Ring current decay rates of magnetic storms: A statistical study from 1957 to 1998

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[1] We perform a statistical study of the decay times for the recovery phase of the 300 most intense magnetic storms that occurred from 1 January 1957 to 31 December 1998. The *Dst* index in the decaying stage has been fitted by an exponential function, and a very good correlation has been obtained for most of the storms. Statistically representative values for the decay time (τ) are obtained by averaging the most reliable τ values, which resulted from applying a least squares method to the *Dst* index time series during every recovery phase. The mean value of τ turned out to be $\sim$14 ± 4 hours. We have also found that for very intense storms ($Dst_{min} < -250$ nT) the values of τ tend to decrease as the intensity of the storm increases. *INDEX TERMS:* 2778 Magnetospheric Physics: Ring current; 2788 Magnetospheric Physics: Storms and substorms; 2716 Magnetospheric Physics: Energetic particles, precipitating; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2708 Magnetospheric Physics: Current systems (2409); *KEYWORDS:* decay time, recovery phase, ring current, intense magnetic storm, *Dst* index

1. Introduction

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

[3] The magnetic field of the Earth is essentially a dipole, whose field lines are born in the Southern Hemisphere and run northward to reenter the Earth at the Northern Hemisphere. Therefore, when the interplanetary magnetic field reaches the Earth's bow shock with a southward orientation, a reconnection process can take place. Magnetic reconnection is the topological change of oppositely directed magnetic structures being pushed to one another, which allows for the mixing of the ensuing flows. As a result, energetic particles coming from the Sun as part of the solar wind, are free to enter the magnetosphere and, after a period of storage, some of these particles are injected into the ring current system. However, ionospheric particles also contribute to the ring current and can even become the dominant source during the main phase of major magnetic storms.

[4] The ring current induces a magnetic field, which opposes the dipole geomagnetic field at the Earth's surface. The ring current index *Dst* was introduced as a measure of the ring current magnetic field. The present *Dst* index is calculated from measurements of the horizontal (H) component of the magnetic field recorded at several low-latitude observatories (at ground level) and represents the global H component of the geomagnetic field. However, it should be noted that other sources contribute to the *Dst* index besides the ring current, such as the magnetopause current or a substorm current wedge [*Akasofu*, 1981].

[5] However, the main variations of the *Dst* index during magnetic storms are found to display a direct relationship with the energy stored in the ring current, which is given by [*Dessler and Parker*, 1959; *Sckopke*, 1966]

$$Dst(t)/B_0 = 2E(t)/(3E_m). \tag{1}$$

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. To compare the measured *Dst* index with the theoretical prediction given in equation (1), at least five important effects should be considered: (1) variations in the magnetopause currents driven by variations of the solar wind pressure on the external front of the magnetosphere (the so-called ram pressure effect) [*Burton et al.*, 1975; *Gonzalez et al.*, 1989], (2) induced currents in the solid Earth [*Stern*, 1984, and references therein; *Gonzalez et al.*, 1994, and references therein], (3) variations in the inner magnetospheric tail current system [*Alexeev et al.*, 1996; *Turner et al.*, 2000], (4) an asymmetric ring current or partial ring current [*Baumjohann*, 1986], and (5) a substorm current wedge [*Akasofu*, 1981; *Baumjohann*, 1986].

[6] The temporal variation of the ring current energy is related to the injection of charged particles from the magnetotail and also to the energy lost by the circuit. A simple relationship describing this energy balance is given by

$$\frac{d}{dt}E(t) = U(t) - E(t)/\tau, \tag{2}$$

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where $U(t)$ is the rate of energy input and τ is the decay time. The main energy losses of the ring current are given by the following processes: (1) charge exchange, (2) Coulomb scattering, (3) resonant interactions with plasma waves [*Gonzalez et al.*, 1994], and (4) flow-out ions [*Reiff et al.*, 1981; *Stern*, 1977]. Each of these processes depend rather strongly on several properties of the particles, such as their pitch angle, ion energy, composition, and location in the radiation belt. While at an early stage during the recovery phase, flow out at the dayside magnetopause is the dominant loss process [*Takahashi et al.*, 1990; *Ebihara and Ejiri*, 1998; *Liemohn et al.*, 1999], charge exchange becomes dominant at later stages [*Daglis et al.*, 1999]. The energy decay time (τ) in the ring current is therefore the final result of a rather complex combination of all these effects.

[7] One of the first estimates for the ring current decay time (τ) was reported by *Burton et al.* [1975], where a typical value of τ of the order of 7 hours (with a rather large uncertainty) was obtained. This estimate corresponds to storms with intensity thresholds given by $Dst_{\min} < -40$ nT. *Burton et al.* [1975] corrected the *Dst* index by ram pressure effects. However, their study was restricted to just seven storms, which took place during 1967 and 1968.

[8] Various authors have analyzed decay times for the ring current system (e.g., [*Feldstein*, 1992; *Gonzalez et al.*, 1989; *MacMahon and Gonzalez*, 1997]). In particular in the study by *Pudovkin et al.* [1985], where 13 magnetic storms with -120 nT $< Dst_{\min} < -50$ nT were considered, values between 7 and 17 hours were obtained for the decay times during the recovery phase. Also, using a combined model which considers the injection of energy during the main phase, values for the recovery phase of $\tau \sim 3-7$ hours were obtained for two intense storms [*Gonzalez and Gonzalez*, 1998]. A summary of previous studies of decay times can be found in the review by *Feldstein* [1992], which shows the large dispersion among the estimates found by different authors. More recently, several authors have studied the influence of the solar wind conditions on the ring current [*O'Brien and McPherron*, 2000; *Valdivia et al.*, 1996; *Klimas et al.*, 1997; *Fenrich and Luhmann*, 1998; *Vassiliadis et al.*, 1999]. More specifically, *O'Brien and McPherron* [2000] propose that the dawn-to-dusk electric field ($E = -VB_z$) controls the position of the ring current edge, which in turn changes the charge exchange rate because of the radial dependence of the density of neutral particles. As a result of this process and using data from the OMNI database, these authors derive an empirical dependence of the decay rate with the dawn-to-dusk electric field.

[9] Within this general framework we decided to perform a statistical study of the recovery phase for a large number of intense geomagnetic storms. Our statistical study involves 300 recovery phases corresponding to the most intense magnetic storms ($Dst_{\min} < -100$ nT) that occurred from 1 January 1957 to 31 December 1998. With this goal in mind we made the following working hypotheses: (1) once the decay phase starts, energy injection is negligible (i.e., $U(t) \cong 0$), (2) the value of τ is constant, and (3) the *Dst* index represents the magnetic perturbations induced by the activity of the ring current system. According to these hypotheses, for any given storm the *Dst* index will decay exponentially like

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

where $t = 0$ corresponds to the peak of activity (i.e., where *Dst* reaches its minimum).

[10] Although we are aware that the working hypotheses listed above are probably too simplistic for some events, they allow us to use the same techniques for the whole data set. On the other hand, we want to stress that from our results a large fraction of the storms studied are consistent with these three assumptions. For those events that cannot accurately be fitted by an exponential decay, probable causes are the following: (1) nonnegligible injection during the decay phase, (2) nonconstant decay time, which might be either a function of *Dst* or an explicit function of time, and (3) corrections for ram pressure effects and other sources of magnetic fluctuations not originated in the ring current.

[11] In the section 2 we outline the procedure that we adopted for our statistical analysis. The main results are presented in section 3. Interplanetary data are analyzed in section 4 to test our hypotheses, and in section 5 we list our conclusions.

2. Fitting Procedure

[12] A numerical procedure to identify intense magnetic storms (according to the classification of [*Gonzalez et al.*, 1989], i.e., $Dst_{\min} < -100$ nT) and to fit their decay times was developed. The time coverage for the present study extends from 1 January 1957, to 31 December 1998. We use the *Dst* series with a time resolution of 1 hour, which was obtained from the National Oceanic Atmospheric Administration National Geophysical Data Center (NOAA NGDC) Solar Terrestrial Physics Division data sets (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/DST/).

[13] We define the starting time ($t_{s,i}$) of each storm (labeled with the index *i*), at the time in which the value of *Dst* during the main phase crosses below a threshold defined as $Dst^* = -100$ nT. In a similar way, during the recovery phase we define the final time of an intense storm ($t_{f,i}$) when the *Dst* value crosses again Dst^* returning the time series to normal conditions. The *Dst* peak for every event ($Dst_{\min,i}$) is the minimum *Dst* value in the time interval $t_{s,i} \le t \le t_{f,i}$. We define $t_{M,i}$ as the time corresponding to the peak value. In this way we construct subseries, each of them containing the *Dst* data for each intense event analyzed here, which from 1957 to 1998 yielded a total of 300 subseries.

[14] We consider the 10 *Dst* values after Dst_{min} (including $Dst_{\min}$), which correspond to the first 10 hours of the recovery phase. That is to say, we obtain 300 new subseries with 10 elements, Dst_{ij} ($i = 1, 2, \ldots, 300$; $j = 1, 2, \ldots, N = 10$). The decay time is estimated by fitting the value of τ_i for each of the 300 recovery phases, assuming an exponential decay according to equation (3). These τ_i are computed using a standard least squares linear procedure (see below). When the exponential decay assumption is correct (i.e., $U \sim 0$ and *Dst* represents the perturbation only due to the ring current energy), our procedure provides an estimate of τ_i, which is better than the method based in the substraction of two consecutive values of *Dst* (i.e., $\tau(t) = \Delta t/\log\,[Dst(t)/Dst(t + \Delta t)]$) [e.g., *Burton et al.*, 1975].

[15] Figure 1 shows one example corresponding to the intense magnetic storm that occurred on 13 September 1957. This storm started at 0400 UT and had its peak value ($Dst_{\min} = -427$ nT) at 1000 UT. After this peak the data returned to values larger than Dst^* between 0100 and 0200 UT on the day after. The asterisks in Figure 1 correspond to the measured values, while the solid line shows the fitted exponential decay. The estimated decay time for this particular event is $\tau = 9.6$ hours.

[16] From a visual inspection of the set of 300 events we find that more than 50% are in good agreement with an exponential decay, similar to the behavior shown in Figure 1. In general, the decay time tends to increase as we increase the time interval considered for the fitting procedure. This behavior is consistent with measurements of two-phase decays (as was observed in the intense magnetic storm of February 1986), i.e., an early rapid decay followed by a much slower stage of the decay phase [*Kozyra et al.*, 1998]. This two-phase scenario is consistent with storms where the weakening of the convective electric field induces a transition from a flow-out (small τ) to a charge exchange (larger τ) regime.

[17] For the remaining storms we observe a systematic difference with respect to the fitted curve. We speculate that almost 50% of the storms studied probably receive a significant energy input during the first 10 hours of their recovery phase ($U \neq 0$). In

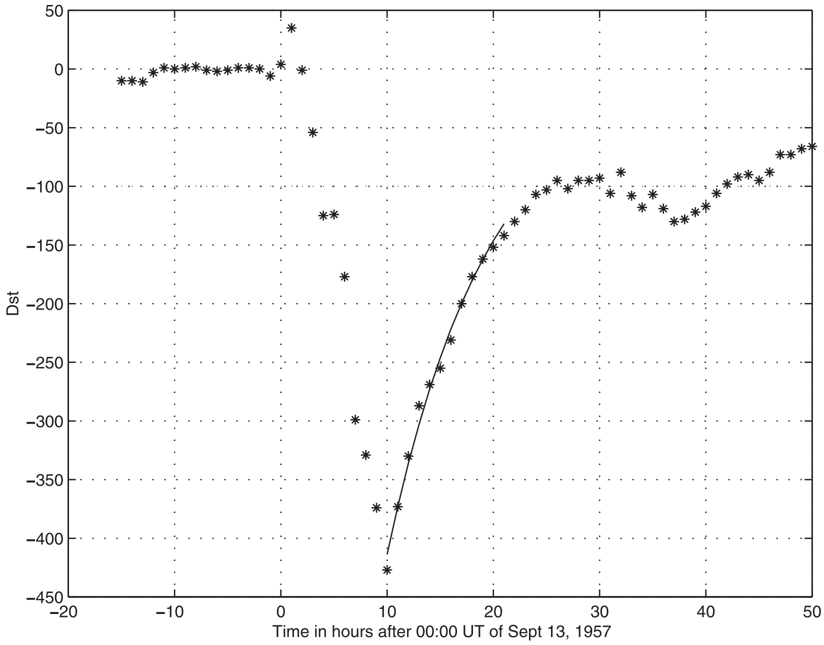

Figure 1. Asterisks indicate the values of the *Dst* index during the storm that occurred on 13 September 1957.

particular, additional peaks during the recovery phases were visually and significantly observed in ~30% of the cases (similar to the peaks reported by [*Kamide et al.*, 1998]). These multiple peaks could be associated with multiple magnetic structures having several regions with negative B_z inside the CME, which produce spiky energy injection as was observed in the magnetic cloud of 18–20 October 1995 studied by *Farrugia et al.* [1998]. Because of the complexity involved, we do not consider these storms in our study.

[18] Below we describe the standard linear least squares method that we used. We assume a linear dependence between $y = \log(-\mathrm{Dst})$ and the time t elapsed from $t_{M,i}$ (i.e., $y = A - t/\tau$, according to equation (3)). The fitting method is carried out in two successive steps. In a first step a fit is done for every storm (i) without considering errors in the measured *Dst* values. The result of this procedure is a first-order estimate for the decay time ($\tau_{1,\,i}$) as well as for A ($A_{1,\,i}$). Then, using the original series Dst_{ij}, $\tau_{1,i}$, and $A_{1,i}$, we compute $\Delta D_{ij} = |Dst_{ij} + \exp(A_{1,i})\exp(-t_j/\tau_{1,i})|$, which gives an estimate of the uncertainty in every measured value. In a second step we use the new series ΔD_{ij} and perform a second least squares fit considering uncertainties for Dst_{ij}. Therefore we obtain a better estimate for τ_i and its uncertainty $\Delta\tau_i$ from the following expressions:

$$\tau_i = \frac{\Delta_i}{\sum_j \omega_{ij} t_j \sum_j \omega_{ij} y_{ij} - \sum_j \omega_{ij} \sum_j \omega_{ij} y_{ij} t_j} \quad (4)$$

$$\Delta\tau_i = \left[\frac{\sum_j \omega_{ij}}{\Delta_i}\right]^{1/2} \tau_i^2, \quad (5)$$

where

$$t_i = (1, 2, \ldots, 10), \quad (6)$$

$$y_{ij} = \log\left(-\mathrm{Dst}_{ij}\right), \quad (7)$$

$$\omega_{ij} = \left(Dst_{ij} / \Delta D_{ij}\right)^2, \quad (8)$$

$$\Delta_i = \sum_j \omega_{ij} \sum_j \omega_{ij} t_j^2 - \left(\sum_j \omega_{ij} t_j\right)^2. \quad (9)$$

3. Statistical Results for a Period of 42 Years

[19] In Figure 2 we show a histogram of the number of intense magnetic storms for different linear cross-correlation coefficients (r_i), computed for variables y_j and t_j. The recovery phases displaying a small cross-correlation value correspond to events that do not follow at least one of our working hypotheses. On the other hand, whenever $r \sim -1$, the effects mentioned in the introduction are negligible, and our working hypotheses seem therefore appropriate.

[20] From Figure 2 we find that 200 intense storms (~67% of the events studied) have $|r| > 0.9$. Also, almost 80% of the events (i.e., 239 storms) have $|r| > 0.8$, and 77 storms (i.e., 26%) display an excellent correlation, such as $|r| > 0.97$. Considering only these 77 cases, we have obtained a mean value for the decay time, $\tau = 14.0$ hours, with a standard deviation of $\sigma_\tau = 4.0$ hours. From a visual inspection of the 300 cases we may assert 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 with multiple interplanetary structures.

[21] Figure 3 shows the τ_i values (with their error bars) obtained for the 200 events with $r < -0.9$. Asterisks in Figure 3 correspond to very intense storms, $Dst_{\min} < -200$ nT (44 events), while dots mark the rest of the events. We find that when the value of r becomes close to -1, the values of τ_i do not converge to a unique number. Quite the contrary, they spread a rather wide range between 6 and 23 hours. This is mostly evident when we consider $r < -0.97$. Notice that the error bars in Figure 3 are significantly lower (~0.1–1 hours in most of the cases shown) than the above mentioned standard deviation. This result indicates that the decay time characterizing the recovery phase of any given storm is an intrinsic property of that particular event, rather than a universal constant which is common to all of them. The relatively large dispersion of values of τ might be an indication of the different solar wind conditions for different storms.

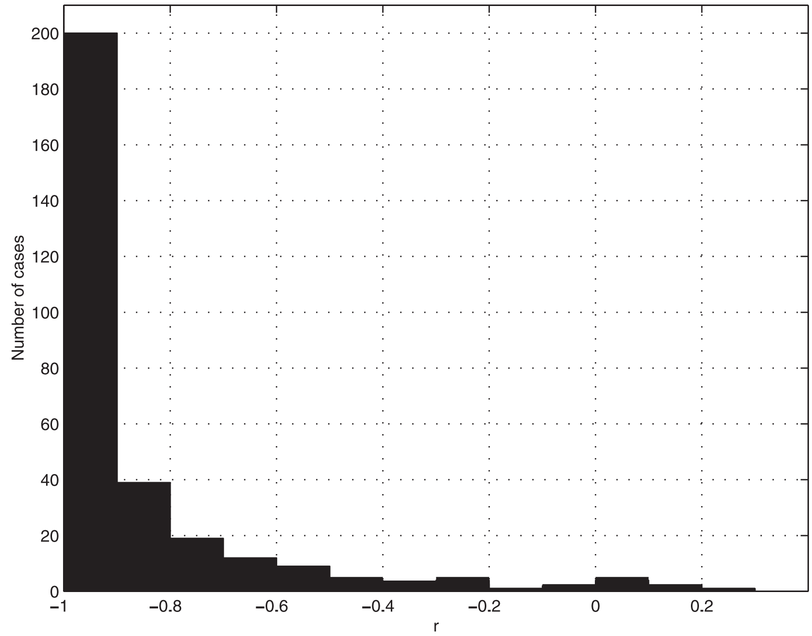

Figure 2. Histogram shows the distribution of events according to their linear correlation coefficient (r) between $\log(-Dst)$ versus time. All magnetic storms with $Dst_{\min} \leq -100$ nT, from 1 January 1957 to 31 December 1998, are displayed.

[22] The solid line in Figure 3 shows the partial average decay time as we change the value of r (i.e., all data with values lower than r are averaged). For fitting qualities worse than $r \sim -0.97$, a monotonic increase of this partial average time is observed as the quality requirements are relaxed (i.e., as the threshold for $|r|$ is reduced). 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. However, this curve also indicates that this spurious trend is negligible for quality fits better than $r \sim -0.97$.

[23] The histogram shown in Figure 4 considers all the storms with $r < -0.97$, i.e., those events whose decay times can be reliably described by an exponential decay. These are 77 events, which are over 25% of the storms analyzed in this paper. The histogram bars classify the storms according to their decay time. Overlayed to the histogram bars we also show (solid line) the result of a moving average smoothing procedure with a very narrow bin size. This average is performed by the convolution of the histogram counts with a triangular function with a base of 4.2 hours. This smoothed curve displays three peaks, a main peak at ~13 hours and two secondary peaks at ~9.5 and 20 hours. This result

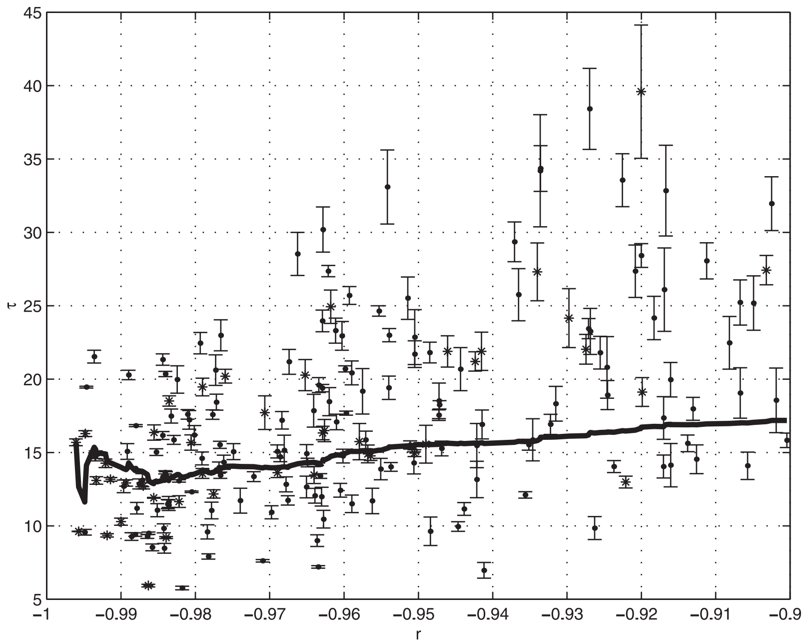

Figure 3. Decay time as a function of the fitting quality. The solid line indicates the partial average decay time for storms with quality better than r (see text). The asterisks correspond to storms with $Dst_{\min} < -200$ nT.

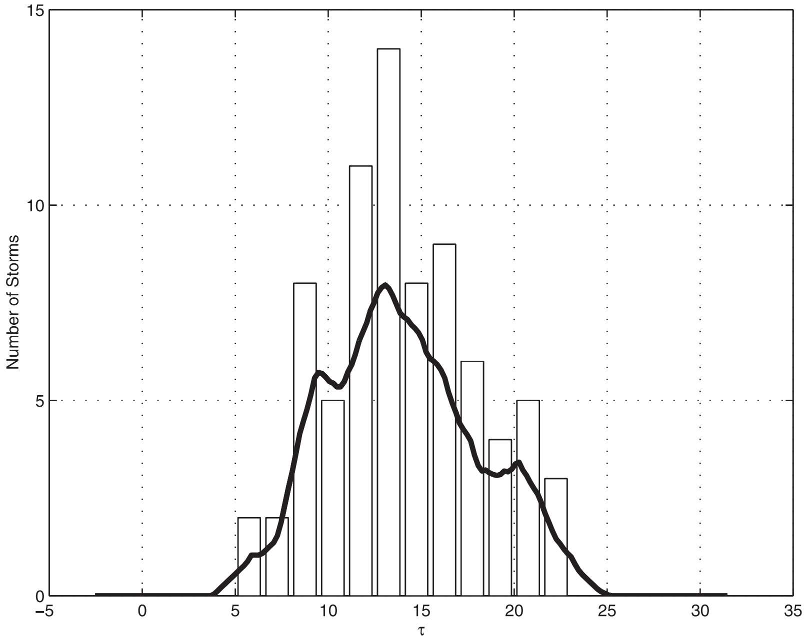

Figure 4. Histogram of the number of storms versus the decay time. The thick line shows an average of the histogram with a triangular weight function (see text).

tentatively suggests the existence of three groups of storms, characterized by different decay times. Different decay times might be caused by solar wind conditions in the terrestrial environment [*O'Brien and McPherron*, 2000] or by a combination of different levels of energies and/or populations of O+ and H+ at different altitudes [*Smith and Bewtra*, 1978].

[24] Asterisks shown in Figure 5a represent the values of τ as a function of their intensity (i.e., $Dst_{\min}$) for very intense storms ($Dst_{min} < -250$ nT) displaying high cross correlation (i.e., $r < -0.97$). Note that τ decreases with the intensity of the storm. We perform a least squares fit, $\tau = aDst_{min} + b$, to characterize this trend and obtained $a = 0.0370$ hours/nT and $b = 27.45$ hours (shown in Figure 5a as a solid line). The lifetime of ions due to the charge exchange process goes like the inverse of their velocities [*Daglis et al.*, 1999] and the abundance (absolute and relative) of oxygen ions (O^+) increases during the occurrence of intense storms [*Daglis*, 1997]. Therefore we suggest that the trend discussed above might correspond to a combination of a higher- energy level and a higher abundance of O^+ in the ring current. An alternative explanation might be along the lines

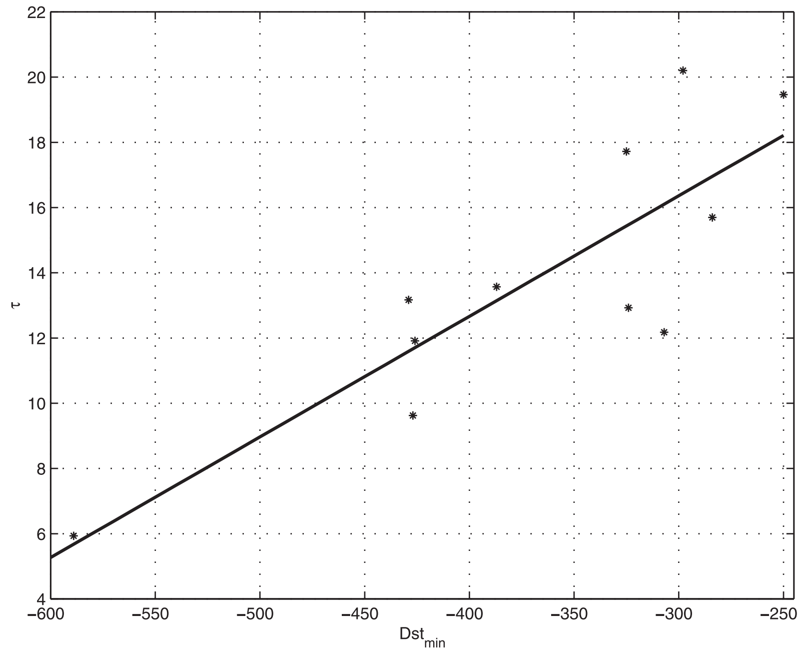

Figure 5a. Decay time as a function of the intensity of the storm for $r < -0.97$ and for very intense storms ($Dst_{\min} < -250$ nT).

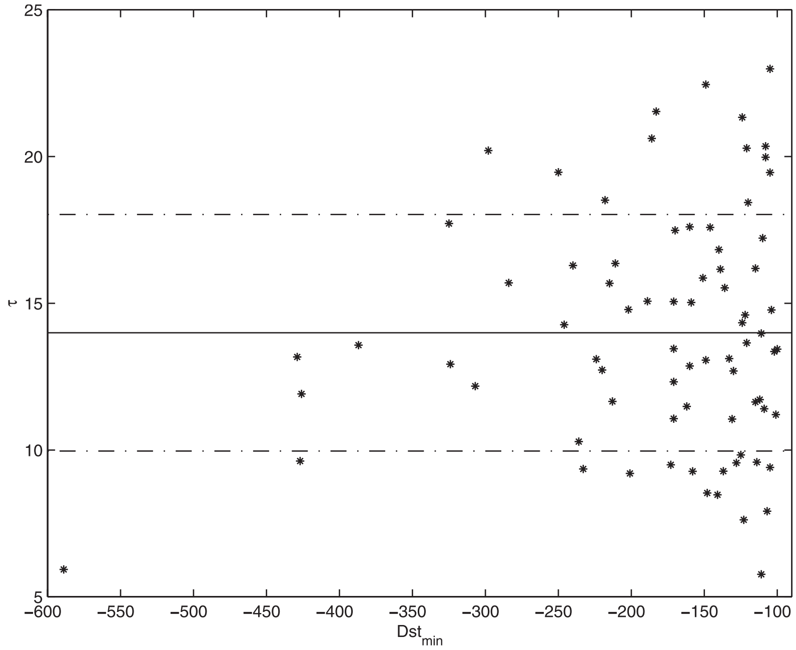

Figure 5b. Same as Figure 5a, but for intense storms ($Dst_{\min} < -100$ nT). The solid line (dashed-dotted) corresponds to the mean value (standard deviation).

described by [*O'Brien and McPherron*, 2000], since they obtain functional dependences of τ and Q versus *VBs* (the convective electric field) that are consistent with a positive correlation between τ and $Dst_{\min}$. Figure 5b shows the decay time for all storms with $r < -0.97$. The mean value of τ and its standard deviation are also plotted in this figure as solid and dashed-dotted lines, respectively. Events with intensities lower than those shown in Figure 5a, do not show a clear trend, probably owing to the contribution of other loss mechanisms.

[25] We have also repeated this fitting procedure extending it to 30 hours after $Dst_{\min}$, but in these more extended fits the level of noise involved is higher. The values of τ thus derived tend to be somewhat larger, and the quality of the fit turns out to be poorer. For instance, 18% of the events (i.e., 55 storms) show linear correlations better than $r = -0.97$, and the mean decay time for them is $\langle\tau\rangle = (24.0 \pm 4.2)$ hours. If we only consider the first 4 hours after each peak, we obtain 99 cases with $r < -0.97$ (33%), and a mean decay time of $\langle\tau\rangle = (13.1 \pm 7.2)$ hours.

[26] In order to analyze the temporal variation of τ during the same event, we compare the value of τ fitting the first 10 hours of the recovery phase (for storms with $r < -0.97$) with a second value obtained by fitting the next 10 hours (i.e., 11–20 hours after the peak value). We find that in most cases the second value of τ was larger, consistent with observations of two stages during the recovery phase, an early fast stage followed by a slower stage [*Kozyra et al.*, 1998]. A similar result is obtained if the recovery phase is divided into two subphases, each of 5 hours of duration. These results suggest that the assumption of constant τ during the recovery phase is probably too simplistic.

[27] Several authors have recently shown that during the early phase, the ring current is mainly composed by open drift paths [e.g., *Liemohn et al.*, 1999; *Ebihara and Ejiri*, 1998]. However, during the later stage of the recovery phase the ring current system losses its energy mainly by charge exchange. One of the first quantitative estimations of the flow-out effect was made by *Takahashi et al.* [1990]. These authors found that flow-out phenomena and charge exchange might produce two-step recovery phases, as our results indicate. Furthermore, as suggested by *O'Brien and McPherron* [2000], the slow increase of the parameter τ might be explained through the dependence of τ with a time-decreasing convective electric field (*VBs*) as the decay phase progresses.

4. Solar Wind Influence on Recovery Phases

[28] In the present section we use solar wind data to analyze the role of ram pressure and energy injection during the recovery phase of events. Note that the solar wind data are not available for a substantial fraction of the events considered in the present study. For instance, while in the period 1964–1990, 140 intense magnetic storms have occurred, the OMNI database only contains 14 storms with simultaneous measurements of solar wind variables inside a period of 10 hours around the peak of each storm.

[29] In order to analyze the influence of the solar wind conditions on the decay time of the recovery phase, we select (from our data set ranging from January 1957 to December 1998) the subset of intense magnetic storms that occurred in the same period of time that the spacecraft Wind was operative. Thus we choose a set S composed by all the events with $r < -0.97$ (i.e., events with good fitting quality, see section 3), occurred from November 1994 to December 1998. Solar wind data were downloaded from the Wind database (http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/) for this set of storms.

[30] We correct the *Dst* index for ram pressure effect by using $Dst^* = Dst - 7.26P^{1/2} + 11$ nT [*O'Brien and McPherron*, 2000]. We find that for most cases (78%) the correction is virtually negligible, since the values of τ when we use Dst^* depart less than 40 min from the original prediction. For the remaining cases (22%) the corrections are marginally appreciable, since the changes introduced in τ by this effect are smaller than the obtained standard deviation of 4 hours (see section 3). Furthermore we note that, when present, these corrections contribute to either larger or smaller values of τ, as reported by *O'Brien and McPherron* [2000]. As a result, ram pressure corrections do not produce significant deviations from the statistical results of the previous section. Figure 6 shows the uncorrected and the corrected index for two storms, which are respectively representative of cases where Dst^* is essentially equal to Dst for the whole recovery phase

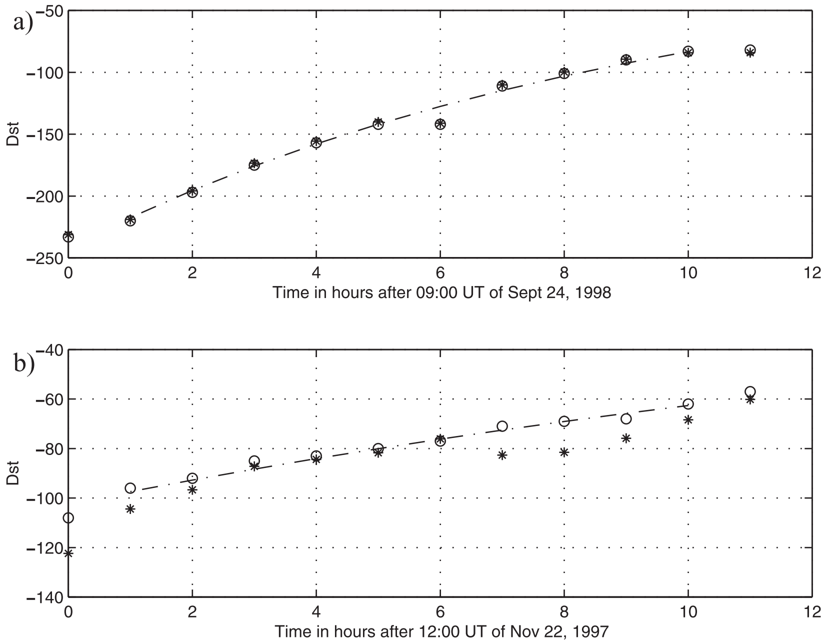

Figure 6. Ram pressure effect on the cases studied. Asterisks represent the corrected *Dst* values considering the ram pressure. Circles show the measured *Dst* values, and the line (dashed-dotted) corresponds to a pure recovery phase with a decay time equal to the fitted τ value. The upper panel (a) is representative of cases where *Dst** is essentially equal to *Dst* for the whole recovery phase. The lower panel (b) corresponds to cases where the ram pressure effect produces nonnegligible corrections.

(Figure 6a) and cases where the ram pressure effect produces nonnegligible corrections (Figure 6b).

[31] Another working hypothesis that we have used for the present analysis was to neglect the energy injection (Q) during the recovery phase. From equation (1) and equation (2) (see introduction), the dynamical evolution of *Dst* can be modeled by

$$\frac{d}{dt}Dst(t) = Q(t) - Dst(t)/\tau. \tag{10}$$

[32] We estimate Q from interplanetary data measured by Wind (for the set S). We use the recent model by *O'Brien and McPherron* [2000], according to which $Q = a'(-VB_z - Ec)$ for $Bz < -Ec/V < 0$, with $Ec = 0.49$ mV/m and $a' = -4.4$; and $Q = 0$ otherwise. From equation (10), injection effects are nonnegligible whenever $|Q| \gtrsim |Dst/\tau|$. To quantify the cases where Q is negligible, we integrate equation (10) numerically and estimate the deviation of the observed *Dst* respect to the solution of equation (10), $\widehat{D}(t) = D_0 \exp[-t/\tau] + \int dt'\, Q(t) \exp[-(t - t')/\tau)]$; i.e., we estimate $\epsilon = \frac{\widehat{D}(t) - D_0 \exp[-t/\tau]}{D_0 \exp[-t/\tau]}$, where D_0 is the observed peak value of the storm.

[33] The mean value of ϵ is smaller than 0.01 in almost 50% of the events in set S and remains smaller than 0.15 for the whole set. Furthermore, we note that in those cases where $\langle\epsilon\rangle$ is not negligible, the most important contribution occurs only during the final stage of the recovery phase. Therefore, in these cases our fitted value of τ is only slightly affected.

5. Conclusions

[34] We have performed a statistical analysis of the decay times for the 300 recovery phases corresponding to the most intense magnetic storms that occurred from 1 January 1957 to 31 December 1998. We have fitted the *Dst* index during the first 10 hours of the recovery phase with an exponential function. We have found a very good correlation for $\sim$25% of the cases, with a mean value for the decay time of $\tau \sim 14 \pm 4$ hours. For storms reaching a minimum value of *Dst* lower than -250 nT the results of our study show a trend toward a decrease of τ with increasing storm intensity. We have also found that τ tends to increase as the recovery phase of a given storm progresses.

[35] For very intense storms ($Dst_{\min} < -250$ nT) the values of τ decrease with the intensity of the storm. This can be interpreted through the following: (1) an increase of the energies and abundances of protons and oxygen ions or (2) the functional dependencies of the decay time and energy injection rate with the convective electric field. However, this trend is not clear for storms with lower intensities.

[36] In summary, the simple scenario of an exponential decay to describe the recovery phase seems appropriate for $\sim$50% of the storms studied (a total of 300). However, it is also apparent that geomagnetic storms are rather complex phenomena, because (a) 50% of the storms cannot be described by this scenario and (b) for those that can be considered as exponentially decaying, the associated decay time is different for different storms, spanning a range from $\sim$6 to 23 hours and also does not seem to remain constant in time as the recovery phase progresses. Notwithstanding, we believe that the average value of $\tau \sim 14 \pm 4$ hours can be regarded as a useful observational prediction for future data analysis and theoretical modeling.

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References

Akasofu, S. I., Energy coupling between the solar wind and the magnetosphere, *Space Sci. Rev.*, *28*, 121–190, 1981.

Alexeev, I. I., E. S. Belenkaya, V. V. Kalegaev, Y. I. Feldstein, and A. Grafe, Magnetic storms and magnetotail currents, *J. Geophys. Res.*, *101*, 7737–77,417, 1996.

Baumjohann, W., Merits and limitations of the use of geomagnetic indices in Solar Wind-Magnetosphere coupling studies, in *Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 3–15, Terra Sci., Tokyo, 1986.

Burton, R. K., R. L. McPherron, and C. T. Russell, An empirical relationship between interplanetary conditions and *Dst*, *J. Geophys. Res.*, *80*, 4204–4214, 1975.

Daglis, I. A., The role of magnetosphere-ionosphere coupling in magnetic storm dynamics, in *Magnetic Storms, Geophys. Monogr. Ser.*, vol. 98, edited by B. T. Tsurutani et al., pp. 107–116, AGU, Washington, DC, 1997.

Daglis, I. A., R. M. Thorne, W. Baumjohann, and S. Orsini, The terrestrial ring current: Origin, formation, and decay, *Rev. Geophys.*, *37*, 407–438, 1999.

Dessler, A. J., and E. N. Parker, Hydromagnetic theory of geomagnetic storms, *J. Geophys. Res.*, *64*, 2239–2252, 1959.

Ebihara, Y., and M. Ejiri, Modeling of solar wind control of the ring current buildup: A case study of the magnetic storms in April 1997, *Geophys. Res. Lett.*, *25*, 3751–3754, 1998.

Farrugia, C. J., et al., Geoeffectiveness of three Wind magnetic clouds: A comparative study, *J. Geophys. Res.*, *103*, 17,261–17,278, 1998.

Feldstein, Y. I., Modelling of the magnetic field of magnetospheric ring current as a function of interplanetary medium parameters, *Space Sci. Rev.*, *59*, 83–165, 1992.

Fenrich, F. R., and J. G. Luhmann, Geomagnetic response to magnetic clouds of different polarity, *Geophys. Res. Lett.*, *25*(15), 2999–3002, 1998.

Gonzalez, A. L., and W. D. Gonzalez, Analytical study of the energy rate balance equation for the magnetospheric storm-ring current, *Ann. Geophys.*, *16*, 1445–1454, 1998.

Gonzalez, W. D., B. T. Tsurutani, A. L. C. Gonzalez, E. J. Smith, F. Tang, and S. Akasofu, Solar wind-magnetosphere coupling during intense magnetic storms, *J. Geophys. Res.*, *94*, 8835–8851, 1989.

Gonzalez, W. D., J. A. Joselyn, Y. Kamide, H. W. Kroehl, G. Rostoker, B. T. Tsurutani, and V. M. Vasyliunas, What is a geomagnetic storm?, *J. Geophys. Res.*, *99*, 5771–5792, 1994.

Kamide, Y., N. Yokoyama, W. Gonzalez, B. T. Tsurutani, I. A. Daglis, A. Brekke, and S. Masuda, Two-step development of geomagnetic storms, *J. Geophys. Res.*, *103*, 6917–6921, 1998.

Klimas, A. J., D. Vassiliadis, and D. N. Baker, Data-derived analogues of the magnetospheric dynamics, *J. Geophys. Res.*, *102*, 26,993–27,009, 1997.

Kozyra, J. U., M. C. Foc, E. R. Sanchez, D. S. Evans, D. C. Hamilton, and A. F. Nagy, The role of precipitation losses in producing the rapid early recovery phase of the Great Magnetic Storm of February 1986, *J. Geophys. Res.*, *103*, 6801–66,814, 1998.

Liemohn, M. W., J. U. Kozyra, V. K. Jordanova, G. V. Khazanov, M. F. Thomsen, and T. E. Cayton, Analysis of early phase ring current recovery mechanisms during geomagnetic storms, *Geophys. Res. Lett.*, *26*, 2845–2848, 1999.

Mac-Mahon, R. M., and W. D. Gonzalez, Energetics during the main phase of geomagnetic superstorms, *J. Geophys. Res.*, *102*, 14,199–14,207, 1997.

O'Brien, T. P., and R. L. McPherron, An empirical phase space analysis of ring current dynamics: Solar wind control of injection and decay, *J. Geophys. Res.*, *105*, 7707–7719, 2000.

Pudovkin, M. I., A. Zaitseva, and L. Z. Sizova, Growth rate and decay of magnetospheric ring current, *Planet. Space Sci.*, *33*, 1097–1102, 1985.

Reiff, P. H., R. W. Spiro, and T. W. Hill, Dependence of polar cap potential drop on interplanetary parameters, *J. Geophys. Res.*, *86*, 7639–7648, 1981.

Sckopke, N., A General Relation between the Energy of Trapped Particles and the Disturbance Field near the Earth, *J. Geophys. Res.*, *71*, 3125–3130, 1966.

Smith, P. H., and N. K. Bewtra, charge exchange lifetimes for ring current ions, *Space Sci. Rev.*, *22*, 301–318, 1978.

Stern, D. P., Large-scale electric fields in the Earth's magnetosphere, *Rev. Geophys.*, *15*, 156–194, 1977.

Stern, D. P., Energetics of the magnetosphere, *Space Sci. Rev.*, *39*, 193–213, 1984.

Takahashi, S., T. Iyemori, and M. Takeda, A simulation of the storm-time ring current, *Planet. Space Sci.*, *38*, 1133–1141, 1990.

Turner, N. E., D. N. Baker, T. I. Pulkkinen, and R. L. McPherron, Evaluation of the tail current contribution to *Dst*, *J. Geophys. Res.*, *105*, 5431–5439, 2000.

Valdivia, J. A., A. S. Sharma, and K. Papadopoulos, Prediction of magnetic storms by nonlinear models, *Geophys. Res. Lett.*, *23*(21), 2899–2902, 1996.

Vassiliadis, D., A. J. Klimas, J. A. Valdivia, and D. N. Baker, The Dst geomagnetic response as a function of storm phase and amplitude and the solar wind electric field, *J. Geophys. Res.*, *104*, 24,957–24,976, 1999.

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