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On the Magnetosphere Stand-Off Distance at the Timescale of Geomagnetic Storms

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Abstract

The magnetosphere shape and dimensions are a result of the equilibrium between the magnetic pressure of the geomagnetic field and the dynamic pressure of the solar wind in which the Earth and its magnetosphere are embedded. Our previous studies [Dobrica et al., 2012, Stefan et al., 2013] concerned the long term evolution (the last ~ 150 and, respectively, 300 years) of the stand-off distance, i.e. the sub-solar distance to the magnetopause, commeasured in Earth's radii (R_E). In the present article we tackle the stand-off distance evolution at much shorter time scale, i.e., during 21 moderate and intense geomagnetic storms (Dst<-100 nT) occurred in the solar cycle 24 (2008-2020). While the long-term evolution of the stand-off distance shows variations between 11.6 and 9.5 R_E, during geomagnetic storms it shows variations of 6-12 R_E. An attempt is done to use the superposed epoch analysis in comparing various storms.

Key words: solar activity, solar wind, geomagnetic storms, superposed epoch analysis

Introduction

Generally, the sub-solar distance to the magnetopause (the so-called stand-off distance) results from the equilibrium between the magnetic pressure of the geomagnetic field and the dynamic pressure of the solar wind in which the Earth and its magnetosphere are embedded. At long-term timescale (the last ~150 years) this parameter was evaluated by [Dobrica et al. 2012, Stefan et al., 2013] reconstructed the stand-off distance evolution in the last 300 years. In the present paper we tackle the stand-off distance evolution at the much shorter time scale of geomagnetic storms, looking at 21 moderate and intense geomagnetic storms (Dst<-100 nT) that occurred in the solar cycle 24 which are presented in Table 1.

Two of this 21 geomagnetic storms are excluded from our analysis (August 2011, July 2012) because of no data availability.

Geomagnetic storms are a part of the geomagnetic activity, which is the result of the interaction of the solar wind (SW) and the heliospheric magnetic field with the magnetosphere and ionosphere. Most of intense geomagnetic storms (Dst <-100 nT) are generally caused by coronal mass ejections (CMEs). These involve the expulsion from the solar corona of huge quantities of solar magnetized plasma at high speeds into interplanetary (IP) space. CMEs observed in interplanetary space are also known as interplanetary coronal mass ejections (ICMEs) and are responsible for many major disturbances to the Earth's space environment [Kamide and Chian, 2007]. In general, ICMEs are detected by a number of characteristics measured by the satellite placed in the Lagrange point L1 in space: sudden increase in SW speed, increase in magnetic field, rotation of the magnetic field, decrease in electron density and temperature etc.

Data and method

1-minute data for the interplanetary and solar wind parameters (B, Bx, By, Bz, the heliospheric magnetic field, V, the solar wind speed, P, the solar wind dynamic pressure) available at https://omniweb.gsfc.nasa.gov/form/omni_min.html and data for geomagnetic indices designed to proxy the evolution of magnetospheric ring current and of auroral electrojets (Dst and SymH, and, respectively, AE) available at http://wdc.kugi.kyotou.ac.jp/wdc/Sec3.html, as well as data related to the coefficients of the IGRF-13 main field model (g_1^0, g_1^1, h_1^1), available at https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html, have been used in this study.

Variation of interplanetary and geomagnetic parameters during March 2015, June 2015, and September 2017 geomagnetic storms, chosen as examples, is displayed in Fig. 1.

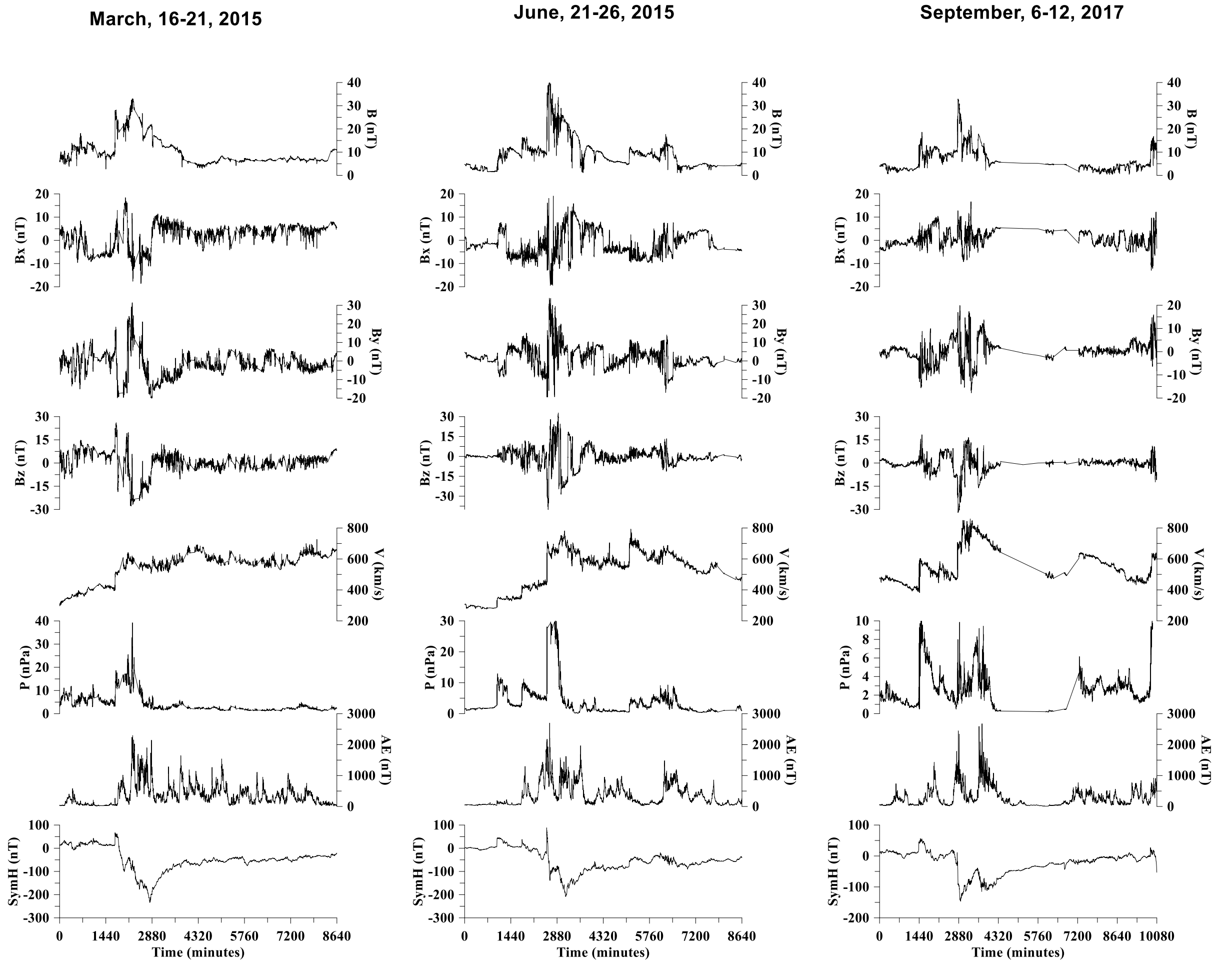

Fig. 1 – Variation of geomagnetic and interplanetary parameters during March 2015, June 2015, September 2017 geomagnetic storms

In order to determine the stand-off distance, we used the expression given by Schield [1996]:

$$L = \left(\frac{k^2 M^2}{2\mu_0 P}\right)^{\frac{1}{6}}, \quad (1)$$

where M is the Earth's magnetic moment, P is the dynamic pressure of the solar wind, μ_0 is the permeability of the vacuum, and k is a given constant.

Though the magnetic moment of the Earth is time-dependent at long-term timescale [Demetrescu and Dobrica, 2020], we consider it constant during the short-time span (hours, days) of geomagnetic storms. The magnetic moment of the dipole was calculated by the formula: $M = \left(\frac{4\pi R_E^3}{\mu_0}\right)\sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}$ where: R_E – Earth radius (6370km), μ_0 = $4\boldsymbol{\pi}$*10-7 is the permeability of vacuum, and g_1^0, g_1^1, h_1^1 are the first order coefficients of a spherical harmonic model of the main field [Chapman and Bartels, 1940]. As regards the latter, the IGRF13 model [Alken et al., 2021] was chosen.

The evolution of the magnetic moment during the solar cycle 24 is presented in Fig. 2.

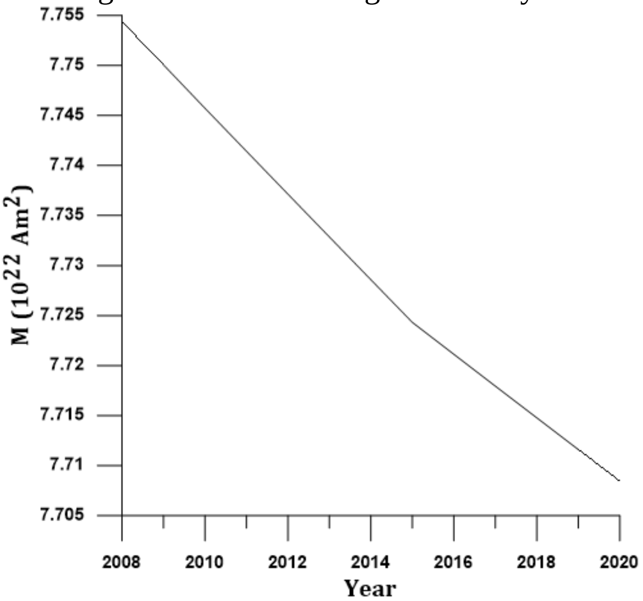

Fig. 2 Intensity of geomagnetic dipole during 2008-2020 (SC 24)

Further, the behavior of this relationship, at the timescale of the solar cycle 24 geomagnetic storms, was treated using a superposed epoch analysis, separately for single and multiple steps storms. The superposed epoch method of analysis was originally proposed by Chree, [1912].

Results

The evolution of the solar wind pressure and the magnetopause stand-off distance during the three geomagnetic storms, chosen as examples, are presented in Fig. 3.

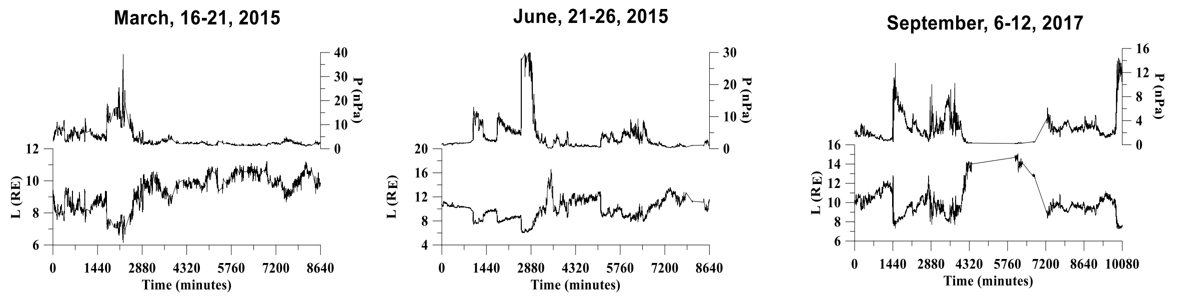

Fig. 3 – Evolution of solar wind pressure P, magnetopause stand-off distance L, in case of March 2015, June 2015, September 2017 geomagnetic storms

The correlation plots between the magnetopause stand-off distance and the solar wind pressure for the three geomagnetic storms are given in Fig. 4.

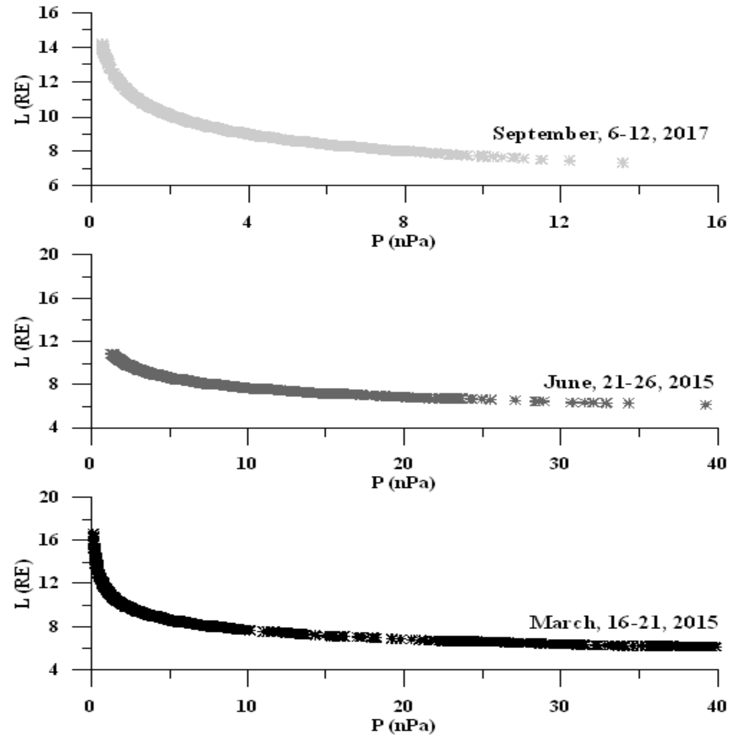

Fig. 4 – Correlation plots between the stand-off distance and the solar wind pressure for the three geomagnetic storms

The results of the superposed epoch analysis are shown in Fig. 5 for simple storms. The upper panel illustrates the evolution of the solar wind dynamic pressure, the middle panel the evolution of the SymH index, and the lower one the evolution of the magnetopause stand-off distance during the selected geomagnetic storms. We superimposed the evolution of the geomagnetic index SYM-H for the 13 selected one-step storms, referring the time of the minimum value of the index as zero time. The minimum value of SYM-H varies between – 234 nT and - 117 nT. At the maximum of the geomagnetic storm (minimum SymH values), L shows values between 6 R_E and 12 R_E. In Fig.5 L curves are standardized against the value at the time of the minimum SymH.

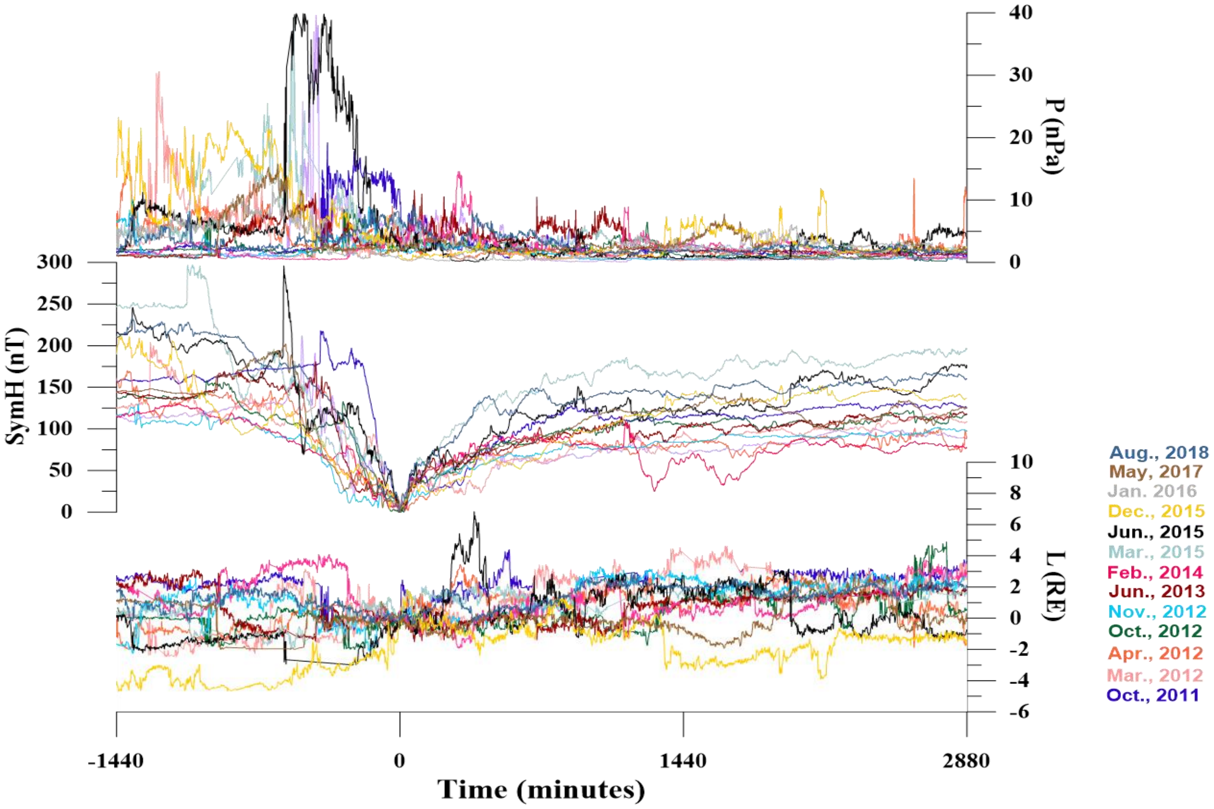

Fig. 5 – Superposed epoch analysis in case of 13 simple geomagnetic storms. The initial time is the time when SymH reached the minimum value.

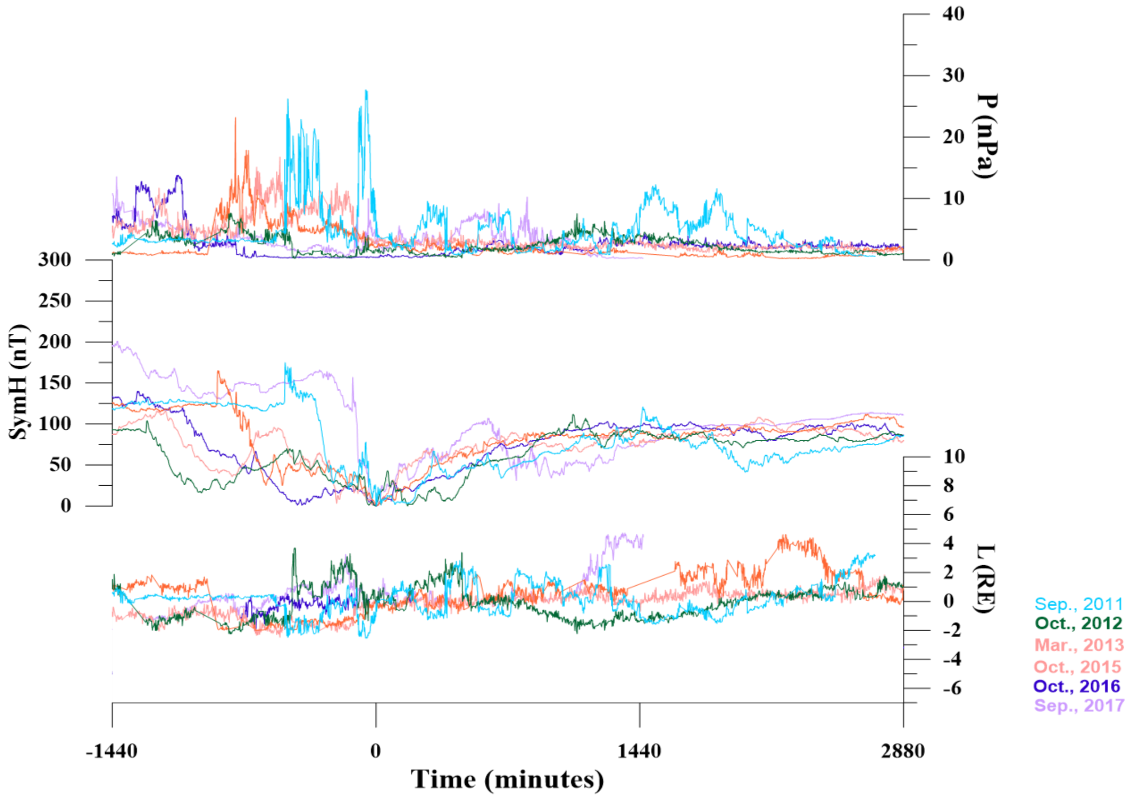

Fig. 6 - Superposed epoch analysis in case of 6 complex geomagnetic storms. The initial time is the time when the SymH reached the minimum value.

The results of the superposed epoch analysis for complex geomagnetic storms (storms with two or more steps morphology) are shown in Fig. 6. Data are organized as in Fig.5. The time of the SymH minimum values was taken as origin, no matter the number of steps of the storm. No particular regularity is observed.

The variation of the magnetosphere stand-off distance during the main phase of the geomagnetic storm has amplitudes between 2 R_E and 6 R_E.

Concluding remarks

The magnetosphere stand-off distances were calculated for moderate and intense geomagnetic storms in solar cycle 24. A similar evolution of the analyzed storms is noted.

An attempt to use the superposed epoch analysis in comparing various storms is done. The main results are: (1) the minimum stand-off distance varies between 6 and 12 R_E, (2) in the case of some storms (e. g. September 2012, August 2011) the stand-off distance can reach values as high as 6-7 R_E, depending on the conditions in the solar wind (very low SW dynamic pressure). The stand-off magnetopause distance variations are much larger than long-term ones are considered [Dobrica at al., 2012, Stefan et al., 2013].

The low values of L indicate times when there is an increased space weather hazard to technical networks (power networks and/or hydrocarbon pipes networks) at the Earth's surface. This subject will be approached in a separate paper.

Table 1 – Geomagnetic storms (SC 24)

Year	Date	Dst (nT)	SymH (nT)
2011	Aug, 06	-115	-126
2011	Sep, 26	-118	-113
2011	Oct, 25	-147	-160
2012	March, 09	-145	-150
2012	Apr, 24	-120	-125
2012	July, 15	-139	-123
2012	Oct, 01	-122	-138
2012	Oct, 09	-107	-116
2012	Nov, 14	-108	-118
2013	March, 17	-132	-132
2013	June, 01	-124	-137
2014	Feb, 19	-119	-127
2015	March, 17	-223	-234
2015	June, 23	-204	-208
2015	Oct, 07	-124	-124
2015	Dec, 20	-155	-170
2016	Jan, 01	-110	-117
2016	Oct, 13	-104	-114
2017	May, 28	-125	-142
2017	Sep, 8	-124	-146
2018	Aug, 26	-174	-206

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