	0.01	465.80	23.64
10	10/07/2018	A	13:52	0.029	213	—	—	23.17
11	21/07/2018	B	10:11	0.064	504	−2.78	509.20	22.60
12	11/08/2018	A	07:10	0.099	222	−5.17	379.70	23.47
13	19/08/2018	A	22:31	0.282	161	−2.93	498.20	23.75
14	26/08/2018	A	09:49	0.079	749	−12.89	407.50	02.59
15	05/09/2018	B	10:40	0.145	851	−1.70	482.50	21.35
16	09/09/2018	A	08:31	0.130	183	−1.07	396.00	21.77
17	13/09/2018	A	11:06	0.153	552	−5.24	492.00	21.69
18	14/09/2018	A	04:56	0.057	299	−4.92	558.70	21.54
19	22/09/2018	A	13:51	0.247	612	−5.08	498.10	00.33
20	09/10/2018	B	05:46	0.156	523	−3.92	632.40	00.89
21	10/10/2018	A	16:52	0.218	440	−6.71	508.70	20.75
22	01/12/2018	A	16:09	0.317	227	−6.90	367.10	21.47

The table gives the information of the substorm onset time, the interplanetary parameters like: IMF B_z, solar wind velocity, the spacecraft MLT at the onset of the substorm. The Wp index and AE values of the substorm which are used in the present study are also mentioned.

storm onset, we clearly observe an enhancement in the O⁺ ion flux at energies > 100 eV whereas, the H⁺ ion flux moderately changes above L* > 3.

To understand the cause of ion flux variation it is important to observe the ion flux data and the magnetic field data simultaneously. Fig. 3 shows a close view of the substorm and its associated magnetic field dipolarization event in the inner magnetosphere. This substorm event was

observed by RBSP-B from 13:32 to 14:02 UT on 05 May 2018. From top to bottom displayed are the energy time spectrogram for H⁺ ions (panel a); the energy time spectrogram for O⁺ ions (panel b); the O⁺/H⁺ ion flux ratio (panel c); ΔB_x (panel d); ΔB_z (panel e); electric field in MGSE coordinate system (panel f) and; the Wp index (panel g). The black vertical dashed line indicates the onset of the substorm (i.e., the beginning of the substorm expansion

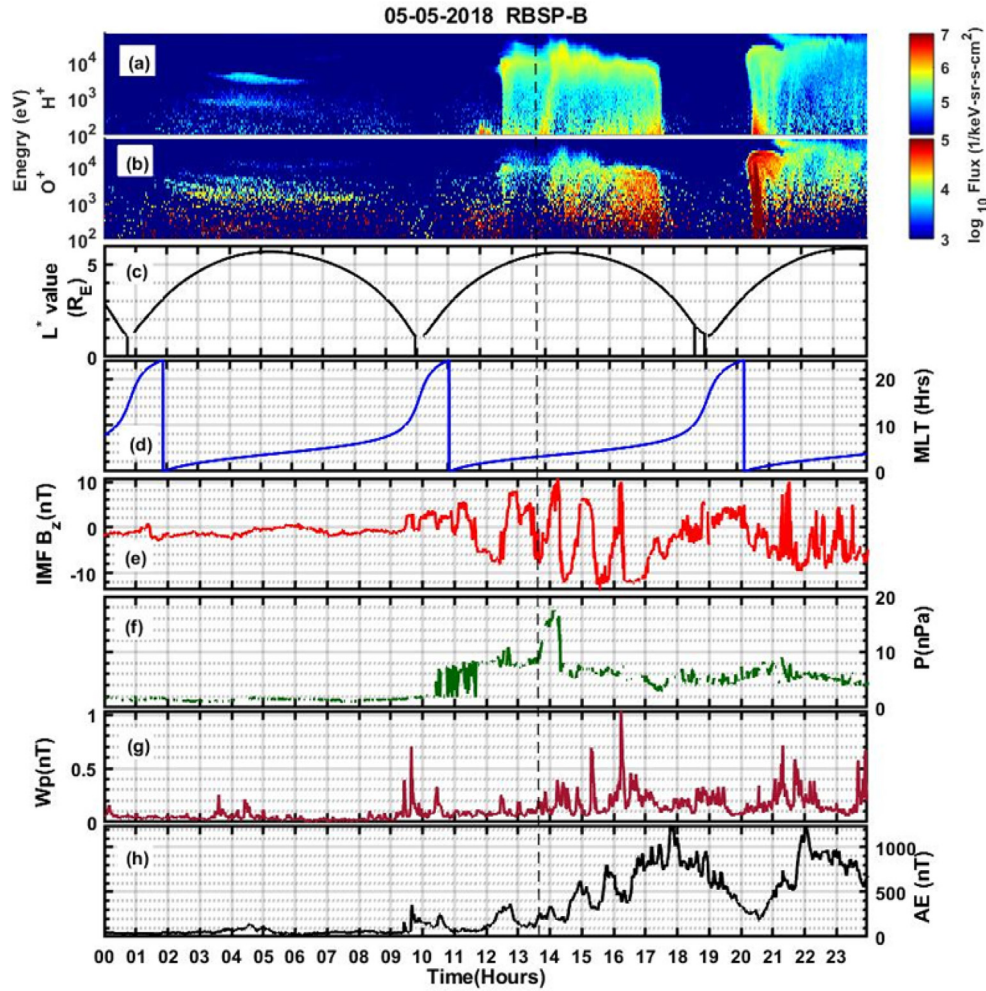


Fig. 2. Geomagnetic indices and RBSP-B data during 00:00 UT to 23:59 UT on 05 May 2018. From top to bottom displayed are (a) the energy time spectrogram for H^+ ions, (b) the energy time spectrogram for O^+ ions, (c) the L^* value, (d) the MLT, (e) the IMF B_z , (f) the solar wind pressure (P_{sw}), (g) the W_p index and (h) the AE index. The vertical black line represents the onset of the substorm occurred on 05 May 2018.

phase) at 13:47 UT. The clear variations of B_x and B_z indicates the dipolarization. The W_p index increases to 0.25 nT within 10 min after the substorm onset. Simultaneous to this we observe a gradual increase of the O^+ ion flux at energy channels > 1 keV. The O^+ ion flux in these energy channels increases in the range of 10^4 to 10^5 counts/ cm^2 -s-sr-keV. This enhanced flux at energies > 1 keV shows the flux enhancement of O^+ ions into the inner magnetosphere during the expansion phase of the substorm (the expansion phase begins at 13:47 UT). The H^+ ion flux also show a moderate increase at energies > 1 keV. The flux value varies between 10^5 to 10^6 counts/ cm^2 -s-sr-keV after the substorm onset. It is observed that the H^+ ion flux in the range of 10^5 counts/ cm^2 -s-sr-keV exists in all energy channels up to 20 keV before the substorm onset which is due to the constant interaction of proton-rich solar wind with the earth's magnetosphere. To confirm the noticeable enhancement in the O^+ ion flux, we plot the O^+/H^+ ion flux ratio (Fig. 3, panel c). We observe a sudden increase in the O^+/H^+ ion flux ratio in the 3–8 keV energies at 13:53 UT. These variations in the O^+ ion flux, and the

O^+/H^+ ion flux ratio is accompanied by the fluctuations in the electric and magnetic field as observed in Fig. 3 (panels d, e, f). At 13:53 UT ΔB_x decreases (by 5 nT) and ΔB_z increases (by 5 nT) confirming the signature of magnetic field dipolarization (Dai et al., 2015). The spin resolution electric field from the Electric Field and Waves (EFW) instrument (Wygant et al., 2013) in the modified GSE coordinates is shown in Fig. 3 panel f. Here, we observe the fluctuations E_y and E_z components of the electric field. At 13:53 UT E_z increases to 1.5 mV/m and at 13:59 UT E_y increases to 1.5 mV/m, which provides further information regarding the cause of flux enhancement. A similar analysis has been done for all the substorms given in Table 1 and two events with details are shown (Figs. 3 and 4).

Fig. 4 is in the same format as Fig. 3 except for the substorm of 19 August 2018 observed by RBSP-A spacecraft, corresponding MLT, L -value and MLAT of RBSP-A at the onset are 23.75, 6.1 and -5.40° respectively (electric field data is not available). The substorm onset as indicated by the black vertical line is at 22:31 UT. It is observed at 22:34 UT ΔB_x decreases (>5 nT) and ΔB_z increases (>5

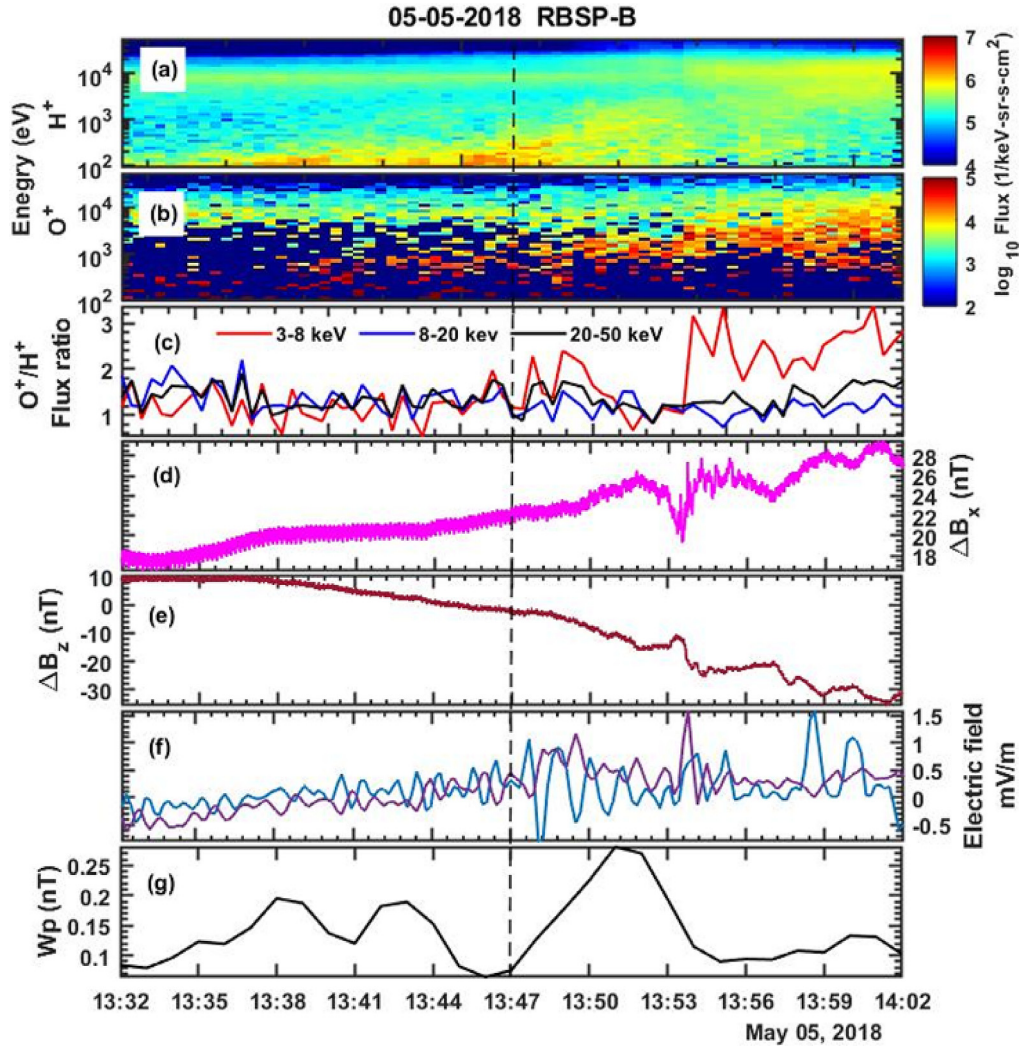


Fig. 3. RBSP-B data during 13:32–14:02 UT on 05 May 2018. From top to bottom displayed are (a) the energy time spectrogram for H^+ ions, (b) the energy time spectrogram for O^+ ions, (c) the O^+/H^+ flux ratio, (d) ΔB_x (e) ΔB_z (f) $V \times B$ subtracted electric field in MGSE coordinate system, and (g) the W_p index.

nT) thus confirms the magnetic field dipolarization. Simultaneous with the magnetic field fluctuations we observe an enhancement in the O^+ ion flux at energies > 500 eV. The O^+ ion flux is enhanced to 10^4 to 10^5 counts/cm²-s-sr-keV. However, the H^+ ion flux also shows a moderate change in flux at energies > 20 keV. The H^+ ion flux is noted to be 10^5 counts/cm²-s-sr-keV after the substorm onset. The O^+/H^+ ion flux ratio in the energy range of 3–8 keV shows a peak at 22:34 UT. This peak is simultaneous with the magnetic field variations. Thus, it confirms the dominance of the O^+ ion flux after the substorm onset. The contribution of the decrease of H^+ ion flux may be due to charge exchange losses (Nosé et al., 2018).

3.2. Superposed epoch analysis of magnetic field change and ion flux change

To understand the variations observed in ΔB_x , and ΔB_z we perform a superposed epoch analysis of the magnetic

field change and the results are shown in Fig. 5 (a, b). The black vertical line depicts zero epoch time ($T = 0$ min) which marks the onset of the substorm. As a typical dipolarization persists for a very short time (approx. 5 min) and typical substorm persists for 2–4 h, magnetic field data of 15 min before and 15 min after the onset of the substorm is taken into consideration and the average value for 22 events is plotted. The vertical orange line denotes $T = 5$ min and the vertical blue line denotes $T = 10$ min after the substorm onset.

It is clear from Fig. 5 that ΔB_x , and ΔB_z start to fluctuate at $T = 0$ min. These changes in the magnetic field persist for $T = 5$ min. This clearly explains that the 22 events studied are dipolarization events and are completely different from dipolarization fronts. The time scale of the dipolarization front is reported to be of several seconds (Fu et al., 2012a, 2012b, 2013).

Magnetic field dipolarization is one of the main magnetospheric substorm signature. While dipolarization

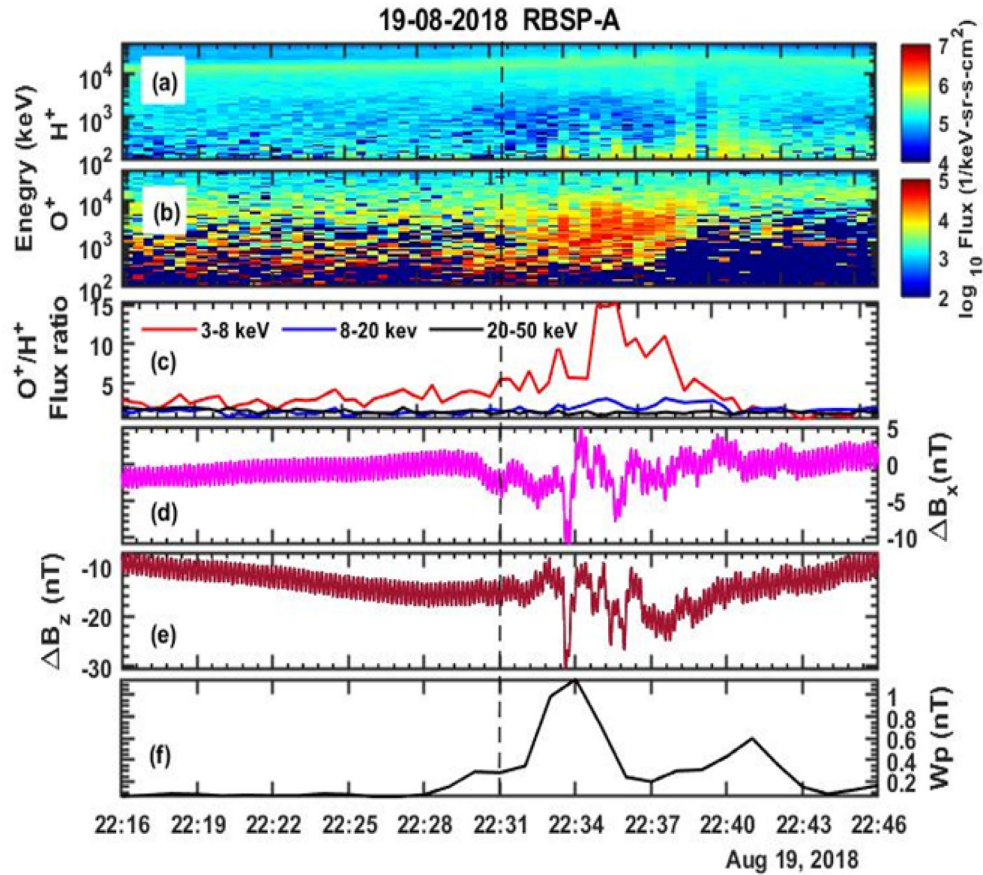


Fig. 4. RBSP-A data during 22:16–22:46 UT on 19 Aug 2018. From top to bottom displayed are (a) the energy time spectrogram for H^+ ions, (b) the energy time spectrogram for O^+ ions, (c) the O^+/H^+ flux ratio, (d) ΔB_x , (e) ΔB_z , and (f) the Wp index.

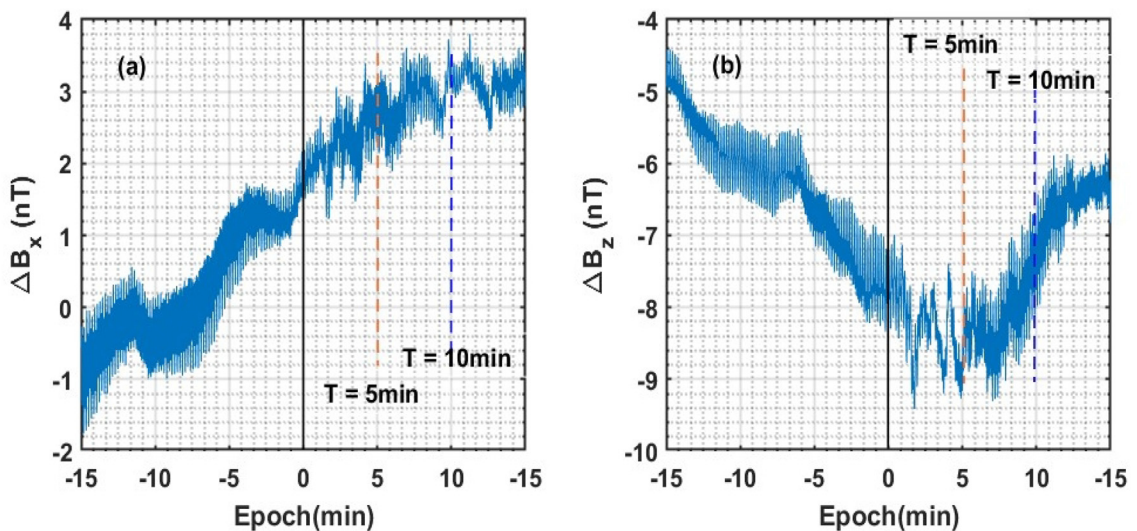


Fig. 5. Results of the superposed epoch analysis of the magnetic field variations. Above displayed are (a) ΔB_x , and (b) ΔB_z . Average of the magnetic field data of 22 events is shown. The vertical black line marks zero epoch time i.e., the onset of the substorm. The dashed vertical orange and blue lines correspond to $T = 5$ min and 10 min after zero epoch time, respectively.

front is a thin front layer which is formed when the bursty bulk flows (BBF's) jetting earthward during substorm expansion phase interact with the ambient plasma (Nakamura et al., 2017; Liu et al., 2018). The time scale

of dipolarization which is approximately 5 min is much longer than that of the dipolarization front. Thus, the 22 events selected in this study are the magnetic field dipolarization events.

The strong O^+ flux enhancement at energies > 1 keV is a typical characteristic associated with the magnetic field dipolarization in the inner magnetosphere. However, based on the earlier Figs. 3 and 4, it is observed that the ion flux enhancement is not the same for O^+ and H^+ and it depends on the energy range. Considering it, the energies are divided into 3 groups viz. 3–8 keV, 8–20 keV and 20–50 keV for both ion flux and a superposed epoch analysis of ion flux change shown in Fig. 6. For each of the 22 events, the ion flux data of the H^+ and O^+ are averaged and normalized with the highest value of flux for the above-mentioned groups and the average value of the ion flux is plotted in Fig. 6. The black vertical line corresponds to zero epoch time ($T = 0$ min) and marks the onset of a substorm. The dashed black, red, and blue line plot illustrates the H^+ ion flux of 3–8 keV, 8–20 keV, and 20–50 keV respectively. While the solid black, red, and blue line plot represent the O^+ ion flux of 3–8 keV, 8–20 keV, and 20–50 keV respectively. To compare the fluxes visually, the data are shifted by several factors (the factor is chosen such that the O^+ before the onset becomes similar to H^+ flux) as indicated in the figure and the data for individual events are not shown. It is observed that after substorm onset the O^+ ion flux is enhanced at 3–8 keV and at 8–20 keV, whereas, for the energy range of 20–50 keV at the substorm onset the O^+ ion flux is pronounced after 10 min of onset. This enhancement of the O^+ ion flux at energies > 1 keV is a typical characteristic of dipolarization (Nosé et al., 2016). To further understand the variations of ions in relation to the quiet period we plot the Ion Energy spectrum which is explained in the further section.

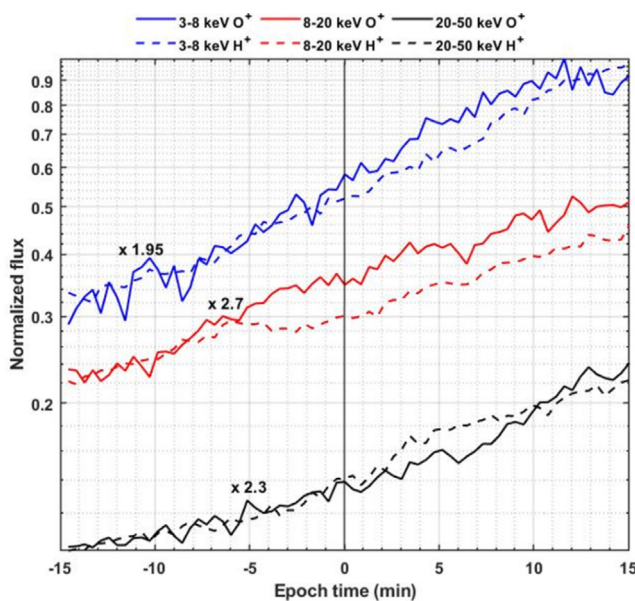


Fig. 6. Results of the superposed epoch analysis of the ion flux variations. The solid lines represent averaged flux of the O^+ ions and the dashed lines represent averaged flux of H^+ ions.

3.3. Ion energy spectrum

To understand the significant acceleration processes and to examine the variations in the H^+ and O^+ ion the Ion Energy spectrum is plotted in Fig. 7. Here we plot the ion flux before (Preonset) and after the substorm onset (Postonset). The preonset interval consists of the 2 min average value of the ion flux before the substorm onset. While the postonset indicates the 2 min average value of ion flux after the substorm onset. The solid black and red lines represent the O^+ ion flux during preonset and postonset respectively. Whereas, the dashed black and red lines specify the H^+ ion flux during preonset and postonset respectively. During the postonset times it is observed that H^+ ion flux at energies > 10 keV enhances, whereas the O^+ ion flux enhances at energies > 1 keV. It is worth noting that at energies > 10 keV, the H^+ ion flux starts to decrease gradually but the O^+ ion flux continues to enhance compared to the preonset flux. Thus, the ion energy spectra depict that there is an increment in both the ion fluxes between the energies 1–20 keV however, for energies > 20 keV, the enhancement of the O^+ ion flux dominates over the H^+ ion flux. This relative enhancement of the O^+ ion fluxes during the postonset period which dominates the H^+ ion flux at energies > 20 keV is also a significant characteristic of the substorm-induced dipolarization.

In the studied set of substorms, the presence of O^+ ions was enhanced, but protons remained the major ion species.

3.4. Role of the IMF B_z , the V_{sw} , and the AE index in the variation of the O^+ ion flux at 20–50 keV energy

The southward IMF B_z and the V_{sw} play a very important role in initiating the substorm development. So, it is essential to understand the role of these interplanetary

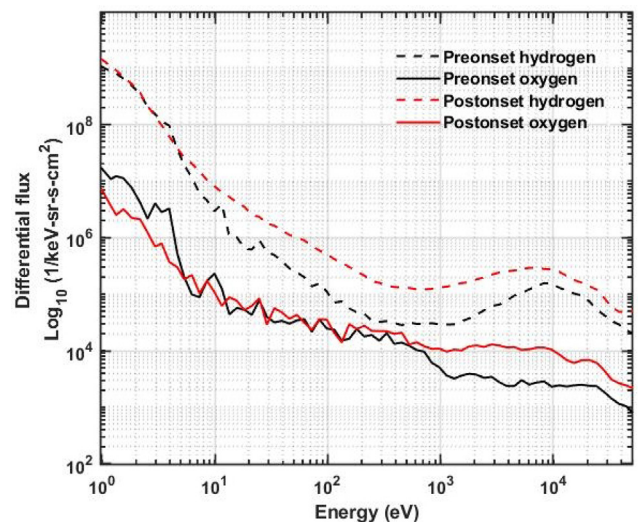


Fig. 7. Energy spectra of H^+ and O^+ ions during the preonset and postonset intervals.

parameters in energizing the ions in the plasma sheet during substorm intervals. The structure of the earth's magnetosphere is highly dependent on strength and orientation of the IMF B_z . The southward IMF B_z enhances convection of the magnetic field lines through the magnetic reconnection at the dayside magnetopause. As convection in the earth's magnetosphere is not always in steady state the magnetic flux gets added to the magnetotail (Baumjohann et al., 2002). The magnetic energy stored in the magnetotail is transported to the inner magnetosphere through plasma sheet region. Changes in the plasma sheet ion composition will also affect the inner magnetospheric plasma population and transport. In this study we attempt to examine the correlation between the observed enhanced fluxes of the O^+ and the H^+ ion flux with interplanetary parameters like the IMF B_z and the V_{sw} and also with the AE index.

Figs. 8, and 9 demonstrate the correlation of the IMF B_z and the V_{sw} with the O^+ ion flux of energies 20–50 keV. We particularly choose the O^+ ion flux of the 20–50 keV energy as the relative enhancement of the O^+ ion fluxes during post onset conditions dominate the H^+ ion flux (Fig. 7). It is clearly seen that the plasma sheet ion outflow is well correlated with the IMF B_z and the V_{sw} (Figs. 8 and 9). The correlation coefficient of the O^+ ion flux of 20–50 keV energy with the southward IMF B_z is 0.66 and that with the V_{sw} is 0.63. It indicates the crucial role of the IMF B_z and the V_{sw} in giving rise to the change in the plasma sheet ion composition during substorms. A similar investigation has been done to find the dependency of the O^+ ion flux with the P_{sw} however, the correlation coefficient was found to be poor (0.04).

The AE index specifies the intensity of geomagnetic disturbance resulting from enhanced auroral electrojets and hence, acts as a proxy to specify the state of the ionosphere during a substorm. Fig. 10 shows the correlation between the O^+ ion flux of 20–50 keV energy and the AE index. The correlation coefficient between these two parameters is 0.78. This signifies that the enhancement in O^+ ion flux of this energy range increases with the increasing strength of AE index.

3.5. Dependence of the O^+/H^+ ion flux ratio on the MLT of the spacecraft

As the satellite paths are confined to the night side for all substorm events (Fig. 1), it is examined to see dusk to dawn changes in the ratio of O^+/H^+ ion flux. Fig. 11 presents the plot of the O^+/H^+ ion flux ratio with the corresponding MLT of the spacecraft at substorm onset. The enhanced differential flux after the substorm onset is averaged over particular energy for a 2-minute interval. The blue, red, and black shapes represent the energy range of 3–8 keV, 8–20 keV, and 20–50 keV respectively. It is observed that a peak of the O^+/H^+ ion flux ratio centred near midnight around 23:00 to 00:00 MLT for the particular energy range of 8–20 keV. Whereas, the O^+/H^+ ion flux ratio of the energy 20–50 keV is high within post-midnight i.e., from 00:00 to 03:00 hrs. A clear variation in the O^+/H^+ ion flux of energy 3–8 keV is not seen.

4. Discussion and conclusions

The enhanced ion composition during substorm plays a key role in plasma and field dynamics in the inner magnetosphere. Our study is focused on flux of O^+ and H^+ ions of energy 1–50 keV for 22 clear substorm onset events during the year 2018. The fluxes of the O^+ and H^+ ions increase after substorm onset, but the magnitude of the flux enhancement for the O^+ ions is greater than that for H^+ ions. Some studies reported such results using different datasets (Matsui et al., 2016; Nosé et al., 2016, 2018). However, the ratio of ion flux is studied for energies > 1 keV to identify the dominance of the O^+ ions, the relationship of the enhanced population of the O^+ ion flux with the IMF B_z , the V_{sw} , and the AE index is studied and good correlation parameter is found. Importantly, the study reports the dependence of the MLT during substorm onset on the O^+/H^+ ion flux ratio. These are new findings and not reported earlier.

The HOPE observations for selected substorm events reveal that the magnetic field dipolarization in the inner

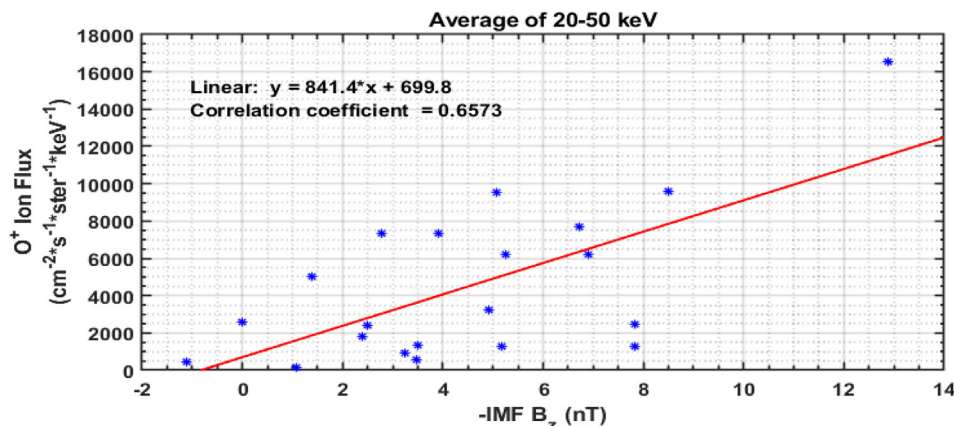


Fig. 8. The correlation analysis of IMF B_z with O^+ ion flux. The blue asterisk marks represent the average value of flux in the energy range 20–50 keV O^+ ions for each one of the 22 events. The red line is the linear fit to the data points.

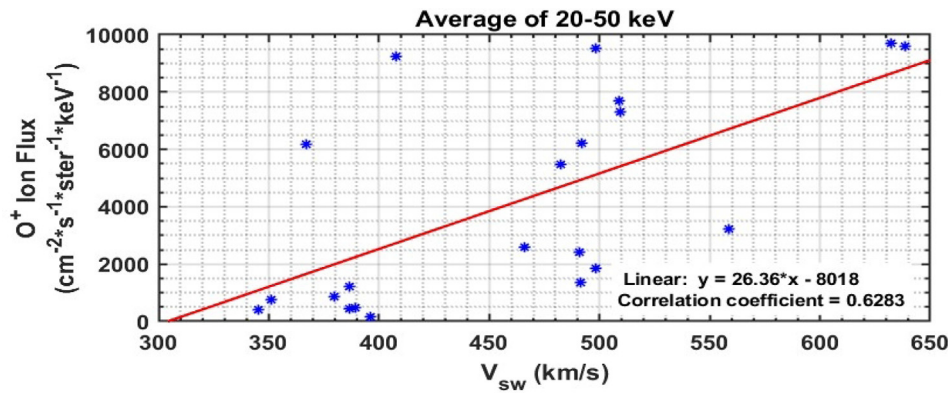


Fig. 9. The correlation analysis of solar wind velocity (V_{sw}) with O^+ ion flux. The blue asterisk marks represent the average value of flux in the energy range 20–50 keV O^+ ions for each one of the 22 events. The red line is the linear fit to the data points.

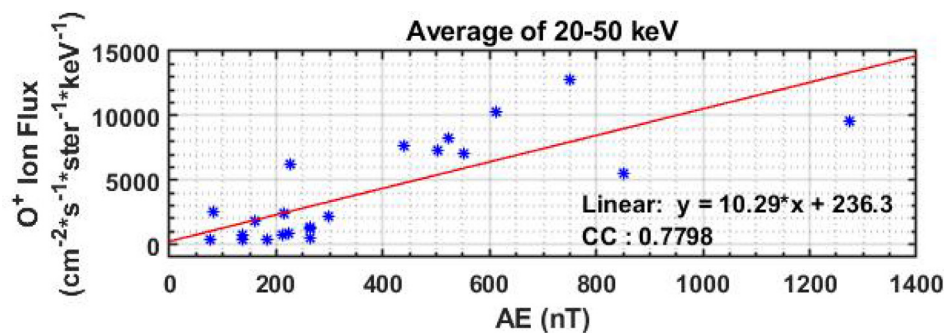


Fig. 10. The correlation analysis of AE index with O^+ ion flux. The blue asterisk marks represent the average value of flux in the energy range 20–50 keV O^+ ions for each one of the 22 events. The red line is the linear fit to the data points.

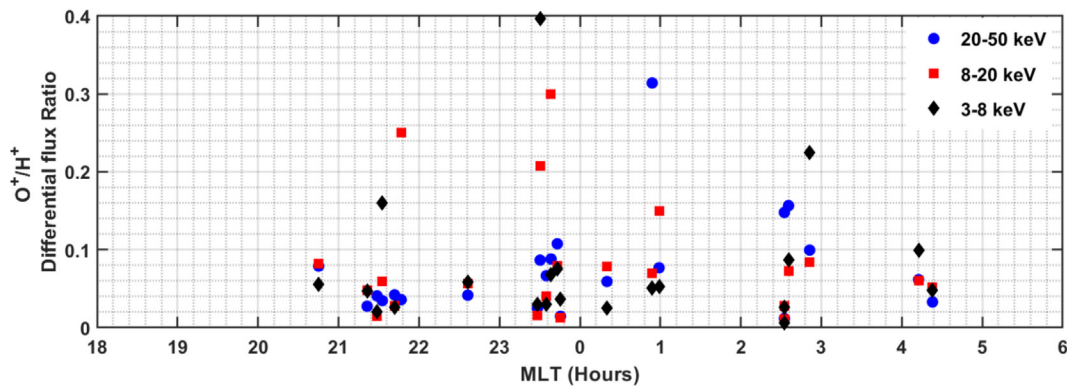


Fig. 11. The plot of O^+/H^+ differential flux ratio with the corresponding MLT of the spacecraft.

magnetosphere causes ion flux enhancement at energies above 1 keV (Fig. 6). However, at energies of 20–50 keV this ion flux enhancement is more intense for the O^+ ions than for the H^+ ions (Fig. 7). This enhanced population contributed to the ring current. The enhancement in these energetic ions may result in the alteration of characteristics or excitation condition of electromagnetic ion cyclotron waves, standing Alfvén waves along with geomagnetic field and magnetospheric cavity resonance (Nosé et al., 2018). Also, they can lead to the excitation of magnetosonic waves in the inner magnetosphere (Fu et al., 2014). Therefore, it is

important to study the enhanced population of the O^+ ions in the inner magnetosphere.

The possible mechanisms to explain the selective acceleration of the O^+ ions at substorm intervals are reviewed by Keika et al., 2013. It is suggested that adiabatic convective transport from the plasma sheet by the impulsive electric field to be one of the possible mechanisms for the enhancement observed. The impulsive electric field induced by the magnetic field reconfiguration does not work for local and non-adiabatic acceleration of O^+ ions in the inner magnetosphere (Nosé et al., 2016). But this electric field

may transport plasma from the near-earth plasma sheet into the inner magnetosphere by the $E \times B$ convection. This mechanism will play a role only when near-earth plasma sheet contains a population of warm (<10 keV) O^+ ions. In this mechanism, the O^+ flux enhancements are expected in the energy ranges above and below 20 keV energy. Fig. 6 and Fig. 7 clearly indicate that the O^+ ion flux is enhanced in energy range of 3–50 keV. Super-efficient particle acceleration during the magnetic reconnection by betatron mechanism has been reported (Fu et al., 2019). It can also be considered as a possible cause for the energetic ion enhancement observed in present study.

The acceleration mechanisms for enhanced O^+ ion flux is highly dependent on L-value of the spacecraft. The observed larger enhancement of the O^+ ion flux at energy above 20 keV may be likely due to nonadiabatic local acceleration by electric field oscillating at a frequency closer to the gyrofrequency of the O^+ ions (Nosé et al., 2016).

Solar wind parameters and geomagnetic indices are key parameters for forecasting and monitoring space weather activities. Enhanced heavy ion outflow at high latitudes results in an increase in the heavy ion concentration in the tail plasma sheet. Consequently, the plasma injected

into the inner magnetosphere has a relatively increased concentration of the O^+ ions, and significantly increases the flux of heavy ions in the ring current. Furthermore, Keika et al., (2013) showed that impulsive electric fields may accelerate heavy ions more effectively compared to light ions, due to their larger gyroperiod, allowing for more effective adiabatic heating. Boakes et al., (2011) showed that substorms are a highly variable phenomenon, with not all substorms being observed to be associated with an injection of energetic particles into the ring current. Substorms are associated with varied injection signatures, with only 33% of substorm events associated with a classical injection signature at geosynchronous orbit. Hence, not all substorms will drive an injection of energized plasma into the inner magnetosphere, and therefore, not all substorms will drive enhancements in the ring current energy content.

The response of the O^+ ion flux to changes in IMF is shown in Fig. 8. When the IMF B_z is southward, its coupling to the Earth's geomagnetic field is strongest. Southward interplanetary magnetic conditions are typically associated with the storms and substorms as they drive reconnection at the day-side and hence enhance convection electric field. Here, 20–50 keV oxygen ions are more sensitive to strength of the IMF B_z . The energetic O^+ ions seem to be correlated with the “openness” of the magnetosphere (Kronberg et al., 2012). However, during the most southward IMF B_z , the enhancement rises.

Processes in the near-earth magnetotail during substorm enhance the field-aligned currents leading to auroral elec-

trojet activity reflected by the AE index. The increase in 20–50 keV oxygen ions are associated with the growth of the AE index (Fig. 10). It indicates that oxygen ions of these energies are accelerated more efficiently than the other energies although the sources of their acceleration have to be different. Similar results of ion enhancement are reported by Ono et al., 2009 for energies of 9 to 36 keV/e during substorms, and Zong et al. 2008, 2009 reported bursty bulk flows responsible for this enhancement. However, Ono et al. 2009 did not find a clear correlation between substorm-associated dipolarization and effective acceleration for the oxygen ions in the energy range 56–212 keV/e.

The present study covers the substorm events within the wide range of MLTs from 20 to 05 (pre-midnight to near dawn, listed in Table 1). We observe enhanced O^+/H^+ flux ratio of the energy 20–50 keV up to the pre-dawn region (Fig. 11). This observation is consistent with a few previously reported results. It is reported using global energetic neutral atom images that the ring current proton distribution of 27–119 keV energy is rotated eastward and has a peak around 01 to 03 MLT during the main phase of the storm (C:son Brandt et al., 2002). This peak around 01–03 MLT suggests that the electric field during the magnetic field reconfiguration is strong enough so that the $E \times B$ drift can compete with the magnetic drift. Similar eastward rotation of ring current distribution in the energy range 27–39 keV during the storm main phase was reproduced with the self-consistent ring current model. During the disturbed conditions, using the electric field measurements it was found that the equipotential contours on the night side are skewed towards the morning side (Fok et al., 2003). This can be one of the reasons we observe the O^+/H^+ flux ratio of the energy 20–50 keV high after post-midnight.

In the present work, we examine O^+ and H^+ ion flux and identify the potential relationship between solar wind parameters and geomagnetic index during the substorm events. The current study is performed for 22 substorm events during the year 2018. The major findings analysed in this study are summarized below:

- 1) The time scale of the magnetic field dipolarization is approximately 5 min.
- 2) The reconfiguration of the magnetic field is accompanied by an enhancement in the flux of O^+ and the H^+ ions at energies 1–50 keV.
- 3) The enhancement in O^+ ion flux for the particular energy range of 20–50 keV appears to be greater in magnitude compared to the enhanced H^+ ion flux.
- 4) The observed increase of O^+ ion flux at energies above 20 keV during the substorm strongly depends on the strength of the IMF B_z , the solar wind velocity V_{sw} , and the higher AE index with correlation coefficients of 0.78, 0.66, and 0.63 respectively.

- 5) The peak of the O^+/H^+ ion flux ratio centred near midnight around 23:00 to 00:00 MLT for the energy range of 8–20 keV, whereas the O^+/H^+ ion flux ratio of the energy 20–50 keV is high within the post-midnight i.e., from 00 to 03:00 MLT.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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