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Long-term variations in the plasma sheet ion composition and substorm occurrence over 23 years

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Abstract

The Geotail satellite has been operating for almost two solar cycles (~23 years) since its launch in July 1992. The satellite carries the energetic particle and ion composition (EPIC) instrument that measures the energetic ion flux (9.4–212 keV/e) and enables the investigation of long-term variations of the ion composition in the plasma sheet for solar cycles 22–24. From the statistical analysis of the EPIC data, we find that (1) the plasma ion mass (*M*) is approximately 1.1 amu during the solar minimum, whereas it increases to 1.5–2.7 amu during the solar maximum; (2) the increases in *M* seem to have two components: a raising of the baseline levels (~1.5 amu) and a large transient enhancement (~1.8–2.7 amu); (3) the baseline level change of *M* correlates well with the Mg II index, which is a good proxy for the solar extreme ultraviolet (EUV) or far ultraviolet (FUV) irradiance; and (4) the large transient enhancement of *M* is caused by strong magnetic storms. We also study the long-term variations of substorm occurrences in 1992–2015 that are evaluated with the number of Pi2 pulsations detected at the Kakioka observatory. The results suggest no clear correlation between the substorm occurrence and the Mg II index. Instead, when the substorms are classified into externally triggered events and non-triggered events, the number of the non-triggered events and the Mg II index are negatively correlated. We interpret these results that the increase in the solar EUV/FUV radiation enhances the supply of ionospheric ions (He^+ and O^+ ions) into the plasma sheet to increase *M*, and the large *M* may suppress spontaneous plasma instabilities initiating substorms and decrease the number of the non-triggered substorms. The present analysis using the unprecedentedly long-term dataset covering ~23 years provides additional observational evidence that heavy ions work to prevent the occurrence of substorms.

Keywords: Long-term variations of geospace environment, Plasma sheet ion composition, Substorm, Ionospheric outflow, Mg II index, Solar EUV/FUV irradiance, Geotail satellite, Pi2 pulsation

Introduction

The ion composition of plasma in the magnetosphere and the plasma sheet is one of important parameters in space physics, because it affects the Alfvén velocity that is a fundamental physical quantity of plasma. When plasma contains ion species heavier than H^+, such as He^+ and O^+, the plasma mass increases to more than 1 amu and the Alfvén velocity decreases. For example, the plasma mass with 95 % H^+ and 5 % O^+ is 1.75 amu, and the Alfvén velocity in this plasma decreases to approximately 76 % of that in a proton only plasma. It is expected that various plasma phenomena are altered in such low Alfvén velocity environments. Another aspect of the ion composition change is that the plasma acquires multiple spatial scales corresponding to the gyroradii of ions or increases in the effective ion gyroradius. This may affect the threshold of plasma instabilities.

Thus, information on the long-term change of the ion composition in terrestrial plasma is crucial in studies of space weather or space climate. Previous studies using data of 2–7 years showed that the number densities or energy densities of He^+ and O^+ ions have a good correlation with the F10.7 index (e.g., Young et al. 1982;

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Stokholm et al. 1989; Lennartsson 1989; Pulkkinen et al. 2001). More recently, using data obtained by the energetic particle and ion composition (EPIC) instrument onboard the Geotail satellite, Nosé et al. (2009) studied the variations of the ion composition in the plasma sheet for more than 16.3 years (from 17 October 1992 to 21 February 2009) to confirm that the He^+/H^+ and O^+/H^+ flux ratios depend on the F10.7 index with stronger correlation for O^+/H^+.

The Geotail satellite continues observations after the study of Nosé et al. (2009) and accumulates ion flux data up to the present (as of December 2015) that cover almost two solar cycles and are very valuable for the study of long-term variations of the ion composition in the plasma sheet. In this paper, we expand upon the work of Nosé et al. (2009) by using longer-term and updated data from the Geotail/EPIC instrument. Although Nosé et al. (2009) used the F10.7 index to measure the long-term variations of solar activity, we adopt the Mg II index, because it is a better proxy for the solar extreme ultraviolet (EUV) or the far ultraviolet (FUV) irradiance that directly affects the ionospheric ion outflow. We also introduce a new scheme to identify the effect of ion composition on substorm occurrence by classifying the substorms into externally triggered or non-triggered events.

Data set

Geotail/EPIC

The Geotail satellite was launched on 24 July 1992 to investigate the structure and dynamics of the geomagnetic tail (Nishida 1994). Figure 1a and b show the variations of the Geotail location in X_{GSM} and Z_{GSM} for September 1992 to October 2015. Geotail surveyed the mid and distant tail regions ($X_{GSM} = -50$ to $-210\ R_E$) for ~2.5 years after its launch, and then descended to a near-Earth orbit with a perigee of ~9 R_E, an apogee of ~30 R_E, and an orbital period of ~5.3 days, in March 1995. The near-Earth orbit has the apsidal precession with a period of ~1 year that can be clearly seen in the sinusoidal changes of the location in X_{GSM} (Fig. 1a). Geotail exhausted its thruster fuel in 2002; since then, no orbit control has been possible, and its location largely deviated from the equatorial plane ($Z_{GSM} = 0\ R_E$) in 2006–2012 (Fig. 1b).

Geotail carries the EPIC instrument that can measure the energetic ion flux (9.4–212 keV) with mass and charge state information in almost full solid angle (~4π sr) (Williams et al. 1994). In this study, we use the omnidirectional flux integrated over this energy range (I_a), where a represents ion species (H^+, He^+, O^+, and He^{2+}). A more detailed description of how to calculate I_a is given by Nosé et al. (2009). The data period is from October 1992 to October 2015, covering the declining phase of solar cycle 22, all of solar cycle 23, and the rising phase of solar cycle 24.

Mg II index

The Mg II index is derived from the ratio of the irradiance in the core of the Mg II emission around 280 nm (the h line at 279.56 nm and the k line at 280.27 nm) to the irradiance at neighboring wavelengths (Heath and Schlesinger 1986). The ratio is used to reduce problems due to variations in instrumental sensitivity. The Mg II index is not a direct measure of the solar EUV/FUV irradiance (i.e., 10–200 nm), but strongly correlates (c.c. = 0.96–0.99) with the solar EUV/FUV irradiance measured by the Solar EUV Monitor (SEM) or Extreme ultraviolet Imaging Telescope (EIT) on the Solar and Heliospheric Observatory (SOHO) satellite (Viereck et al. 2001; Floyd et al. 2005). The correlation coefficient between the F10.7 index and the EUV/FUV irradiance is 0.94–0.96, a little smaller than that for the Mg II index. Balan et al. (1994) reported that the EUV/FUV flux is saturated when the F10.7 index exceeds the threshold of ~150 sfu (solar flux unit, 1 sfu = 10^{-22} W/m^2/Hz). Thus, the Mg II index provides a better proxy for solar EUV/FUV radiation than the F10.7 index.

The solar EUV/FUV radiation is absorbed in the terrestrial atmosphere at ~50–200 km altitude (Bowman et al. 2008) and affects the density and temperature of ionospheric ions. The long-term variations of EUV/FUV may control the supply of ionospheric ions into the space plasma and change the ion composition. In this study, we use the "Bremen composite" Mg II index (Snow et al. 2014) for January 1992 to October 2015 and compare them with the Geotail/EPIC observations.

Substorm occurrence

Pi2 pulsation at low-latitude is considered a good proxy for the onset of substorms; thus, we identify Pi2 pulsations from the 1-s geomagnetic field data at Kakioka (27.5° geomagnetic latitude). The period of the 1-s data is from January 1992 to October 2015. Pi2 pulsations are selected in 2100–0100 magnetic local time by using the automated detection algorithm developed by Nosé et al. (1998).

Variations of plasma sheet ion composition for 23 years

Integral flux

Figure 1c–f display the variations of the integral fluxes of H^+, He^+, O^+, and He^{2+} ions, which are averaged over 27 days corresponding to the synodic rotation period of the Sun. In the calculation of the 27-day averages, we remove the data segments when Geotail stayed in the magnetic lobe where the H^+ integral flux is zero, because

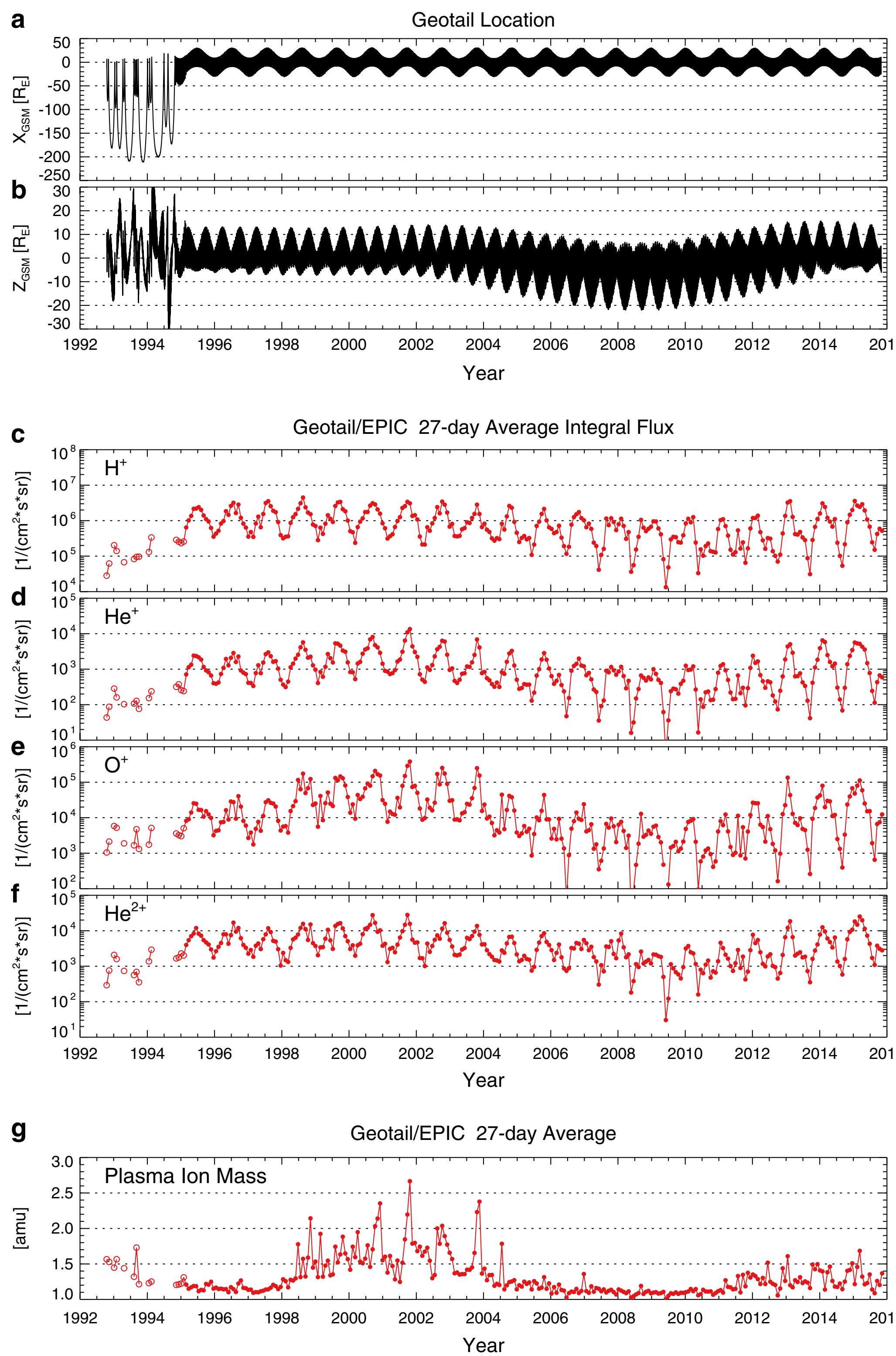

Fig. 1 Geotail location in **a** X_{GSM} and **b** Z_{GSM} for October 1992 to October 2015. Integral fluxes of **c** H^+, **d** He^+, **e** O^+, and **f** He^{2+} ions for October 1992 to October 2015. The integral fluxes are averaged over 27 days corresponding to the synodic rotation period of the Sun. Open and filled *circles* represent the integral fluxes measured in the mid-tail plasma sheet ($X_{GSM} = -32$ to -100 R_E and $Y_{GSM} = -14$ to 14 R_E) and in the near-Earth plasma sheet ($X_{GSM} = -8$ to -32 R_E and $Y_{GSM} = -8$ to 8 R_E), respectively. **g** Plasma ion mass in the plasma sheet calculated from data points in Fig. 1c–f

we are interested in the ion composition in the plasma sheet. The integral fluxes before March 1995 (open circles) are for the mid-tail plasma sheet at $X_{GSM} = -32$ to -100 R_E and $Y_{GSM} = -14$ to 14 R_E, and those after March 1995 (filled circles) are measured in the near-Earth plasma sheet at $X_{GSM} = -8$ to -32 R_E and $Y_{GSM} = -8$ to 8 R_E. It is natural that the former is smaller than the latter by approximately an order of magnitude, because the plasma becomes more tenuous as it moves farther away from the Earth. The integral flux in the near-Earth plasma sheet generally shows ~1-year periodical oscillations since March 1995, which is caused by the change of the Geotail location in X_{GSM}, as seen in Fig. 1a. We also note the suppression of the integral flux around 2006–2012 during which the Z_{GSM} of the Geotail location mostly shifts to negative values (Fig. 1b). This reflects the longer presence of Geotail in the off-central plasma sheet or boundary plasma sheet, where the flux is smaller than that in the central plasma sheet. In addition to these changes, both the He^+ and O^+ integral fluxes show long-term variations with timescale of more than 10 years, that is, gradual increases in 1995–2001 and 2010–2015, and a gradual decrease in 2002–2008. The long-term variations are more significant for O^+ than He^+.

Plasma ion mass

To eliminate the flux variations caused by the Geotail position changes and to clarify the long-term variations, we calculated the plasma ion mass in the plasma sheet (M) with the following equation:

$$M = \frac{I_{H^+} + 4I_{He^+} + 16I_{O^+} + 4I_{He^{2+}}}{I_{H^+} + I_{He^+} + I_{O^+} + I_{He^{2+}}}$$

The results are shown in Fig. 1g. We find that M is around 1.1 amu during 1994–1997 and 2006–2010, whereas it increases to 1.5–2.7 amu during 1998–2004 and 2012–2015. The increases in M seem to have two components, that is, a raising of the baseline levels (~1.5 amu) and a large transient enhancement (~1.8–2.7 amu).

We suppose that the raising of the baseline levels corresponds to the solar cycle and the transient enhancements are caused by geomagnetic activities. To test this supposition, M is compared with the Mg II index and the geomagnetic activity. Figure 2a presents the Mg II index averaged over 27 days. In Fig. 2b, M is reproduced with vertical orange bars that denote the 27-day time intervals when the minimum value of the Dst index is equal to or less than −150 nT. We note that the transient enhancements of M mostly occur during the time intervals of the orange bars. This supports the idea that sudden increases in M to 1.8–2.7 amu are caused by strong magnetic activities, and is consistent with the results for individual magnetic storms reported by previous studies (e.g., Hamilton et al. 1988; Daglis 1997; Nosé et al. 2003, 2005). On the other hand, the changes in the baseline levels of M seem follow those of Mg II; M remains at ~1.1 amu during the solar minimum (1994–1997 and 2006–2010) and increases to ~1.5 amu during the solar maximum (1998–2004 and 2012–2015). It is noteworthy that the temporal decreases of the Mg II index in 2001 and 2014 coincide with the temporal low values of M, as indicated by vertical arrows. From Fig. 3, it is seen that the Mg II index and M are strongly correlated (c.c. = 0.77) when the data points of M in the orange bars are disregarded. These results suggest that the long-term variation of the ion composition in the plasma sheet is controlled by the solar activity measured by the Mg II index, that is, the solar EUV/FUV irradiance.

Variations of substorm occurrence for 23 years

We investigate the long-term variations of the substorm occurrence in 1992–2015. The substorm occurrence is assessed by the daily number of Pi2 pulsations at Kakioka. The daily number of Pi2 pulsations is averaged over 27 days in the same way as the ion composition and the Mg II index. The results are shown in Fig. 4b with the Mg II index in Fig. 4a, which is identical to Fig. 2a, for easier comparison with the substorm occurrence. In Fig. 4b, the substorm occurrence peaks around 1994 and 2003–2004, and decreases gradually until 2002 and 2014. These long-term changes of the substorm occurrence are not similar to the solar cycle. Figure 5a confirms the dissimilarity between them by the small correlation coefficient (−0.28).

This low negative correlation suggests that the substorm occurrence is not related to the solar irradiance. However, we should note that substorms are classified into two types in terms of their occurrence mechanisms, that is, external trigger or internal instability. The externally triggered substorms are caused by the changes in the IMF or solar wind that reduce the large-scale magnetospheric electric field (e.g., Lyons 1995), whereas substorms related to internal instability are not accompanied by such changes and are the results of some spontaneous instabilities in the magnetosphere or the plasma sheet (i.e., non-triggered substorms) (e.g., Lui et al. 1991; Roux et al. 1991). The occurrence of non-triggered substorms is presumably affected by the ion composition, as discussed in the introduction, and may have long-term variations corresponding to the solar activity. Thus, we classify the substorm events into these two types (externally triggered or non-triggered substorm), and compare the daily number of non-triggered substorms with the Mg II index. The classification is performed by using the solar wind dynamic pressure (P_{dy}) and IMF B_z data from

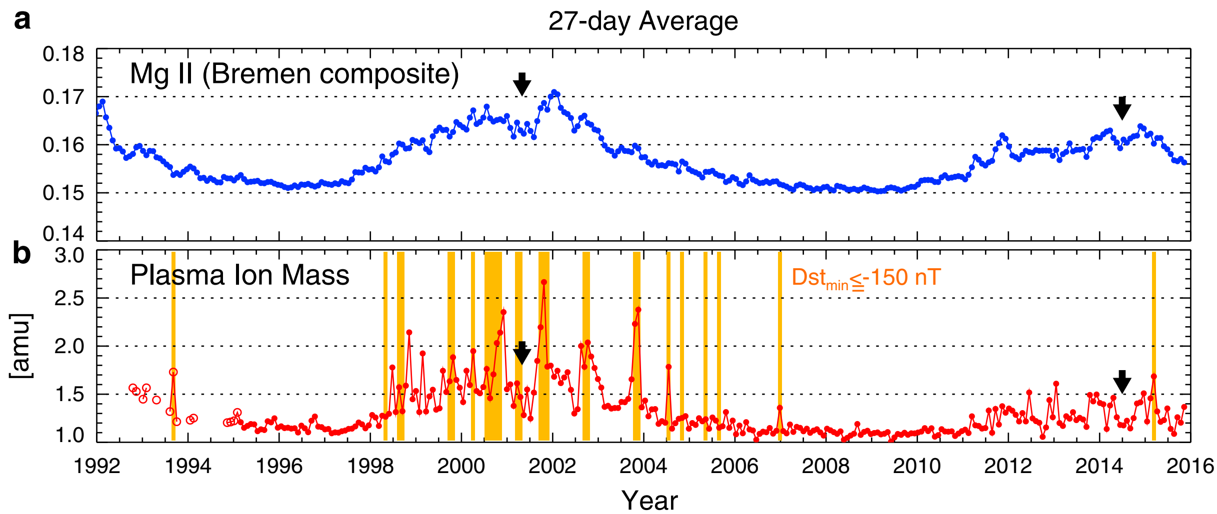

Fig. 2 **a** Mg II index (Bremen composite) averaged over 27 days for 1992–2015. **b** Plasma ion mass in the plasma sheet that is identical to Fig. 1g. Vertical orange bars denote 27-day time intervals when the minimum value of the Dst index is equal to or less than −150 nT. *Vertical arrows* in both panels point to a coincidence of temporal decreases in the Mg II index and the plasma ion mass around 2001 and 2014

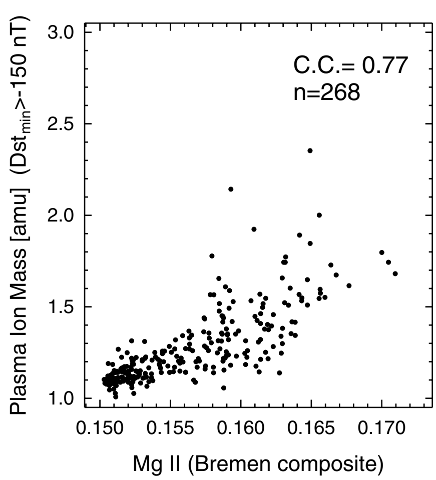

Fig. 3 Relation between the plasma ion mass and the Mg II index after the exclusion of *data points* for $Dst_{min} \leq -150$ nT

the 5-min resolution OMNI database. When a Pi2 pulsation is preceded within 1 h by a ≥0.5 nPa jump in P_{dy} or a ≥1.5 nT jump in the IMF B_z, the Pi2 pulsation is attributed to the external changes and the event is classified as a triggered substorm. When no such jumps are found in both P_{dy} and IMF B_z, the event is labeled as a non-triggered substorm. The 5-min resolution OMNI data are generally continuous after January 1995; thus the classification is for January 1995 to October 2015. Figure 6a and b demonstrate typical examples of the triggered and non-triggered events, respectively. The event in Fig. 6a follows the clear jumps of P_{dy} with ~1 nPa and IMF B_z with ~2 nT, whereas the event in Fig. 6b occurs during very steady solar wind conditions. Out of 13,495 events of Pi2 pulsations while the OMNI data are available, 8793 events (65.2 %) are triggered and 4702 events (34.8 %) are non-triggered. These percentages are consistent with the previous result reported by Hsu and McPherron (2003), in which the triggered and non-triggered events are ~60 % and ~40 % in the number of occurrence, respectively. Figure 4c shows the long-term variation of the daily number of the non-triggered events after averaged over the 27 days. The daily number of the non-triggered events seems to have peaks around 1995–1996 and 2007–2008, and troughs around 2001–2002 and 2014–2015. This long-term variation looks inversely correlated with that of the Mg II index (Fig. 4a) with a correlation coefficient of −0.46, as shown in Fig. 5b, which is much improved from that in Fig. 5a. This result suggests that the non-triggered substorm occurrence is controlled by the solar EUV/FUV irradiance.

Discussion and conclusions

From Figs. 3 and 5b, we find that the Mg II index, a proxy of the solar EVU/FUV, is correlated with the plasma ion mass in the plasma sheet (c.c. = 0.77) as well as the occurrence of the non-triggered substorms (c.c. = −0.46). We interpret this result to mean that (1) the increase in the solar EUV/FUV radiation raises the ionospheric ion density and temperature, enhances the supply of ionospheric ions (He^+ and O^+ ions) into the plasma sheet, and increases *M*; and (2) the large *M* (i.e., heavy plasma sheet)

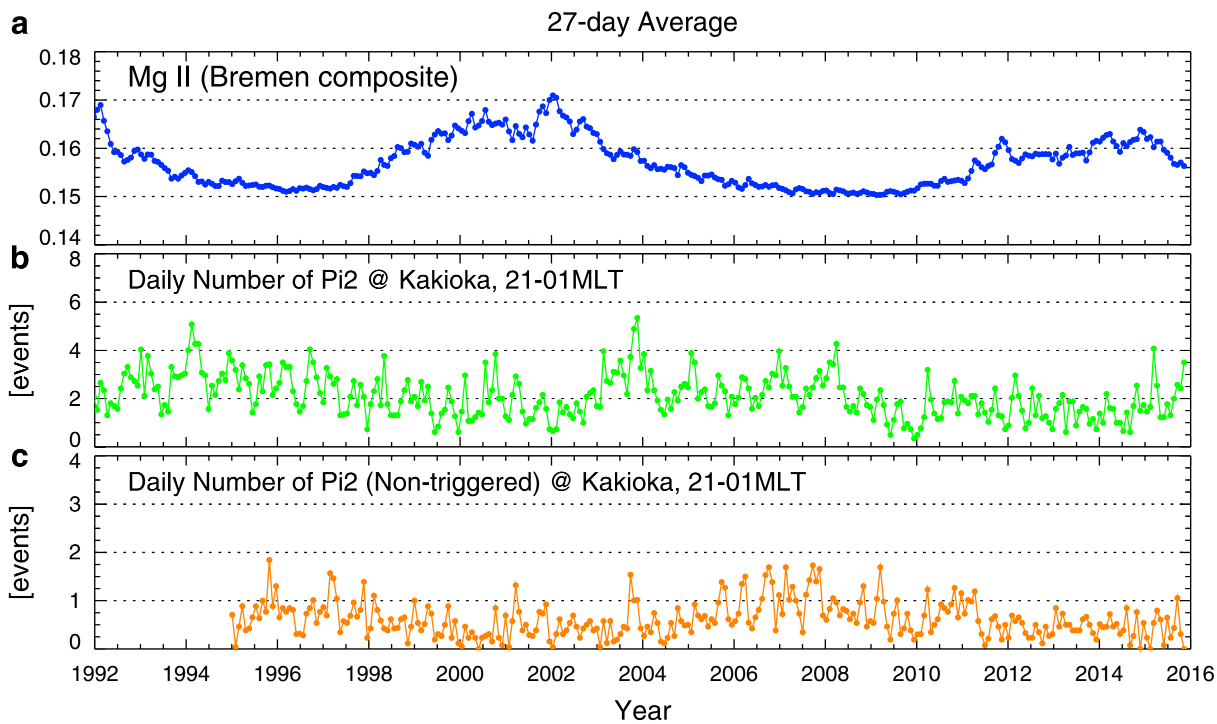

Fig. 4 **a** Mg II index that is identical to Fig. 2a. **b** Daily number of Pi2 pulsations observed at Kakioka at 2100–0100 magnetic local time for 1992–2015. The number is averaged over 27 days in the same way as the integral fluxes and the Mg II index. **c** Daily number of Pi2 pulsations at Kakioka with no clear jumps in solar wind dynamic pressure and IMF B_Z, which are considered non-triggered events

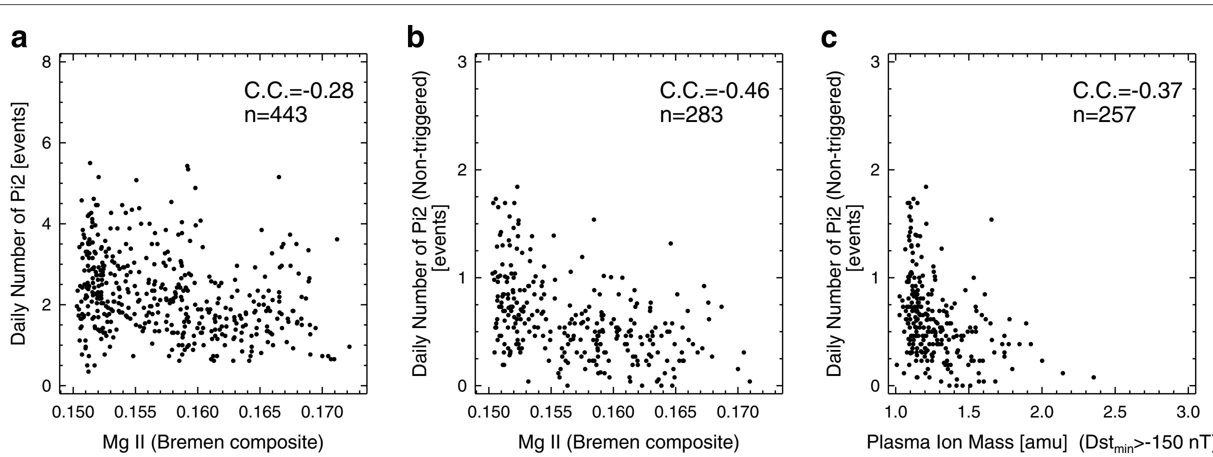

Fig. 5 **a** Relation between the daily number of Pi2 pulsations and the Mg II index. **b** Relation between the daily number of Pi2 pulsations with no clear solar wind discontinuities (i.e., non-triggered events) and the Mg II index. **c** The same as Fig. 5b, except for the plasma ion mass when $Dst_{min} > -150$ nT

may suppress spontaneous plasma instabilities that lead to the onset of substorms and decrease the number of the non-triggered substorms. Although the physical mechanisms of the suppression of plasma instabilities are not identified in this study, the inverse relation is identified between M and the number of non-triggered substorm occurrence (Fig. 5c), which supports the second interpretation. The distribution of data points in Fig. 5c does not seem linear, but we find the linear correlation coefficient to be −0.37 that is statistically significant according to

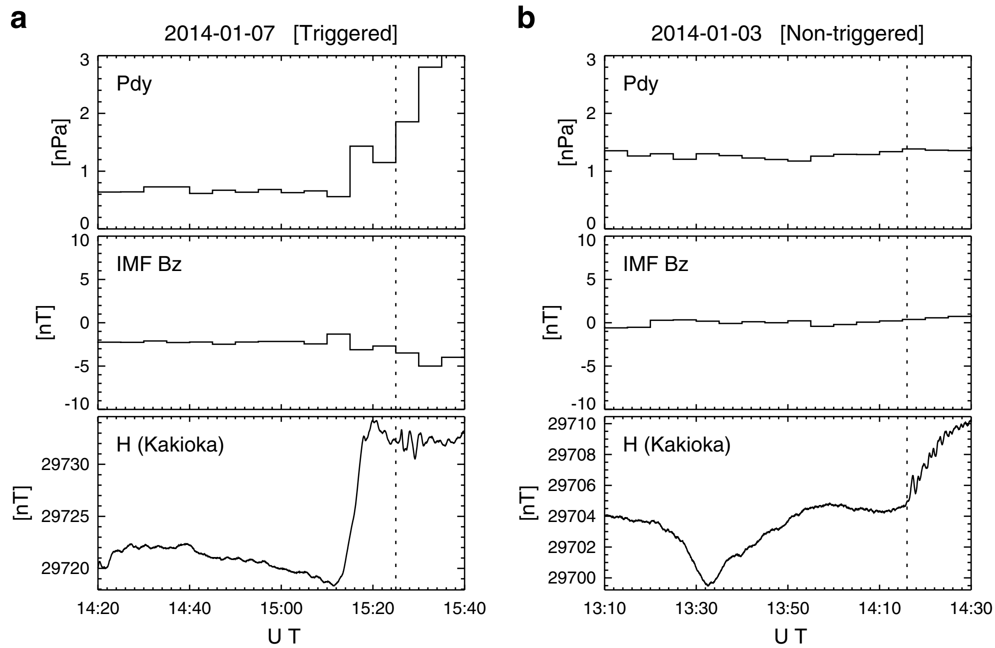

Fig. 6 **a** A typical event of Pi2 pulsation that follows a ≥0.5 nPa jump in the solar wind dynamic pressure (P_{dy}) or a ≥1.5 nT jump in the IMF B_z within 1 h, which is considered an externally triggered event. **b** A typical event of Pi2 pulsation with no clear jumps in P_{dy} and IMF B_z, which is considered a non-triggered event

the correlation coefficient test of Bevington and Robinson (1992).

There has been a long discussion over the last 30 years about the role of heavy ions in substorm occurrence. Baker et al. (1982, 1985), Daglis and Sarris (1998), and Ono et al. (2010) concluded that heavy ions promote the occurrence of substorms. On the contrary, Lennartsson et al. (1993), Kistler et al. (2006), Nosé et al. (2009), and Liu et al. (2013) argued that the substorm occurrence is not related to the large abundance of heavy ions in the plasma sheet. Numerical simulations have examined the role of heavy ions in substorm occurrence. Using the multi-fluid Lyon-Fedder-Mobarry (MFLFM) global MHD code, Wiltberger et al. (2010), Brambles et al. (2011), and Ouellette et al. (2013) proposed a positive feedback loop in the magnetosphere-ionosphere system where the O^+ ion outflow from the ionosphere facilitates the development of the next substorm. From numerical calculation using the multi-fluid Block-Adaptive Tree Solar-wind Roe Upwind Scheme (BATS-R-US) global MHD code, Yu and Ridley (2013) found opposite effects between the different ionospheric sources: O^+ ions from the dayside cusp facilitate substorms, whereas those from the nightside auroral region hinder the development of substorms. As shown here, the influence of heavy ions on substorm dynamics is still a controversial issue and has not been determined definitively. Review papers on this issue are also recently published (Wiltberger 2014; Kistler 2015).

From the statistical analysis of an unprecedentedly long-term dataset covering almost two solar cycles (~23 years), the present study provides additional observational evidence that heavy ions work to prevent the occurrence of substorms. However, more theoretical studies are needed to comprehensively understand the role of heavy ions in the onset of substorms.

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Competing interests
The author declares that he has no competing interests.

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