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Decay rate of recovery phase of Geomagnetic Storms and dissipation of associated Ring Currents

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ABSTRACT. Decay rates of the recovery phases of some 130 geomagnetic storms recorded at Alibag during the period 1924 to 1959, classified as great, are investigated with a view to ascertain (1) the precise relation between amplitude of depression of the main phase and the rate of decay of the recovery phase of storm, (2) the possibility of more than one ring current being associated with each storm and (3) the solar-cycle variation in the decay rate of the recovery phase.

Decay times are determined for the first 36 hours of the recovery phase by fitting an exponential curve and finding the time constant for the amplitude of the fitted curve to decay to $1/e$ of the initial amplitude. As a second method, free-hand smooth curves are drawn best fitting the 36-hourly depressions and picking up the time for the initial amplitudes, given by the fitted curve, to decay to 1/2 its initial value. The recovery phase appears to have two distinct portions, an initial portion of less than 12 hours with a rapid decay rate and a later portion with a slower decay rate, suggesting the possibility of two ring currents being associated with each storm. Decay rates for the two portions of the recovery phase are separately investigated by the method of free-hand smooth curves.

The generally known characteristic that decay rates are faster for the larger intensity storms is seen, but considerable scatter in decay rates is observed for any storm-intensity group. The scatter is less for decay rates of the initial portion of the recovery phase. There is a clear tendency, especially for storms of more than 200γ main-phase depression, for decay rates to be faster for the solar minimum epoch than for the maximum epoch. But the relative rates are far from the factor 3 expected by Dessler *et al.* This factor is, however, approached if extreme values of recovery rates of the initial portion of the recovery phase only are considered. For the later portions of the recovery phase no significant differences in decay rates are observed for the two solar epochs. Currents of the order of 10^6 amperes are associated with the inner ring current which is considered large enough to produce shielding effects on the outer ring current field. The main phase depression appears, therefore, to be largely the effect of the inner ring current, especially for the large intensity storms.

1. Introduction

Geomagnetic storms are believed to be caused by solar plasma interacting with the magnetosphere and eventually forming a ring current to encircle the earth (Chapman and Ferraro 1931, 1932, 1933, Alfven 1955, Chapman and Bartels 1940). In the case of the sudden commencement geomagnetic storm, its different distinct phases in the element H, *viz.*, the initial (positive) phase, the main (negative) phase and the recovery phase, correspond respectively to the initial pressure of the solar plasma on the magnetosphere, the westward-directed ring current formed by the plasma and the dissipation of plasma energy with time. The concept of solar plasma being trapped in the geomagnetic field and then producing the ring current responsible for the main phase of geomagnetic storms, was put forward by Singer (1957). With the discovery of the inner and outer terrestrial radiation belts by Van Allen *et al.* (1958), this concept has been generally accepted and applied with advantage to the formation of ring currents responsible for geomagnetic storm (Dessler *et al.* 1961). The main phase of the storm is attributed to drifts in longitude of solar plasma trapped in the geomagnetic field, the drift being normal to the field line as well as to its gradient. As the trapped charged particles oscillate between mirror points along field lines, they also drift in longitude with a velocity roughly proportional to their energy and inversely proportional to their cyclotron frequency and the radius of curvature of the point on the field line occupied by the particular charged particle. Experimentally too, it has been shown that radiation trapped in the geomagnetic field does in fact produce field disturbances akin to geomagnetic storms, though on a much smaller scale. The Argus experiments of August-September 1958 (Christofilos 1959) and the Johnston Island experiment of 9 July 1962, may be mentioned here. The location of ring currents associated with the former events were too distant to produce any noticeable storm-type effects, though however, they produced auroral effects at the conjugate points of the field lines where the bursts occurred. But the experiment of 9 July 1962 did produce worldwide changes in the geomagnetic field much akin to geomagnetic storms though on a very much reduced scale (Pisharoty 1962, Shirgaokar, *et al.* 1963).

Dissipation of energy of the trapped charged particles forming the ring current naturally means a weakening of the strength of the ring current formed by them and as a consequence the lessening with time of the depression in the geomagnetic field, H (the recovery phase). Dissipation of energy of the trapped radiation (charged particles) sets in mainly in two ways. First, the pitch-angles of the charged particles being reduced by the process of random collisions and as a consequence the charged particles are dumped along field lines into the denser atmosphere and thus their energy getting absorbed (Christofilos 1959). Secondly energy is lost by the process of charge exchange with low energy neutral particles (Dessler and Parker 1959). It is easy to see that for both the processes the rate of energy dissipation will largely depend on the density of the outer atmosphere where the ring current is formed. In addition, the rate of energy dissipation will also depend on the number density of the trapped charges as well as on their energy since a greater number density should be deemed to take a longer time to lose their integrated energy and also the greater the initial energy of the charges the longer should be the time required for their ultimate dissipation. But the number density of the charges and their energy together determine the extent to which the original solar plasma penetrates into the magnetosphere (Obayashi and Hakura 1960, Chapman 1960), this being dependent on the equality of particle pressure of the solar plasma and the geomagnetic field pressure. Thus ultimately the rate of energy dissipation is mainly dependent upon the distance of the ring current from the earth's surface, dissipation being rapid if it is formed in the lower and denser part of the outer atmosphere and gradual when formed in the rarer distant part.

That ring currents associated with the main phase of geomagnetic storms are formed in the outer atmosphere at varying distances from the earth may be inferred with the results from Explorer 12 (Cahill and Amazeen 1962). It is also known that with greater intensity of the main phase of storms, auroral phenomena occur at very much lower latitudes than the usual region of about 67° geomagnetic latitude. One good example of such an incident is the one associated with the main phase of the storm of 11 February 1958, when aurora was observed at geomagnetic latitude of about + 23° (Belon and Clark 1959). The greatest of such events is perhaps the one that occurred on 4 February 1872 with a very great storm of that day, when aurora was seen even at Bombay, 10° geomag. lat. (Rao 1964). If the formation of aurora is taken to be due to dumping of energetic charged particles of the ring current on the lower ionosphere, along field lines, then the equatorial distances of the lower fringe of the ring current from the earth's surface in 11 February 1958 event and in the 4 February 1872 event work out to only about 1200 km and 600 km respectively Akasofu and Chapman (1963) have given several evidences during the IGY, of low latitude auroras associated with great storms. They have shown that the minimum latitude attained by auroral phenomena is related to Dst (H) decrease. These are clear evidences that ring currents are formed at varying distances from the earth's surface, and also that the radial distance of the ring current tends to decrease with increasing intensity of storm. This tendency has also been indicated by Forbush (1963), according to whom, geocentric altitude of the ring current decreased by one earth radius for an increase of 100γ in the ring current field produced at the earth's surface.

From what has been said above about ring currents and geomagnetic storm main phases it is to be expected that much useful information regarding the formation of ring currents and their decay can be gathered by a study of the main and recovery phases of geomagnetic storms. It is with this view that the present study was commenced. Yacob (1963) in a preliminary note connected with this study indicated the possibility of two preferred regions for the formation of ring currents associated with geomagnetic storms and that there was a tendency for dissipation time of ring currents to be larger during years of high sunspot numbers than during years of low sunspot numbers. Akasofu, Chapman and Venkatesan (1963) examining several magnetic storms at Honolulu, find that the recovery phase is composed of two portions, an initial portion with rapid decay and a later portion with a much slower decay. It is supposed that there are two ring current belts with one closer to the earth and the other further away. The closer one, being located in comparatively denser atmosphere, dissipates more rapidly than the distant one. According to Vestine (1963) evidence is to be had for the presence of three ring currents R_1, R_2 and R_3 with maximum particle flux at equatorial heights of 1·6, 3·5 and 2 to 8 earth radii respectively. The ring current R_3 is said to be the main one responsible for most of the main phase intensity. But R_3 is conceived capable of being directly formed within the confines of R_1 and R_2 or driven to these confines by crossed electric and magnetic fields. An interesting concept put forward by Dessler *et al.* (1961), is that the solar plasma interacting with the magnetosphere is not capable of producing effective ring currents to account for the intensity of the main phase of storms. According to them the hydromagnetic waves generated at the interface of the solar plasma and magnetosphere serve to energise the trapped radiation in the Van Allen belts and that these energised radiation that form the ring current responsible for the main phase of geomagnetic storms. Similar views have also been put forward by Kern (1962).

It is abundantly clear that ideas about ring currents are still in a fluid state, with plenty of scope for speculation based on observational and theoretical evidences. In this paper the recovery phases of 130 geomagnetic storms recorded at Alibag during the period 1924 to 1959, classified as great are examined for (*a*) any precise relationship between rate of decay and the intensity of the main phase, (*b*) the possibility of more than one ring current being associated with storms, and (*c*) any solar cycle variation in the decay rate of the recovery phase of storm . The list of geomagnetic storms is given in Table 1.

2. Rate of Decay and Main-Phase Intensity

For each storm the storm-time hourly values in H are freed from the corresponding mean quiet-day hourly values (mean of five quiet days of the month in which the storm occurred), to give the hourly disturbance magnitudes. The largest hourly difference (negative) thus obtained marks the minimum epoch of the main phase of the storm. With this hour as the beginning which hereafter may be called 0^h recovery-phase time, 36 consecutive hourly depressions in H are considered for analysis in two different ways. One is to fit an exponential curve of the form Ae^{-bt}, where A is the amplitude of the fitted curve, and t is recovery-phase time. The time required for the initial amplitude, A, to decay to A/e is given by $1/b$ which is evaluated for each storm recovery phase. The second way is to draw a free-hand smooth curve best fitting the 36 recovery-phase-time depressions in H. The depression in H as given by this smooth curve at 0^h recovery-phase time is taken as the initial amplitude,

TABLE 1

List of geomagnetic storms taken for analysis of decay times of recovery phases

R is the annual mean relative sunspot number

S. No.	Year	Month	Day	U.T. of beginning	*R*
1	1924	May	21	0558	17
2		Jun	9	1906	17
3	1925	May	3	1523	44
4		Sep	21	0217	44
5		Dec	27	1445	44
6	1926	Jan	26	1700	64
7		Feb	23	1625	64
8		Mar	5	1004	64
9		Apr	14	1401	64
10		Jun	1	1106	64
11		Sep	14	0848	64
12		Oct	13	1924	64
13	1927	Jan	7	1025	69
14		Apr	13	2349	69
15		May	7	0300	69
16		Jul	21	2105	69
17		Aug	19	1321	69
18		Aug	29	0002	69
19		Oct	12	1019	69
20	1928	Mar	11	0337	78
21		May	27	1448	78
22		Jul	7	2311	78
23		Aug	25	2236	78
24		Sep	7	1348	78
25		Oct	24	0557	78
26	1929	Feb	26	1924	65
27		Mar	11	1355	65
28		Mar	15	0833	65
29		Jul	14	1632	65
30		Jul	31	2106	65
31		Aug	14	1230	65
32		Oct	7	0913	65
33		Nov	2	2018	65
34		Dec	21	2358	65
35	1930	Mar	11	1130	36
36		Jun	16	0412	36
37		Sep	18	0850	36
38		Oct	17	0530	36
39		Oct	25	1504	36
40		Nov	13	1930	36
41		Dec	3	0108	36
42	1932	Oct	14	1748	11
43	1933	Apr	30	1628	6
44		Sep	8	2124	6
45	1934	Jul	30	0319	9
46	1935	Jul	7	2106	36
47		Oct	24	0642	36
48	1936	Jul	2	0448	80
49		Oct	31	0126	80
50		Nov	28	2336	80
51	1937	Mar	5	0728	114
52		Aug	22	0308	114
53		Sep	30	1346	114
54		Oct	9	0636	114
55		Dec	23	0810	114
56	1938	Jan	16	2232	110
57		Jan	22	0242	110
58		Jan	25	1150	110
59		Apr	16	0545	110
60		May	11	1531	110
61		Jul	15	0314	110
62		Oct	7	0613	110
63	1939	Apr	17	0157	89
64		Apr	24	1737	89
65		Jun	13	1647	89
66		Aug	12	0142	89
67	1940	Mar	24	1350	68
68		Jun	25	0254	68

TABLE 1 (*contd*)

S. No.	Year	Month	Day	U. T. of beginning	*R*
69	1941	Mar	1	0358	47
70		Jul	5	0459	47
71		Sep	18	0414	47
72		Oct	31	0342	47
73		Dec	1	0600	47
74	1942	Apr	4	0438	31
75	1944	Apr	2	0410	10
76		Dec	16	0346	10
77		Dec	26	1022	10
78	1945	Dec	13	1238	33
79	1946	Jan	3	0806	93
80		Mar	28	0635	93
81		Jul	26	1845	93
82		Sep	21	1711	93
83	1947	Feb	16	0259	152
84		Apr	17	1224	152
85		Jul	17	1748	152
86		Aug	15	0950	152
87		Aug	22	0910	152
88		Sep	2	2324	152
89	1948	Mar	15	0334	136
90	1949	Jan	24	1827	135
91		Mar	21	2127	135
92		Apr	7	1049	135
93		May	12	0640	135
94		Oct	13	2011	135
95		Nov	18	1150	135
96	1950	Jan	23	0700	84
97		Feb	19	2340	84
98		Mar	19	0544	84
99		Aug	19	1006	84

TABLE 1 (*contd*)

S. No.	Year	Month	Day	U.T. of beginning	*R*
100	1951	Oct	28	1153	69
101	1952	Jan	27	0400	31
102		Apr	21	1150	31
103		Jun	29	1931	31
104	1953	Jan	5	0546	14
105	1955	Oct	25	0200	38
106	1956	Feb	25	0306	142
107		Mar	2	2342	142
108		Apr	26	2111	142
109		May	16	0417	142
110		Sep	8	1006	142
111		Nov	14	0200	142
112	1957	Jan	21	1255	190
113		Mar	10	0022	190
114		Jun	30	0528	190
115		Sep	13	0046	190
116		Sep	29	0016	190
117		Nov	6	2350	190
118	1958	Feb	11	0650	185
119		Jul	8	1318	185
120		Sep	3	1412	185
121		Oct	28	1221	185
122		Dec	4	0604	185
123	1959	Mar	26	0842	155
124		Apr	9	1826	155
125		Apr	23	1036	155
126		May	11	2329	155
127		Jul	15	0803	155
128		Jul	17	1638	155
129		Nov	27	2351	155
130		Dec	5	0659	155

A, and the time for this amplitude to decay to half its value is picked up from the smooth trend of the fitted curve. It should be mentioned here that the fitted curves (exponential and free-hand smooth curves) did not closely fit the 36-hourly depressions in *H*. The maximum depressions given by the fitted curves were often much less than the maximum depressions of the main phases. The fitted curves, however, indicated the average trends of decay of the recovery phase as a whole (36 hours) and the decay rates are studied against maximum amplitude of depression in *H* at 0^h recovery-phase time (hereafter referred to simply as amplitude) as given by the fitted curves. For each method of investigation the decay times obtained are plotted against the amplitude. Such a plot for all the storms are shown in Fig. 1, for the second method of investigation (smooth curve fitting the 36-hourly depressions). Plot for the first method is not shown, since the distribution of points are more or less the same.

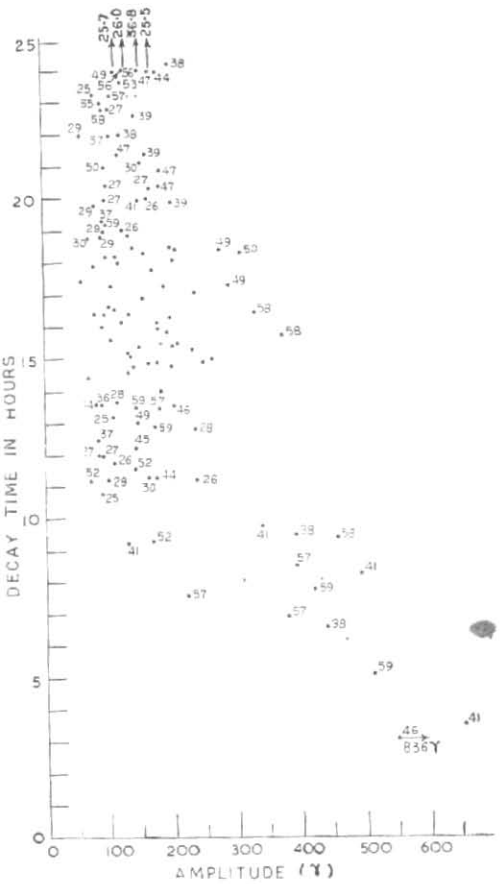
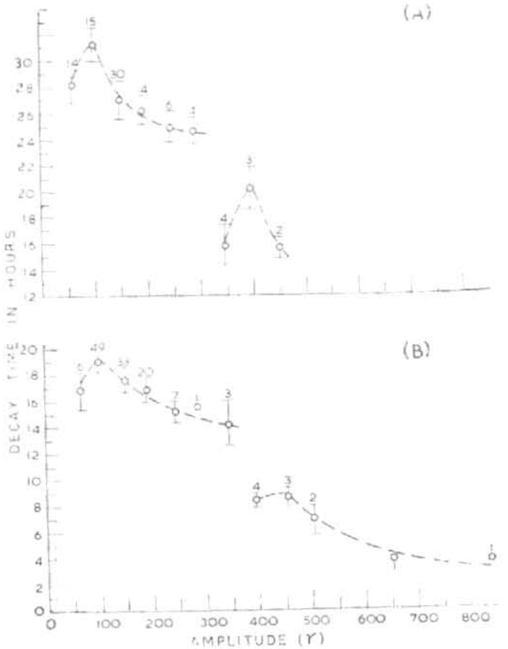
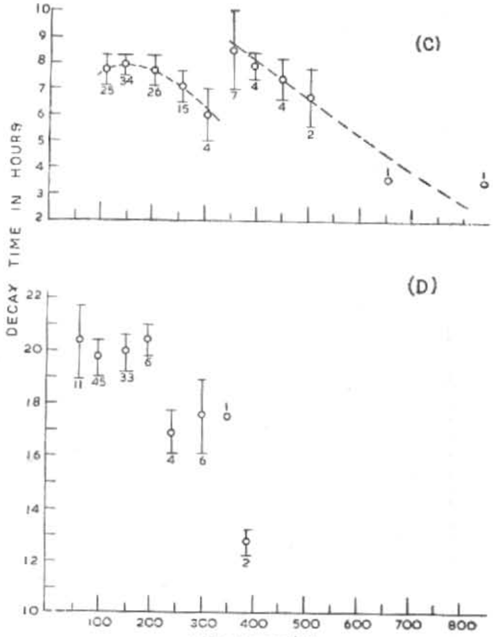


Fig. 1. Plot of decay time for amplitude of free-hand smooth curve, fitted to 36-hourly depressions in H of the recovery phase, to decay to half the value, against initial amplitude (at 0^h recovery-phase-time). The years in which particular storms occurred has been indicated for extreme points



Figs. 2 (A, B). Plot of mean decay times against mean amplitudes for different 50γ-interval class-groups of amplitudes of curves fitted to 36-hourly depressions in H of the recovery phase. (A) is for the case of exponential curves fitted to recovery phases and (B) is for the case of free-hand smooth curves fitted to recovery phases. No. of storms falling into each class-group has been indicated

The scatter of points in Fig. 1 is very considerable and it is almost impossible to make out any systematic relationship between amplitudes A (which are taken to represent the intensities of the main phases of the different storms), and the decay times, except for a very broad trend for decay time to decrease with increasing amplitude. In order to have a closer examination of this trend the amplitudes were grouped into classes of 50γ intervals as follows : < 75, 75-125, 125-175, ……. For each class group the mean amplitude and the mean decay time were computed for both the methods of investigation, and shown plotted in Figs. 2A and 2B. In each figure the standard error of the mean decay time for the mean amplitude of each class group has been indicated. Best possible smooth curves are drawn through the plots in Figs. 2A and 2B. No reasonably smooth curve can be drawn through all the points in either figure. But two smooth curves can easily connect groups of points in each figure, which show the tendency for decay times to decrease with increasing intensity of storms.



Figs. 2 (C, D). Plot of decay times against mean amplitudes for different 50γ interval class-groups of amplitudes of free-hand smooth curves fitted to the earlier portion of the recovery phase (C) and to the later portion of the recovery phase (D). No. of storms falling into each class-group has been indicated

In each of the Figs. 2A and 2B one smooth curve connects the points up to 300-350γ amplitudes while another from about 350-400γ upwards. In each of these portions an initial bulge of increased decay time is seen and thereafter a fairly systematic decrease of decay time with increasing amplitude is in evidence. The bulges of increased decay times occur at about the amplitudes of 100γ and 350γ in both figures, corresponding approximately to main phase maximum depressions of 150γ and 450γ respectively. Their significance is not clear, apart from the indication of two regions in the outer atmosphere where the ring currents take a little more time to decay when formed in these particular regions than when they are formed in adjacent regions. What appears to be significant in Figs. 2A and 2B is the discontinuity in the curve of mean amplitude *vs* decay time when the amplitude increases beyond about 300-350γ, *i.e.*, roughly when the maximum main phase depression increases beyond about 450γ. This naturally leads to the inference that possibly there are two preferred regions for the formation of ring currents responsible for the main phase of geomagnetic storms and that one region is characterised by high values of dissipation time and the other by low values and it was so inferred in a preliminary note connected with this investigation (Yacob 1963). But it is felt that the discontinuity noticed in Figs. 2A and 2B is a consequence of the particular methods of investigation employed in picking up recovery times for amplitudes to decay to certain fractions (A/e and $A/2$) of the initial amplitude. If the recovery phase is made up of an initial portion of high rate of recovery and a later one of a slower rate, the chances are that, for greater intensity storms, the fraction of the amplitude decided upon may occur within the portion of high rate of recovery, thus giving small recovery time for such storms. In fact even a casual inspection of the recovery phases of geomagnetic storms shows that they do have two clear portions with distinctly different rates of decay, a higher rate of decay for the initial part and a much lower rate for the later part. This aspect of the recovery phase will be examined in the next section.

3. Possibility of more than one Ring Current associated with the Main-Phase

While drawing free-hand smooth curves through the first 36 recovery-phase-time hourly depressions in H, it was definitely noticed that, for each storm, the decay was very rapid for the initial portion (less than 12 hours)

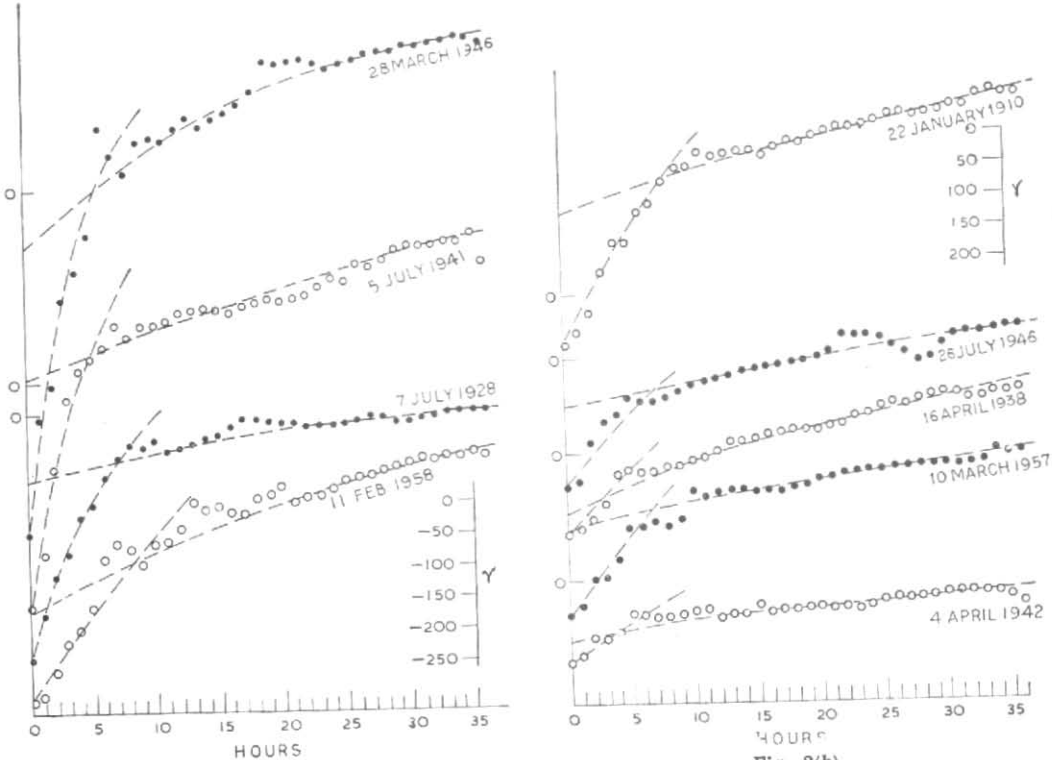


Fig. 3(a) Fig. 3(b)

Figs. 3(a) and 3(b). Recovery phases of some geomagnetic storms. The hourly points are depressions in H. The dashed curves indicate the two clear trends in the decay rate of the recovery phase. The rate for the earlier portion of the recovery phase is much more rapid than that for the later portion

and gradual for the later portion of the recovery phase. Some examples of such trends are shown in Figs. 3(a) and 3(b). There is a clear possibility that these two portions are due to two ring currents. In order to investigate the decay trends of the two portions of the recovery phase separately one freehand smooth curve was drawn best fitting the initial portion and another fitting the later portion. In these cases good fitting curves could be drawn, unless the recovery was very disturbed. As before, the time required for the amplitude A to decay to half its value was picked up for each portion. The smooth curve through the later portion of the recovery phase was produced backwards, following the smooth trend, so that its amplitude of depression A at 0^h recovery-phase-time could be evaluated. The plot of amplitudes at 0^h recovery-phase-time *vs* decay times (to reach half initial amplitude) is shown in Fig. 4, for the initial portion of recovery-phase and that for the later portion in Fig. 5.

An examination of Figs. 4 and 5 shows that decay times for the earlier portion of the recovery phase are on an average half of those for the later portion. The amplitudes of depression A are much greater for the initial portion than the later portion, being about double those of the later portion. These characteristics show that the earlier portion of the recovery-phase is the result of a ring current close to the earth, while the later portion is associated with one, more distant from the earth. The ring current

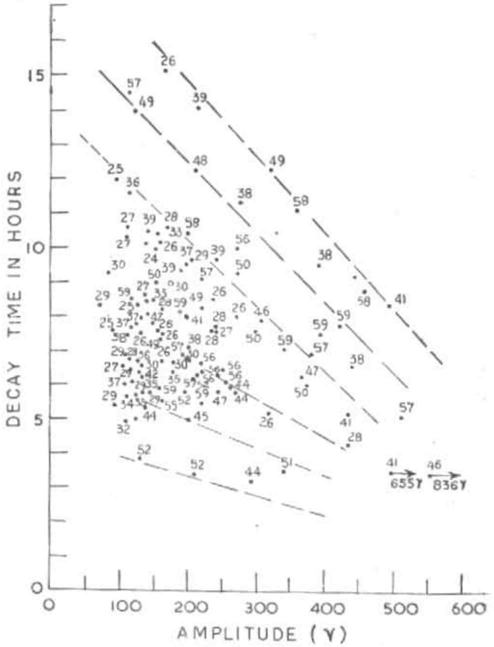


Fig. 4

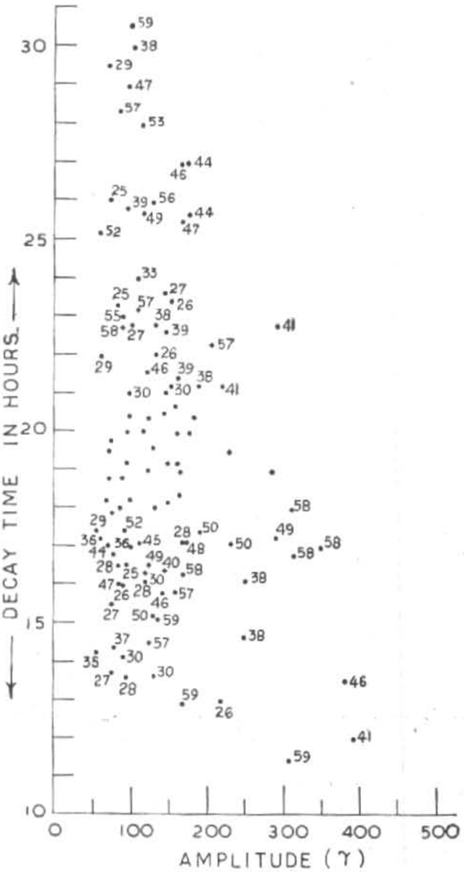


Fig. 5

Figs. 4 and 5. Plot of decay time for amplitude of free-hand smooth curve, fitted to the earlier portion (Fig. 4) and fitted to the later portion (Fig. 5) of the recovery phase, to decay to half the value, against initial amplitude (at 0^h recovery-phase-time). The years in which particular storms occurred has been indicated for each point (Fig. 4)/for extreme point (Fig. 5)

closer to the earth being formed in the denser part of the outer atmosphere, decays much more rapidly than the outer ring current.

The scatter of the points in Fig. 4 is still large but is much less than that seen in Fig. 1, *i.e.*, for the recovery-phase as a whole. Here again only a broad trend of decay times decreasing with increasing amplitude is seen. (In the case of the smooth curves fitted to the earlier portion of the recovery phases, the amplitudes are almost the same as the maximum depression of the main-phase). If the points for years of high sunspot numbers and those for low sunspot numbers are considered separately, a more systematic decrease in decay time with increasing amplitude is very much in evidence, though, there is a good deal of mixing towards the low amplitude side. This is unambiguously clear for years of high sunspot numbers. Moreover, examination of points in Fig. 4 shows that the extreme low decay times are associated with solar minimum epoch and extreme high decay times with solar maximum epoch. This feature brings up the question of solar cycle variation of decay times of the recovery phase which will be examined in detail in the next section.

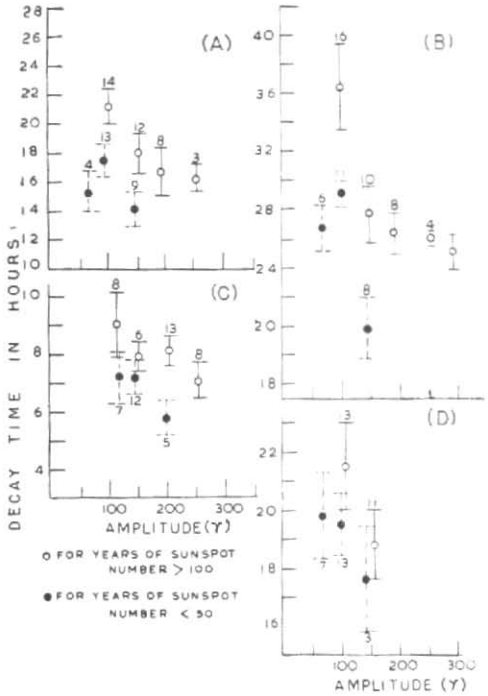


Fig. 6. Plots of mean decay times against mean amplitudes of curves, fitted to recovery phases, for different amplitude class-groups. (A) is for the case of exponential curves fitted to 36-hourly depressions in H of the recovery phase. (B) is for the case of free-hand smooth curves fitted to the 36-hourly depressions. (C) and (D) are respectively for cases of free-hand smooth curves fitted to the earlier and the later portions of the recovery phase. No. of storms falling into each class group has been indicated

The points in Fig. 5 show extremely large scatter and there is very little of an indication that decay times decrease with increasing amplitude. The variation in amplitude is itself confined to narrow limits. There is much mixing of points for years of high and low sunspot numbers.

As was done for the recovery-phase as a whole, mean decay times were determined for different class groups of amplitudes of 50γ intervals for the earlier portion and the later portion of the recovery-phase and the plot of mean decay time *vs* mean amplitude of class group is shown respectively in Fig. 2C and 2D. In the case of the earlier portion of recovery-phase a definite tendency for decay time to decrease with increasing amplitude is seen up to an amplitude of about 400γ. A sudden increase in decay time occurs at about this amplitude and thereafter again the same relationship between amplitude and decay time is seen. What is striking in Fig. 2C is the sudden increase in decay time at about the amplitude of 400γ, in contrast with the sudden decrease seen in Figs. 2A and 2B (for the recovery-phase as a whole). The sudden increase in Fig. 2C is accountable by the fact that higher amplitudes pertain to very great storms which mostly occur during the solar maximum epoch. Decay times tending to be high during the maximum epoch (Section 4), a sudden shift of the amplitude *vs* decay-time curve occurs towards the high decay time region at about the amplitude of 400γ. In the case of the later portion of the recovery-phase (Fig. 2D) there is no indication of a systematic relation between decay times and amplitude. Decay times appear to be rather random with respect to amplitude.

4. Solar-cycle variation in decay time of the recovery-phase

In Figs. 6 A and 6B are shown mean decay times for different class-groups of amplitudes separately for years with sunspots greater than 100 and for years with sunspots less than 50. Fig. 6A is for the method of investigation in which exponential curves were fitted to the 36 recovery-phase-time hourly depressions, and Fig. 6B is for the method of drawing free-hand smooth curves fitting them. It is obvious that the comparison in decay rates between the sunspot maximum epoch and minimum epoch has to be confined to lower amplitudes since high intensity storms are rare during the solar minimum epoch. Further, the comparison should be made with approximately equal amplitudes for the two solar epochs to ensure that the associated ring currents are located at more or less the same region of the outer atmosphere. It is readily seen in Figs. 6A and 6B that there is a clear tendency for decay times to be higher during years of high sunspot numbers than during years of low sunspot numbers. In Table 2 are collected

TABLE 2

Mean decay times of recovery-phase for years of sunspot numbers R greater than 100 and less than 50 and the significance of the difference in decay times between the two groups of years

	Amplitude class-group γ	Mean amplitude γ		Mean decay time (hours)		Difference d in mean decay times for the two groups of years (hrs)	Standard error E of the difference (hrs)	Ratio d/E
		years $R<50$	years $R>100$	years $R<50$	years $R>100$			
For 36 hours of recovery-phase fitted with exponential curve	75—125	101	102	29·1	36·3	7·2	1·61	4·5
	125—175	147	150	19·8	27·7	7·9	2·85	2·8
For 36 hours of recovery-phase fitted with free-hand smooth curve	75—125	97	103	17·5	21·1	3·6	1·64	2·2
	125—175	149	154	14·1	18·0	3·9	1·79	2·2
For earlier portion of recovery-phase fitted with free-hand smooth curve	75—125	106	114	7·2	9·0	1·8	1·41	1·3
	125—175	143	151	7·2	7·9	0·7	0·57	1·2
	175—225	199	204	5·8	8·1	2·3	0·73	3·2
For later portion of recovery-phase fitted with free-hand smooth curve	75—125	97	103	19·5	21·5	2·0	1·90	1·1
	125—175	137	153	17·6	18·8	1·2	2·11	0·6

the mean decay times for different class-groups of amplitudes and the statistical significance of the difference in the mean decay times for solar maximum and minimum epochs has been indicated. It may be seen that for each class group the difference in the mean decay times for years of high sunspot numbers and low sunspot numbers is a little more than twice the standard error of the difference indicating that the difference is just about the level of being statistically significant. The number of storms making up each class group being small the significance shown may not be considered conclusive.

For the initial portion of the recovery phase, the difference in the mean decay times for years of high sunspot numbers and low sunspot numbers, for different amplitude class-groups, has been shown in Fig. 6C and also in Table 2. The differences for low amplitudes are small and no significance is indicated. But for the higher amplitudes the differences are significantly appreciable. A more convincing difference in decay times between years of high sunspot numbers and years of low sunspot numbers, for the initial portion of the recovery phase, is noticeable in Fig. 4 when extremes of decay times are taken for exclusive consideration. In this figure the extreme high decay times are for years of high sunspot numbers, while the extreme low decay times are mainly for years of low sunspot numbers, for amplitudes greater than 150γ. The areas of extreme decay times in Fig. 4 have been demarcated by pairs of broken lines. The axis of each pair of lines may be taken to represent the run of average extreme values of decay time. The order of extreme difference in decay times, for solar maximum and minimum epochs may then be readily gauged. Thus for the amplitude of depression (which is almost the same as main phase maximum depression) equal to 150γ decay time (for amplitude to reach half its value) for solar minimum epoch is 5·4 hrs and that for solar maximum epoch it is 13·5 hrs. Corresponding pairs of decay times for initial amplitudes 200, 250, 300 and 350γ are respectively 5·0 and 12·5 hrs, 4·6 and 11·5 hrs, 4·2 and 10·5 hrs, 3·8 and 9·5 hrs. It thus turns out that for the initial portion of the recovery-phase decay times for solar maximum epoch is about 2·5 times those for solar minimum epoch when only the extreme decay times are considered.

For the later portion of the recovery-phase decay times between years of high sunspot numbers and those of low sunspot numbers are not significantly different (Fig. 6 D and also Table 2).

5. Discussion

The generally known characteristic that the decay rate of the main-phase of geomagnetic storms has an inverse dependence on intensity of the main phase (Chapman and Bartels 1940, Sugiura and Chapman 1958) has also emerged in this investigation. Considerable scatter is, however, seen when the entire recovery phase (up to 36 hours of recovery-phase-time) is studied for all years. The large scatter, in a way, indicates the extent of variability of storm parameters. The ring currents responsible for the main-phase of storms are formed by the drift in longitude of charged particles and the intensity of the current depends on the number density of the charges, their energy, as well as on the geomagnetic field lines where the charges are trapped. The rate of decay is thus dependent on all these factors, which in themselves are capable of varying through considerable ranges.

If, on the other hand, attention is restricted to the earlier portion of the recovery-phase the scatter in decay time for any intensity group is very much reduced. The extreme values of decay times for sunspot maximum years and minimum years in Fig. 4, especially for higher storm intensities (main-phase depression $> 150\gamma$) show well defined trends. In fact more precise relationships between decay times and amplitudes are in evidence for the different solar-cycle epoch if only the extreme values are considered. The linear relationship between decay times and intensity of main-phase for the solar maximum epoch is of the form $T_{\max} = 16{\cdot}5 - 0{\cdot}02 \triangle H$ and for the solar minimum epoch it is of the form $T_{\min} = 6{\cdot}6 - 0{\cdot}008 \triangle H$, where T is in hours and $\triangle H$ in gammas. It thus appears that not only the decay times are higher for the solar maximum epoch, but the rate of change of decay time with intensity of the main phase is also higher by a factor of about 2·5.

Johnson (1961) has given the distribution of atomic hydrogen concentration in the exosphere up to a distance of 60,000 km from the earth, for solar maximum and minimum epochs. The differences are about constant till about the distance of 20,000 km from the earth, the minimum epoch concentrations being about two-fold those of the maximum epoch. For lower altitudes the difference tends to increase so that for the altitude of 10,000 km the minimum epoch concentration is three-fold that of the maximum epoch. The distribution of the atomic-hydrogen concentration in the exosphere has a bearing on the decay-rate of the main phase of geomagnetic storms. The energetic trapped charges lose their energy in collisions with neutral particles, and also among themselves, which cause their pitch angles to be randomised, feeding particles into small pitch angles and causing them to be dumped into denser altitudes. Another way by which the energetic particles lose their energy is by the process of charge-exchange with atomic-hydrogen, which according to Dessler, Hanson and Parker (1961) is the main energy loss process. Accordingly the rate of decay of the recovery phase of geomagnetic storms, as a consequence of dissipation of the ring currents, will depend on the concentration of atomic hydrogen, in the regions where the ring currents are formed.

In the present investigation it has been seen that differences in the decay rates of the recovery phase exist for solar maximum and minimum epochs. The difference for average extreme values in the case of the initial portion of the recovery phase, is such that, for comparable main phase depression the recovery time for the solar maximum epoch is about 2·5 times that for the minimum epoch. This is approximately the factor by which the concentration of atomic-hydrogen is said to vary through the solar cycle by Johnson (1961). This agreement between the variation in decay times and the variation in atomic hydrogen concentration through the solar cycle implies that the main process by which the trapped energetic charged particles lose their energy is by charge exchange with atomic-hydrogen.

Matsushita (1962) has analysed geomagnetic storms for the solar maximum epoch and the minimum epoch and given their *Dst* variation. He has shown that decay of the recovery phase is much faster for the minimum epoch than for the maximum epoch. He estimates the difference as of the same order as expected by Dessler *et al.* (1961). It has, however, to be noted that the maximum depressions for the two solar epochs are not comparable in his presentation. Actually the average main phase intensity for the solar maximum epoch is about twice as large as for the minimum epoch, which apparently means that the average ring currents for the two solar epochs are not located in about the same region of the outer atmosphere. Since, as indicated in this investigation, decay rates are dependent on the main-phase intensity, Matsushita's presentation for the solar maximum and minimum epochs will not be strictly comparable, though the trends may be indicated. The present analysis has shown that, when the entire recovery-phase is taken into account, there is, no doubt, a difference in recovery times for the solar minimum and maximum years which is just about the level of being statistically significant (Section 3), but the difference is far from the factor of about 3 expected by Dessler *et al.* (1961). The expected factor is indicated only when the initial portion of the recovery phase is taken for analysis and extremes of decay times only are considered.

In this investigation it has emerged beyond reasonable doubt that two ring currents are associated with the main phase of geomagnetic storms, which is in agreement with the findings of Akasofu, Chapman and Venkatesan (1963). The main-phase depression is apparently the sum of the effects of the two ring currents, assuming that the effect of the outer one is not appreciably shielded by the inner one. It follows that the initial portion of the recovery phase is the sum of the dissipation effects of the two ring currents while the later portion is largely due to the dissipation of the outer ring current. If the effect of the outer ring current from 0^h recovery phase time can be ascertained, the effect due to the lower one can be found by subtraction from the total effect of the two, as given by the initial portion of the recovery phase. The separate effects of the two ring currents for any storm were estimated by fitting quadratic curves (of the form $\triangle H = a + bt + ct^2$ where $\triangle H$ in γ is the depression and t recovery-phase time in hours) to the smooth curves (Figs. 3 a and 3 b) drawn for the initial portion and the later portion of the recovery phase, by considering three points along each of the free-hand smooth curves (at 0^h, 5^h and 10^h for smooth curve of the initial portion and at 10^h, 20^h and 30^h for smooth curve of the later portion) and then subtracting one from the other. This was done in the case of 15 storms of fairly large main phase depression to examine the relative magnitudes of maximum effects (depression at 0^h recovery-phase-time) due to the two ring currents.

The results are shown in Table 3. It is seen that the effect of the inner ring current is greater than that of the outer one for only

TABLE 3

Estimates of maximum field contributions by the inner and outer ring currents for a few storms

Date of storm commencement (U.T.)	Maximum Field, $\triangle H$	
	for inner ring current $-\gamma$	for outer ring current $-\gamma$
1928 Jul 7 2311	290	146
1938 Jan 22 0242	180	250
1938 Jan 25 1150	33	353
1941 Mar 1 0358	82	394
1941 Jul 5 0459	364	289
1944 Apr 2 0410	173	123
1946 Mar 28 0635	461	380
1951 Oct 28 1153	183	159
1952 Jun 29 1931	90	105
1956 Feb 25 0306	117	127
1957 Jan 21 1255	150	226
1957 Mar 10 0022	91	165
1957 Sep 29 0016	150	242
1959 Jul 15 0803	152	268
1959 Dec 5 0659	92	108

storms of very large intensity, while for others it is often smaller, even for some whose maximum main phase depressions are of the order of 400γ. These relative effects tend to conform to the expectations of Akasofu, Chapman and Venkatesan (1963), (Fig. 2 of their paper). But the comparatively smaller effects shown for the inner ring current even for fairly large intensity storms, appear to indicate that probably the initial recovery phase is not exactly the sum of the effects of the two ring currents, but mainly that of the inner one. Perhaps the inner ring current has some shielding effect on the outer ring current field. This view is compatible with the large current intensities associated with the inner ring current. For a ring current of geocentric distance of 3 earth radii, producing magnetic field effects of -100γ on the earth's surface, the current intensity is of the order 10^6 amps, which should be considered large enough to produce effective shielding on the other ring current beyond its location. It, thus appears that the initial portion of the recovery phase is mainly the effect of dissipation of the inner ring current and not the summed dissipation effects of the two ring currents.

It is natural to expect the outer ring current to be formed first. The solar plasma being retarded by the magnetosphere and trapped there, drifts in longitude to form the outer ring current. The inner ring current should be considered to be formed later. The mechanism of its formation can be the downward acceleration of charged particles, arising from the crossed electric and magnetic fields in the vicinity of the outer ring current, these being ultimately trapped in field lines much closer to the earth to give rise to the inner ring current. With the formation of the inner ring current the effect of the outer ring current presumbaly gets shielded off, till it dissipates to a large extent.

6. Conclusion

The decay characteristics of the recovery-phase of some 130 geomagnetic storms, recorded at Alibag during the period 1924 to 1959 have been investigated and the following findings have emerged.

1. The generally known characteristic that decay rates are faster for the larger intensity storms is seen but a good deal of scatter in decay rates is observed for any storm intensity group.

2. Two clear trends in decay rates are seen for each recovery phase. The initial portion of less than 12 hours, decays more rapidly than the later portion of the recovery phase.

3. As a consequence of (2) two ring currents with different geocentric radii appear to be associated with the main and recovery phases of geomagnetic storms.

4. The relative maximum magnitude of the two ring current fields at the earth's surface vary according to the intensity of the main phase. For the greatest storms the field of the inner ring current is larger.

But for a number of great intensity storms it is smaller than the outer ring current field. Currents of the order of 10^6 amperes are associated with the inner ring current. This order of magnitude for the current can have considerable shielding effect on the outer ring current field with the result that the main phase depression is not exactly the sum of the effects of the two ring currents but mainly the effect of the inner ring current.

5. There is a clear tendency, especially for storms of main phase depression greater than about 200γ, for decay rates to be faster during years of low sunspot number than during years of high sunspot numbers. But the relative rates are far from the factor of 3 expected by Dessler *et al.* (1961). This factor is, however, approached if the extremes of recovery rates of the initial portion of the recovery phase only are considered. For the later portion of the recovery phase no significant differences in decay rates are observed for the two solar epochs.

In conclusion it has to be pointed out that the treatment the recovery phase has received here is not adequate, since the hourly depressions of the recovery phase are not pure ring current effects. A considerable part of the hourly depressions arise from the disturbance effects that vary according to local time (SD or DS) and ionospheric currents are supposed to be associated with them. Perhaps more tangible results would emerge if the pure *Dst* part of the recovery phase of individual storms is taken for analysis. Derivation of even the approximately pure *Dst* involves a very elaborate process. This aspect will, however, be examined as a continuation of the present study.

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