RING CURRENT DECAY RATES
DURING THE RECOVERY PHASE OF MAGNETIC STORMS

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Abstract

We study the decay times corresponding to the recovery phase of the 300 most intense magnetic storms which occurred from Jan 1, 1957 to Dec 31, 1998.

A typical value for the decay time ($\tau$) is obtained by averaging the most reliable $\tau$ values that resulted from applying a least square method to the Dst index during each recovery phase.

The Dst index in the decaying stage of the storm has been fitted with exponential functions and a very good correlation has been obtained. Considering 10 hours after the peak of each storm, which corresponds to a minimum of the Dst index, a mean value of $\tau \sim 14 \pm 4$ hours has been found. More than 65% of the cases show correlation coefficients better than 0.9.

The remaining 35% events, probably correspond to cases where there was a non-negligible injection of particles during the recovery phase. The group of storms with poor correlation also includes cases with double (or several times triple) peaks in the storm structure.
1 Introduction

Magnetic storms are characterized by a sudden enhancement in the ring electric current circulating around the Earth. This current is transported by protons, oxygen ions, and electrons (in the 10-300 keV energy range), and it is located between 2 to 7 $R_E$ (see [Gonzalez et al., 1994] and references therein), where $R_E$ is the radius of the Earth.

When the interplanetary magnetic field which encounters the Earth’s bowshock points southward, a reconnection process can take place. As a result, energetic particles coming from the sun as part of the solar wind, enter to the magnetosphere and, after a period of storage, part of these particles are injected into the ring current system. The increase of the ring current produces a magnetic field which opposes to the dipole geomagnetic field.

The Dst index is constructed from measurements of the horizontal component of the magnetic field at low latitudes. Modifications to the ring current produce strong perturbations of the horizontal component of the equatorial magnetic field. Therefore, the Dst index is modified during magnetic storms and it has a direct relationship with the energy stored in the ring current, which is given by (see the review [Gonzalez et al., 1994])

$$\frac{Dst(t)}{B_0} = \frac{2E(t)}{3E_m}$$

Here $B_0$ is the average equatorial surface field, $E(t)$ is the total energy of the ring current, and $E_m$ is the total magnetic energy of the geomagnetic field.

Several effects should be considered to construct a corrected $Dst$ index which provides a better proxy to the energy stored in the ring current. In order to compute this ‘ideal $Dst$ index’, at least five important effects should be considered: (1) the variations in the magnetopause currents, regulated by variations of the solar wind pressure on the external front of the magnetosphere (ram pressure effect) [Burton et al., 1975; Gonzalez et al., 1989]; (2) the induced currents in the solid Earth [Gonzalez et al., 1994]; (3) the variations in the inner magnetospheric tail current system [Alexeev et al., 1996]; (4) the asymmetric ring current or partial ring current [Baumjohann, 1986]; and (5) the substorm current wedge [Baumjohann, 1986].

The temporal variation of the energy in the ring current is related to the injection of charged particles from the magnetotail and also by the energy lost by the circuit. The relationship that expresses the energy balance is given by,

$$\frac{d}{dt}E(t) = U(t) - \frac{E(t)}{\tau}$$

where $U(t)$ is the rate of energy input and $\tau$ is the decay time. A set of 305 geomagnetic storms was studied in [Yokoyama and Kamide, 1997] and the value of $\tau$ was varied from 4 to 12 hours to estimate the energy injection rate. The main losses of energy of the ring current are the following three basic processes: (1) charge exchange, (2) Coulomb scattering, and (3) resonant
interactions with plasmons [Gonzalez et al., 1994]. Each process depends strongly of several properties of the particles (pitch angle, ion energy, composition, and location in the radiation belt). The energy decay time (\( \tau \)) in the ring current is the result of a rather complex combination of all these processes.

The decay time has been studied in several particular storms. For instance in [Burton et al., 1975] a typical value of the order of 7 hours was obtained considering storms in the period of time from 1967 to 1968, which had a \( Dst_{min} < -40 \) nT. Gonzalez et al. [1994] studied several intense storms and the result was a shorter time, of about 0.5-4 hours.

In this paper we statistically study the recovery phase, assuming that during this phase: (1) the energy injection is negligible (i.e., \( U(t) \equiv 0 \)) and (2) the value of \( \tau \) is constant. According to these hypothesis, for any given storm the \( Dst \) index will decay exponentially like

\[
Dst(t) = Dst(t = 0) \exp\left[-t/\tau\right] \tag{3}
\]

where \( t = 0 \) corresponds to the peak of activity (given by \( Dst(t = 0) \)) for this particular storm.

Our statistical study involves 300 recovery phases corresponding to the most intense magnetic storms \( (Dst_{min} < -100 \) nT) which occurred from Jan 1, 1957 to Dec 31, 1998. In the next section we outline the procedure that we adopted for such statistical analysis, and also present the results that we obtained.

\section{Procedure and Results}

We developed a numerical procedure to recognize and fit structures in the \( Dst \) timeseries. These structures correspond to the recovery phases of intense magnetic storms. Thereafter, a storm is considered intense if its peak value \( (Dst_{min}) \) satisfies \( Dst_{min} < -100nT \).

We use the \( Dst \) series with a temporal resolution of one hour. The events on which we concentrate have been selected according to the following scheme. We construct a set of time series, extracted from the original \( Dst \) series according to the following criteria: a) All values in each sub-series are smaller than \( -100nT \), which we set as our threshold value. b) A new sub-series starts when one value of the original \( Dst \) series becomes lower than the threshold and finishes when the \( Dst \) value returns to values above this threshold. We associate each of these sub-series to a single intense magnetic storm. We have identified 300 intense storms following this procedure. For each of these events we select the absolute minimum (the peak of the storm) and also retain the \( Dst \) values within 10 hours after the peak (i.e., the first ten hours of the recovery phase).

Therefore, we have 300 series of 10 elements each, \( Dst_{ij} (i = 1, 2, ..., 10; j = 1, 2, ..., 300) \). We fit each of these events (labeled with \( j \)) with an exponential decay, and obtain the decay time \( \tau_j \) by a standard least-squares procedure.
We thus obtain a list of decay times $\tau_j$ corresponding to each intense storm. In order to estimate the quality of the fit, we calculate the linear correlation index $c_j$ between the natural logarithm of the measured Dst values ($\log(Dst_i)$) and the time ($t_i$).

For the present study, we decided not to include any of the corrections to the original Dst series listed above. For instance, to consider ram pressure effects, interplanetary data are required, but these data are not available for the whole set of events studied in the present paper. Therefore, in order to optimize the statistics, we considered all events present in the raw Dst timeseries, without introducing any corrections.

Figure 1 shows a histogram in which all the events studied were classified according to their lineal correlation ($c_j$). Almost the 80% of the events (i.e., 239 storms) have $c_j < -0.8$ (i.e., the decay of the $-Dst$ index is very similar to an exponential decay). We also find (not shown) that 67% of the events (201 storms) have $|c_j| > 0.9$, and that 56 storms (i.e., 19%) have an excellent correlation, such as $|c_j| > 0.98$. Considering only these 56 best cases, with $c_j < -0.98$, a mean value of $\tau = (13.4 \pm 3.8)$ hours was obtained. The very good agreement with an exponential decay, supports our hypothesis of no significant energy injection during the recovery phase and approximately constant decay time.

We also repeated this fitting procedure, extending it to 30 hours after each peak. The values of $\tau$ thus derived tend to be somewhat larger, and the quality of the fitting to be poorer. For instance, 15% of the events (i.e., 45 storms) show linear correlations better than $c = -0.98$, and the mean decay time for them is $<\tau> = (19.5 \pm 6)$ hours. This larger time might suggest the contribution of more than one particle species within different decay times, but the higher level of noise involved in these more extended fitting do not allow us to reach a firm conclusion in this regard.

Finally, we also fitted the behavior of the first 4 hours after each peak. We obtain 72 cases with $c < -0.98$ (24%), and a mean decay time of $<\tau> = (12.3 \pm 6.4)$ hours. This value is closer to the value obtained by [Burton et al., 1975] of $<\tau> = (7.7 \pm 7)$ hours for a total of 10 events.

From a visual inspection of the 300 cases, we find that most of the poorly correlated cases display double or triple minima, similar to the cases reported by [Kamide et al., 1998] for the main phase. Therefore, it is possible that these cases are associated to multiple interplanetary structures.

Figure 2 shows one typical event that has been fitted with a particulary good correlation. In Figure 3 we show how the average decay time changes as the threshold value for the correlation coefficient is changed. A monotonic increase of the average decay time is observed as the requirements for the fitting quality are relaxed (i.e., the threshold for $|c|$ is lowered). This trend indicates that those events that cannot cleanly be fitted by exponentials, display recovery phases which are rather extended in time, perhaps connected to the presence of a sustained source of injection or perhaps due to the combination of multiple decay times.

The number of intense storms versus their intensities (minimum Dst reached) displays a
power law as shown in Figure 4. By a least square fit we find that

$$n(I) = AI^\gamma$$

with $A = 6.4 \times 10^8$ and $\gamma = -3.37$.

3 Conclusions

In the present paper we derive average decay times for the recovery phase of the most intense magnetic storms, from statistical analysis of the $Dst$ timeseries between 1957 and 1998.

The average values of $\tau$ obtained in this paper tend to be larger than those reported in previous studies [Burton et al., 1975; Gonzalez et al., 1989]. The e-folding time characterizing the recovery phase of geomagnetic storms are $\tau \sim (13 \pm 4)$ hours, as arises from a statistical analysis of the 300 most intense storms that occurred between 1957 through 1998. Among those events displaying a poor correlation, several cases with two or three secondary peaks were observed. A detailed study of these multiple structures together with theoretical studies of the relevant energy losses (charge exchange, Coulomb scattering, and resonant interactions with plasma waves) might contribute to a better understanding of the physical processes operating during the recovery phase of a magnetic storm.

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References


Figure Captions

Figure 1: A histogram showing the distribution of events with their linear correlation coefficient \((c)\), for the fit between \(\log(-Dst)\) vs. time. All magnetic storms larger than \(Dst = -100\) nT occurred from Ene 1, 1957 to Dec 31, 1998 are displayed.

Figure 2: The \(Dst\) index corresponding to the first 10 hours of the recovery phase of the storm that occurred at 22:00 UT on March 8, 1970.

Figure 3: Average value of the decay time considering all events with correlation better than \(c\).

Figure 4: A least-square fit of the number of storms versus their \(Dst\) peak value.
Average decay time vs. correlation coefficient threshold
300 most Intense Magnetic Storms from Jan 1, 1957 to Dec 31, 1998

Number of cases

Correlation Coefficient between log(-Dst) and time