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Geophysical Research Letter

Supporting Information for

The global statistical response of the outer radiation belt during geomagnetic storms

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Introduction

The supporting information here includes a detailed description of the algorithm used to identify the start and end time of geomagnetic storms.

Text S2.

The Van Allen Probes phase space density (PSD) is calculated from the background corrected MagEIS [Claudepierre et al., 2015] and REPT electron fluxes as outlined Boyd et al. [2014]. Overlapping energy channels between MagEIS and REPT are combined using a spline fit. For the MagEIS data, background corrected data from MagEIS-LOW and M75 are included at all times and data from MagEIS-HIGH is only included when the counts are sufficiently high (determined by the estimated error < 60%). There are times when MagEIS is not in the correct mode and background corrected fluxes are not available. During these times the non-background corrected fluxes are used. Typically, in the outer radiation belt the background correction at these energies is small however if the channel was set to 0 because the background was large, the non-corrected fluxes would not be used. Note that REPT rarely reaches the noise floor of the instrument and no threshold is required for the PSD calculation.

When calculating PSD μ and K are determined by the ECT Science Operations Center at 18 pitch angles calculated using TS04D [Tysganenko and Sitnov, 2005]. This provides both μ and K as a function of pitch angle. For K this function is fit to provide K as a continuous function of pitch angle from which data from the combined MagEIS and REPT data product is used to determine the PSD. For use in this paper K logarithmically spaced in 17 equal steps from 0.01-10 $R_E G^{1/2}$; at each point in time the pitch angle corresponding to each K is determined and used to build the PSD spectra. A similar process is done for μ however we note that μ calculated at each time point using the onboard magnetic field measurements from EMFISIS.

Text S3.

Defining the start and end of a geomagnetic storm can pose challenges. There is no obvious signal in Dst alone, and storm dynamics are driven by various processes including those internal to the Earth's magnetosphere, such as unstable ion distributions and substorms, as well as those external to the magnetosphere, such as dynamic or enhanced solar wind conditions. The study described in the paper relies on an algorithm we have developed to determine the start and end times of a geomagnetic storm based on storm-time solar wind and geomagnetic conditions. The algorithm determines a storm start and end time, t_{-1} and t_1 respectively, and an epoch time t_0 with which to perform a statistical analysis of storm time solar wind, geomagnetic and radiation belt conditions. An initial list of storms [Turner et al., 2014] is used to identify periods of interest on which to apply our algorithm. This list identifies storms as times when Sym-H lies below a threshold value of -50 nT from September 2012 to March 2016 (note that this is a slight extension of the list from that used in Turner et al., [2014]). The time of minimum Sym-H t_{Sym-H} during each period of interest is used as a seed time to determine t_{-1}, t_0, and t_1. The algorithm uses solar wind velocity and dynamic pressure and the geomagnetic index Dst to characterize the storm start and end times. Solar wind velocity and dynamic pressure are used to help define periods of enhanced solar wind driving, as they are always positive and have clear enhancements during the storms. The algorithm does not use interplanetary magnetic field (IMF) conditions, as the IMF can fluctuate significantly during storms, and can be both positive and negative, making it difficult to unambiguously determine a clear onset of enhanced IMF conditions. Dst is used to characterize the epoch time of each storm as well as the recovery as it shows a very clear and repeatable signature during storms, an initial decrease followed by a slow recovery. The solar wind and Dst data are obtained from the OMNI database at a 1 hour cadence [King and Papitashvili, 2005].

For each geomagnetic storm we identify a period of interest between $t_{min} = t_{Sym-H} - 2\ days$ and $t_{max} = t_{Sym-H} + 8\ days$. From previous studies it has been shown that the length of the main phase and recovery phase of storms is generally less than 2 and 8 days, respectively [e.g., Hutchinson et al., 2011].

Of the three storm times the simplest to identify is the epoch time t_0. This is defined as the time of minimum Dst between t_{min} and t_{max}.

The start of each geomagnetic storm t_{-1} is identified from solar wind parameters. A peak-finding algorithm is used to identify peaks in solar wind velocity and dynamic pressure above a specific threshold between t_{min} and t_0. The solar wind velocity and dynamic pressure thresholds are 500 km/s and 5.5 nPa respectively and have been defined from previous studies of solar wind conditions during geomagnetic storms [Kataoka and Miyoshi, 2006; Hutchinson et al., 2011]. For both solar wind velocity and dynamic pressure, the earliest peak in the period of interest is identified. We then trace back both quantities in time to the first local minimum before the peak, providing us with two times, the start of enhanced solar wind velocity t_{Vsw} and the start of enhanced solar wind dynamic pressure t_{Pdyn}. The start of the storm t_{-1} is defined as the earliest of these two times.

For some storms, such as those driven by relatively small CMEs, dynamic pressure never peaks above the threshold of 5.5 nPa. For these storms no peaks can be identified to define the start of enhanced dynamic pressure t_{Pdyn}. In these cases, the dynamic pressure threshold is reduced by 0.25 nPa and the peak finding algorithm searches the time series for peaks satisfying the new threshold. This process is repeated until a peak in dynamic pressure is identified and can be traced backward to the start of enhanced dynamic pressure t_{Pdyn}. Note, for the storms studied here a peak is always identified for the 500 km/s threshold, thus this methodology is only applied to the dynamic pressure. Both solar wind velocity and dynamic pressure are used to characterize the start of a storm as enhancements in dynamic pressure can precede enhancements in solar wind velocity during storms, and vice versa. Hence both are required to properly identify the start of enhanced solar wind driving and the start of a geomagnetic storm, regardless of the details of the solar wind event that drives it. In this way we hope to capture all storms, and not just storms of a particular type.

The end of each storm t_1 is defined by the recovery of Dst following the reduction in enhanced solar wind driving. The end of enhanced solar wind driving is defined by monitoring the length of time between successive peaks in solar wind velocity and pressure. We identify peaks in solar wind velocity and dynamic pressure above thresholds of 450 km/s and 3.5 nPa respectively during the period t_0 to t_{max}. Again, these thresholds have been taken from previous studies of the solar wind during geomagnetic storms [Kataoka and Miyoshi, 2006; Hutchinson et al., 2011]. The peaks in solar wind velocity and pressure are combined into a single array and sorted in increasing time. The time difference between concurrent peaks $\Delta t = t_i - t_{i-1}$ is calculated and the end of enhanced solar wind driving is defined when $\Delta t > 1\ day$ and given by $t_{end\ SW} = t_{i-1}$. This method defines the end of solar wind driving when solar wind velocity and dynamic pressure have dropped below enhanced conditions for longer than a day and during which we can expect storm-time solar wind driving to have stopped. The end of enhanced solar wind driving $t_{end\ SW}$ is then used to define the recovery of Dst. The recovery of Dst is defined between $t_{end\,SW} < t_{max}$ as the latest time Dst becomes positive. If Dst is never positive during this interval, then peaks in Dst > -10 nT are identified and the recovery of Dst is defined when $\Delta Dst = Dst_{t_i} - Dst_{t_{i-1}} > 0$ given by $t_{Dst} = t_{i-1}$. This characterizes a time when Dst is no longer increasing or recovering. The end of the storm is then defined by $t_1 = t_{Dst}$ characterizing a period in time when enhanced solar wind driving has stopped and Dst has recovered.

Together these three times, t_{-1}, t_0, and t_1 allow a superposed epoch analysis of storm time solar wind, geomagnetic and radiation belt dynamics to be studied using three independently identified times that allow for storms to have different lengths.

Table S1.

Epoch times of the 73 storms.

t_{-1}	t_0	t_1
2012-09-29/18:00:00	2012-10-01/03:00:00	2012-10-05/08:00:00
2012-10-07/17:00:00	2012-10-08/12:00:00	2012-10-16/04:00:00
2012-10-31/11:00:00	2012-11-01/14:00:00	2012-11-05/13:00:00
2012-11-12/19:00:00	2012-11-14/07:00:00	2012-11-17/06:00:00
2013-01-16/20:00:00	2013-01-17/22:00:00	2013-01-23/00:00:00
2013-01-25/11:00:00	2013-01-26/22:00:00	2013-01-30/03:00:00
2013-02-28/15:00:00	2013-03-01/10:00:00	2013-03-05/21:00:00
2013-03-16/23:00:00	2013-03-17/20:00:00	2013-03-25/09:00:00
2013-04-23/10:00:00	2013-04-24/18:00:00	2013-04-29/11:00:00
2013-04-30/21:00:00	2013-05-01/18:00:00	2013-05-05/14:00:00
2013-05-17/15:00:00	2013-05-18/04:00:00	2013-05-21/22:00:00
2013-05-24/03:00:00	2013-05-25/06:00:00	2013-05-30/17:00:00
2013-05-31/11:00:00	2013-06-01/08:00:00	2013-06-05/12:00:00
2013-06-05/12:00:00	2013-06-07/05:00:00	2013-06-08/22:00:00
2013-06-27/10:00:00	2013-06-29/01:00:00	2013-07-03/17:00:00
2013-07-05/12:00:00	2013-07-06/18:00:00	2013-07-09/15:00:00
2013-07-09/15:00:00	2013-07-10/15:00:00	2013-07-13/10:00:00
2013-07-13/15:00:00	2013-07-14/23:00:00	2013-07-18/06:00:00
2013-08-04/08:00:00	2013-08-05/02:00:00	2013-08-08/18:00:00
2013-08-15/09:00:00	2013-08-16/04:00:00	2013-08-24/01:00:00
2013-08-27/02:00:00	2013-08-27/21:00:00	2013-08-30/10:00:00
2013-09-30/21:00:00	2013-10-02/07:00:00	2013-10-06/08:00:00
2013-10-07/18:00:00	2013-10-09/01:00:00	2013-10-12/16:00:00
2013-10-13/23:00:00	2013-10-15/03:00:00	2013-10-18/20:00:00
2013-10-29/09:00:00	2013-10-30/23:00:00	2013-11-06/03:00:00
2013-11-06/17:00:00	2013-11-07/12:00:00	2013-11-08/11:00:00

2013-11-08/11:00:00	2013-11-09/08:00:00	2013-11-12/13:00:00
2013-12-07/06:00:00	2013-12-08/08:00:00	2013-12-12/12:00:00
2014-02-18/07:00:00	2014-02-19/08:00:00	2014-02-21/21:50:00
2014-02-23/00:00:00	2014-02-23/23:00:00	2014-02-26/22:00:00
2014-02-26/22:00:00	2014-02-27/23:00:00	2014-03-05/13:00:00
2014-04-10/14:00:00	2014-04-12/09:00:00	2014-04-18/06:00:00
2014-04-29/08:00:00	2014-04-30/09:00:00	2014-05-02/01:00:00
2014-05-03/14:00:00	2014-05-04/08:00:00	2014-05-07/11:00:00
2014-05-07/18:00:00	2014-05-08/08:00:00	2014-05-13/01:00:00
2014-06-07/10:00:00	2014-06-08/11:00:00	2014-06-10/06:00:00
2014-08-26/05:00:00	2014-08-27/18:00:00	2014-09-01/17:00:00
2014-09-11/18:00:00	2014-09-12/23:00:00	2014-09-16/14:00:00
2014-10-07/12:00:00	2014-10-09/07:00:00	2014-10-13/05:00:00
2014-10-13/05:00:00	2014-10-14/22:00:00	2014-10-18/10:00:00
2014-10-19/17:00:00	2014-10-20/17:00:00	2014-10-27/15:00:00
2015-01-03/02:00:00	2015-01-04/21:00:00	2015-01-06/03:00:00
2015-01-06/03:00:00	2015-01-07/11:00:00	2015-01-15/01:00:00
2015-01-26/01:00:00	2015-01-26/10:00:00	2015-01-28/23:00:00
2015-01-31/14:00:00	2015-02-02/06:00:00	2015-02-05/06:00:00
2015-02-16/16:00:00	2015-02-18/00:00:00	2015-02-22/15:00:00
2015-02-22/18:00:00	2015-02-24/07:00:00	2015-02-26/23:00:00
2015-02-27/19:00:00	2015-03-01/08:00:00	2015-03-09/06:00:00
2015-03-16/08:00:00	2015-03-17/22:00:00	2015-03-25/18:00:00
2015-04-09/14:00:00	2015-04-10/04:00:00	2015-04-13/06:00:00
2015-04-09/15:00:00	2015-04-11/09:00:00	2015-04-15/03:00:00
2015-04-15/03:00:00	2015-04-16/23:00:00	2015-04-20/17:00:00
2015-05-18/10:00:00	2015-05-19/03:00:00	2015-05-22/19:00:00
2015-06-07/02:00:00	2015-06-08/08:00:00	2015-06-16/04:00:00
2015-06-21/10:00:00	2015-06-23/04:00:00	2015-06-28/18:00:00
2015-07-04/01:00:00	2015-07-05/05:00:00	2015-07-10/13:00:00
2015-07-11/21:00:00	2015-07-13/15:00:00	2015-07-19/02:00:00
2015-07-22/09:00:00	2015-07-23/08:00:00	2015-07-29/05:00:00
2015-07-29/20:00:00	2015-07-31/03:00:00	2015-08-04/19:00:00
2015-08-22/19:00:00	2015-08-23/09:00:00	2015-08-25/01:00:00
2015-09-10/00:00:00	2015-09-11/14:00:00	2015-09-18/02:00:00
2015-09-20/00:00:00	2015-09-20/15:00:00	2015-09-26/02:00:00
2015-10-06/14:00:00	2015-10-07/22:00:00	2015-10-15/21:00:00
2015-11-05/17:00:00	2015-11-07/07:00:00	2015-11-14/22:00:00
2015-12-13/07:00:00	2015-12-14/22:00:00	2015-12-19/11:00:00
2015-12-19/11:00:00	2015-12-20/22:00:00	2015-12-28/11:00:00
2015-12-30/23:00:00	2016-01-01/00:00:00	2016-01-05/03:00:00

2016-01-19/09:00:00	2016-01-20/16:00:00	2016-01-25/20:00:00
2016-02-15/15:00:00	2016-02-16/19:00:00	2016-02-22/07:00:00
2016-03-06/09:00:00	2016-03-06/21:00:00	2016-03-11/12:00:00
2016-03-14/02:00:00	2016-03-15/07:00:00	2016-03-22/23:00:00
2016-04-01/11:00:00	2016-04-02/23:00:00	2016-04-06/16:00:00
2016-04-07/01:00:00	2016-04-08/00:00:00	2016-04-09/20:00:00