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Determining the Strength of the Ring and the Magnetopause Currents During the Initial Phase of a Geomagnetic Storm Using Cosmic Ray Data

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During a geomagnetic storm the strength of the magnetospheric current systems is strongly increased. In the initial phase of most events, however, the magnetic field at the Earth's equator (as characterized by the *Dst* index) shows only a relatively small perturbation due to the opposite magnetic effects caused by the magnetopause currents compared to the ring current. Analysis of *Dst* and of the cosmic ray cutoff rigidity changes at about 55° geomagnetic latitude offers the unique possibility to estimate the intensity of these two current systems separately. The procedure is illustrated for the geomagnetic storm on December 17, 1971.

1. Introduction

Magnetic storms are characterized by sudden worldwide variations in the intensity of the geomagnetic field as a consequence of the dynamic interaction between the interplanetary magnetic field embedded in the solar wind and the Earth's magnetosphere. The changes in the low-latitude surface magnetic field, averaged over longitude, are usually represented by the geomagnetic index, *Dst* [*Sugiura*, 1964; *Mayaud*, 1980]. The *Dst* index was initiated by Bartels to monitor the variations of the equatorial ring current, and "among all geomagnetic indices is probably the one that monitors and records with the greatest accuracy the phenomenon for which it was designed" [*Mayaud*, 1980]. However, although during the recovery phase of a magnetic storm this statement is certainly true, it is not necessarily valid for the initial phase. Using solar wind particle and magnetic field data to deduce the compression of the magnetosphere, *Olson and Pfitzer* [1982] separated *Dst* into two contributions due to the ring current (Dst_R) and the magnetopause currents (Dst_{MP}). Their result for the magnetic storm on July 28/29, 1977, is illustrated in Figure 1. It can be seen that, in particular, immediately after the storm sudden commencement (ssc), *Dst* is strongly influenced by the opposite effects of the ring current and the magnetopause currents. As the paper by Olson and Pfitzer demonstrates, it is rather difficult to determine the intensity of the ring and magnetopause currents. In this paper we show that analysis of the changes in the cosmic ray cutoff rigidities at about 55° geomagnetic latitude and of the changes in the low-latitude surface magnetic field (represented by *Dst*) offers a possibility of probing disturbances in the distant geomagnetic field and of estimating the intensity of the ring and the magnetopause currents during the initial phase of a geomagnetic storm. We realize that this technique of estimating the strength of the ring and magnetopause currents is relatively crude and gives only a first-order approximation. In the following we describe the procedure and its limitations and give results for the geomagnetic storm on December 17, 1971, derived from the *Dst* index and the cosmic ray cutoff rigidity variations at Kiel, Federal Republic of Germany.

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2. Method

Flückiger et al. [1983, 1986] have shown that at low and middle latitudes, changes in cosmic ray cutoff rigidities are directly related to the variations in the horizontal component of the magnetic field observed at the equator, and the same authors were able to give quantitative expressions for this relationship. This result implies that the changes in the surface equatorial magnetic field reasonably well represent the average changes in the low-latitude magnetic field within geocentric distances between 1 R_E (Earth radius) and approximately 4 R_E, i.e., within the region where geomagnetic perturbations have the largest effect on cosmic ray cutoff rigidities at low and middle latitudes. For higher latitudes the correlation between geomagnetic perturbations and cutoff rigidity changes is more complex. Figure 2 illustrates for the cosmic ray station Kiel (geographic latitude 54.3°N, geographic longitude 10.1°E, geomagnetic latitude 54.8°N) the regions in near-earth space where disturbances in the z component of the geomagnetic field have a significant effect on the vertical cutoff rigidities (with the z direction oriented parallel to the north pointing dipole axis). The cross-hatched area in Figure 2 shows the longitudinal sector where magnetic perturbations produce the maximum effect. Besides their dependence on the longitudinal structure of the magnetic perturbation, the vertical cutoff rigidities at approximately 55° geomagnetic latitude are most sensitive to variations of the low-latitude magnetic field at geocentric distances between 2.5 R_E and 6 R_E [*Flückiger et al.*, 1983].

The following discussion is restricted to the initial phase of a magnetic storm (characterized by a small increase in *Dst* prior to the main decrease) where in general the variations in

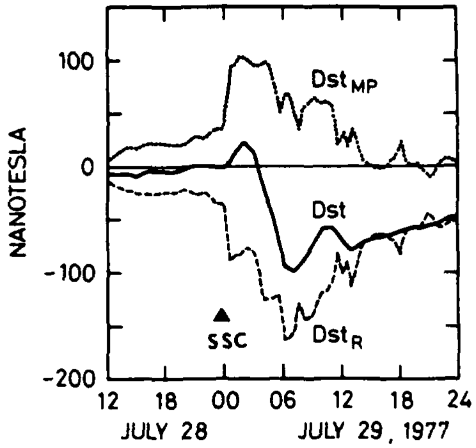

Fig. 1. *Dst*, and its contributions due to the ring current, Dst_R, and due to the magnetopause currents, Dst_{MP}, as derived by *Olson and Pfitzer* [1982] for the magnetic storm on July 29, 1977.

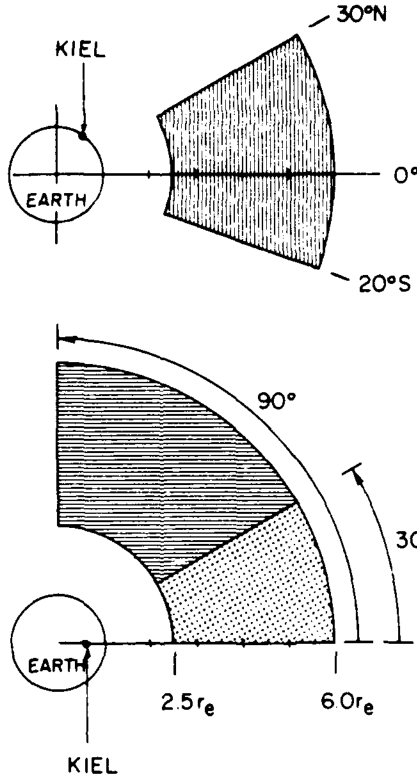

Fig. 2. Schematic representation of the regions in near-Earth space where perturbations in the geomagnetic field have the largest effect on the vertical cutoff rigidities at Kiel. The upper part of the figure is a cross section in the meridian plane through the station, whereas the lower part shows the cross section in the equatorial plane with the location of the station projected into the equatorial plane. The hatched area represents the longitudinal sector where magnetic perturbations produce the maximum effect [from *Flückiger et al.*, 1983].

the low-latitude surface magnetic field show no pronounced dependence on local time. Although the lack of a noticeable local time variation in the low- and mid-latitude surface magnetic field excludes, for example, the existence of a significant partial ring current around 4 R_E [*Fukushima and Kamide*, 1973; *Flückiger et al.*, 1983], it does not necessarily imply an axisymmetric current system if the system is more distant. For a first-order representation of the event we may assume, however, that the main part of the equatorial ring current during the early phase of a magnetic storm is located at around or slightly inside 4 R_E, and that the magnetopause currents are axisymmetric with a minimum standoff distance which is typically $\gtrsim 6$ R_E (see, for example, *Olson and Pfitzer* [1982], although the model used by these authors is quite different from ours).

The cutoff rigidity variations at upper mid-latitudes such as the latitude of the Kiel neutron monitor station are very sensitive to the relative strength of the magnetic perturbation fields produced by the magnetopause currents with respect to those due to the ring current. Based on the amplitude of the variations in the surface equatorial magnetic field and on the cosmic ray cutoff rigidity changes at these latitudes it should be possible, therefore, to determine the magnetic perturbation fields and thus to estimate the strength of the ring current and of the magnetopause currents separately during the initial phase of a magnetic storm.

For a quantitative analysis the following simple geomagnetic field model was constructed: the quiescent geomagnetic field, $\mathbf{B}(r, \theta, \phi)$, as a function of geocentric distance r, geomagnetic colatitude θ, and geomagnetic longitude ϕ, was represented by the international geomagnetic reference field (IGRF) for epoch 1965.0 [*IAGA Commission 2 Working Group 4*, 1969; *Mead*, 1970]. The perturbed geomagnetic field was modeled by superposing upon the quiescent field two specific disturbance fields, $\Delta\mathbf{B}^R$ and $\Delta\mathbf{B}^{MP}$, representing the magnetic storm effects due to the ring current and the magnetopause currents, respectively. We have added the magnetopause currents to the ring current model utilized to describe the perturbed geomagnetic field in an earlier paper [*Flückiger et al.*, 1983]. The disturbance field $\Delta\mathbf{B}^R$ was defined by

$$\begin{aligned} \Delta B_r^R(r, \theta, \phi) &= (2M_R/a_R^3)\cos\theta \\ \Delta B_\theta^R(r, \theta, \phi) &= -(2M_R/a_R^3)\sin\theta \\ \Delta B_\phi^R(r, \theta, \phi) &= 0 \end{aligned} \tag{1a}$$

for $r \le a_R$ and

$$\begin{aligned} \Delta B_r^R(r, \theta, \phi) &= (2M_R/r^3)\cos\theta \\ \Delta B_\theta^R(r, \theta, \phi) &= (M_R/r^3)\sin\theta \\ \Delta B_\phi^R(r, \theta, \phi) &= 0 \end{aligned} \tag{1b}$$

for $r > a_R$, with $a_R = 4$ R_E and M_R denoting the magnetic moment of the ring current.

According to *Treiman* [1953], $\Delta\mathbf{B}^R$ is the magnetic field generated by a current flowing in the azimuthal direction on the surface of a geocentric sphere with radius a_R and having a current density proportional to the sine of the geomagnetic colatitude. It can easily be seen that inside the sphere, i.e., for $r \le a_R$, the magnetic disturbance field $\Delta\mathbf{B}^R$ is uniform. In dipole coordinates, $\Delta\mathbf{B}^R$ is oriented so that the z direction is parallel to the north pointing dipole axis, and the magnetic moment of the current, M_R, is considered to be positive when it is pointing northward. We therefore have

$$\Delta B_z^R(r, \theta, \phi) = Dst_R = 2M_R/a_R^3 \qquad r \le a_R \tag{2}$$

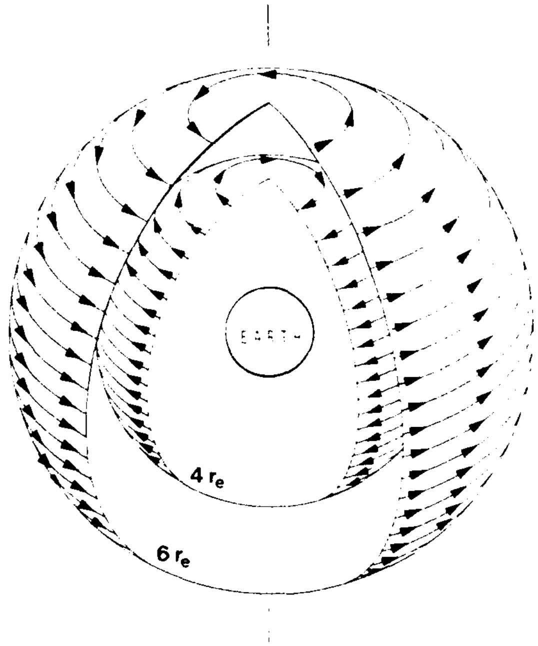

Fig. 3. Three-dimensional visualization of the two Treiman current spheres used in our geomagnetic field model.

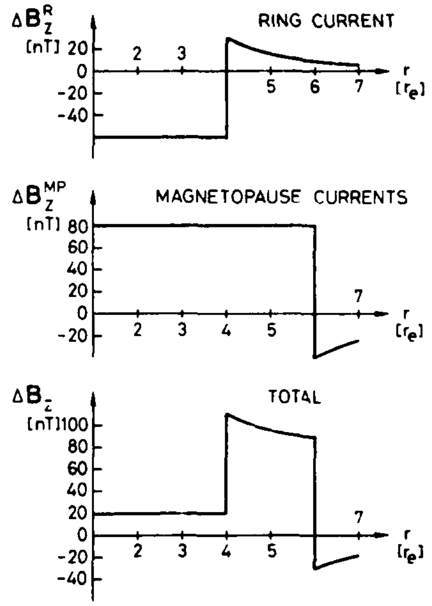

Fig. 4. Example of the model magnetic perturbations, in the equatorial plane, as a function of geocentric distance: (top) ring current: ΔB_z^R $(r, \theta = 90°, \phi)$ for $a_R = 4\ R_E$ and $Dst_R = -60$ nT; (center) magnetopause currents: ΔB_z^{MP} $(r, \theta = 90°, \phi)$ for $a_{MP} = 6$ R_E and $Dst_{MP} = 80$ nT; (bottom) total: sum of top and center curves, representing a total magnetic perturbation with $Dst = 20$ nT. The parameters used in this example are representative for the initial phase of the magnetic storm on December 17, 1971.

For $r > a_R$ the magnetic perturbation $\Delta\mathbf{B}^R$ has dipolar topology. The magnetic disturbance field generated by the magnetopause currents, $\Delta\mathbf{B}^{MP}$, was defined exactly in the same way as $\Delta\mathbf{B}^R$ but with the radius $a_{MP} = 6\ R_E$ instead of $a_R = 4\ R_E$ and with the magnetic moment M_{MP} instead of M_R. In Figure 3 the two Treiman spheres used in our geomagnetic field model are visualized in a three-dimensional sketch.

In the present model the Dst index is given by

$$Dst = Dst_R + Dst_{MP} \tag{3}$$

where Dst_{MP} is defined in analogy to equation (2) and with the signs of Dst_R and Dst_{MP} according to the fact that $M_R < 0$ and $M_{MP} > 0$. By choosing appropriate values for Dst_R and Dst_{MP}, any value of Dst can be represented.

As an illustration of the field model, Figure 4 shows (from top to bottom) the variation of $\Delta B_z^R(r, \theta = 90°, \phi)$, $\Delta B_z^{MP}(r, \theta = 90°, \phi)$, and

$$\Delta B_z(r, \theta = 90°, \phi) = \Delta B_z^R(r, \theta = 90°, \phi) + \Delta B_z^{MP}(r, \theta = 90°, \phi)$$

i.e., the z component of the magnetic perturbations in the equatorial plane, as a function of geocentric distance, r. In this example we have $Dst_R = -60$ nT, $Dst_{MP} = 80$ nT, and therefore $Dst = 20$ nT. As will be discussed later, these parameter values are representative for the initial phase of the magnetic storm on December 17, 1971.

Of course, the model described above can only be considered a crude representation. The model magnetic field perturbations are probably a step closer to reality than the model currents. Although the magnetopause current system would be locally well approximated by a current sphere (at least near the nose of the magnetopause) the ring current is certainly not a sheet at 4 R_E [*Akasofu*, 1984]. For a first-order demonstration of the technique, however, the model used is adequate.

With the very simple model of the perturbed geomagnetic field described above, the trajectory-tracing technique [*Shea and Smart*, 1975, and references therein] was used to determine the effects on the cutoff rigidity at approximately 55° geomagnetic latitude. For this analysis we used Kiel, Federal Republic of Germany, as a representative location. Only the vertical direction of incidence and the rigidity fiducial mark R_1 were considered in these calculations. As defined, for example, by *Flückiger et al.* [1983], R_1 is the rigidity associated with the first discontinuity in asymptotic longitude occurring as the trajectory calculations are progressing down through the rigidity spectrum. As has been pointed out by *Shea and Smart* [1971], the asymptotic longitude systematically increases with decreasing rigidity down to a rigidity value where a sudden discontinuity occurs. *Flückiger et al.* [1983] have shown that at any location the effect of geomagnetic disturbances on R_1 is almost the same as the effect on the other rigidity fiducial marks (e.g., the upper vertical cutoff rigidity and the effective vertical cutoff rigidity). From the comparison with $R_1 = 2.49$ GV obtained for Kiel in the quiescent geomagnetic field model, values for the changes in R_1, ΔR_1, were determined as a function of Dst_R and Dst_{MP} ($\Delta R_1 = R_1' - R_1$, where the primed value refers to the perturbed geomagnetic field). The result of the calculations is summarized in Figure 5. In this figure, lines of constant Dst and ΔR_1 at Kiel are plotted in a coordinate system representing the storm time equatorial surface magnetic field variations, Dst_R and Dst_{MP}, due to the ring current and the magnetopause currents, respectively. Using this plot, the strength of the ring current and of the magnetopause currents during the compression phase of a magnetic storm can

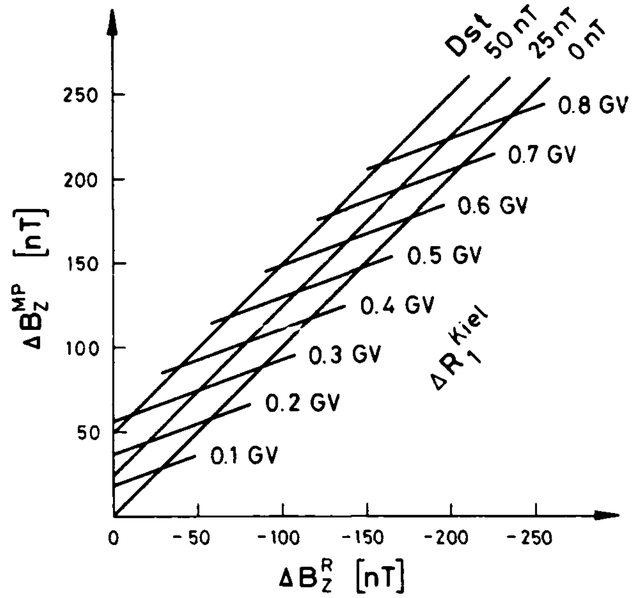

Fig. 5. Lines of constant Dst and ΔR_1 at Kiel plotted in a coordinate system representing the stormtime equatorial surface magnetic field variations, Dst_R and Dst_{MP}, due to the ring current and to the magnetopause currents, respectively. Using this plot, the strength of the ring current and of the magnetopause currents during the compression phase of a magnetic storm can be uniquely determined provided the magnetic index Dst and the change in the cosmic ray cutoff rigidity at Kiel are known.

be uniquely determined provided the magnetic index Dst and the change in the cosmic ray cutoff rigidity at Kiel, ΔR_1, are known.

3. Application to the Magnetic Storm on December 17, 1971

The major magnetic storm which started at 1418 UT on December 17, 1971, has already been discussed in a series of papers [e.g., *Cahill*, 1973; *Kamide*, 1976]. Figure 6, adapted from *Kamide* [1976], shows the superposed ΔH values at middle latitudes, and 5-min and hourly Dst values, as a function of time. As in the example shown in Figure 1, also in this event the Dst index after the ssc at 1418 UT first exhibits a small increase characteristic for the compression of the magnetosphere. In the top panel of Figure 6 it can also be seen that during the time period of increased Dst the superposed mid-latitude surface magnetic field variations show only a small dispersion, indicating that during this part of the event the worldwide magnetic perturbation was almost identical at all local times. By using the procedure described above we will show in the following that already during the initial phase of this magnetic storm the strength of the ring and the magnetopause currents was significantly increased.

The cosmic ray cutoff rigidity variations over Europe during the December 17, 1971, magnetic storm were studied by *Debrunner et al.* [1979], *Arens* [1978], and in more detail also by H. von Mandach et al. (University of Bern, Bern, Switzerland, unpublished work, 1979). Figure 7 shows the results obtained for Kiel by von Mandach et al. These cutoff variations were evaluated on an hourly basis according to the method described by *Flückiger et al.* [1975]. The procedure utilizes the fact that at high latitudes, due to the atmospheric cutoff, the sea level cosmic ray intensity as indicated by the neutron monitor counting rates is not affected by perturbations in the geomagnetic field. Differences in a comparison of the neutron monitor measurements made at Kiel with those made at the two high-latitude stations Kiruna and Oulu can therefore be attributed mainly to geomagnetic effects of the cosmic ray intensity observed at Kiel. It should be pointed out that the cutoff rigidity changes thus obtained primarily represent the changes in the effective vertical cutoff rigidity. However, for the reasons discussed above, these cutoff rigidity variations are very similar to the variations in the parameter R_1 used in this paper [*Flückiger et al.*, 1983].

For the present analysis of the December 17, 1971, magnetic storm we selected the time around 1530 UT. The specific increase in the cutoff rigidity at Kiel of approximately 0.3 GV around 1530 UT illustrated in Figure 7 is a general feature which was observed at all Western European and North American neutron monitor locations whose cutoff rigidities are in the range of 2–3 GV (H. von Mandach et al., unpublished work, 1979). This corresponds to probing the variations of the magnetic field in the prenoon, noon, and postnoon sector of the magnetosphere. At 1530 UT we obtain from Figure 6 $Dst \approx 20$ nT and from Figure 7 $\Delta R_1 \approx 0.3$ GV. Using these values, we then find from Figure 5 that $Dst_R \approx -60$ nT and $Dst_{MP} \approx 80$ nT. The uncertainty of the values obtained for Dst_R and Dst_{MP} is estimated to be about ± 25 nT, while always $Dst = Dst_R + Dst_{MP}$.

4. Discussion

Olson and Pfitzer [1982] evaluated that in a quiet time model of the magnetospheric field the ring current contributes about -40 nT ($= D\text{quiet}_R$) to the field at the Earth, whereas the field from the magnetopause currents near Earth is about 25 nT ($= D\text{quiet}_{MP}$). Correspondingly, for any time t the strength S of the ring current and of the magnetopause currents relative to their quiet time strength can be related to the equatorial surface magnetic field variations by

$$S_R(t) = \frac{D\text{quiet}_R + Dst_R(t)}{D\text{quiet}_R} \qquad (4)$$

and

$$S_{MP}(t) = \frac{D\text{quiet}_{MP} + Dst_{MP}(t)}{D\text{quiet}_{MP}} \qquad (5)$$

respectively. According to these relations the values of Dst_R and Dst_{MP} obtained in this analysis imply that at 1530 UT on December 17, 1971, the equatorial ring current was about 2.5 times stronger than during quiescent geomagnetic conditions whereas the intensity of the magnetopause currents was increased by a factor of about 4.2. Under the assumptions of our model of the perturbed geomagnetic field these values correspond to about 3.6×10^6 A for the intensity of the ring current and to -7.3×10^6 A for the magnetopause currents. This result is consistent with corresponding current intensities derived with a different technique by *Scuntaro* [1985] for the main phase of the December 17, 1971, magnetic storm. The obtained current strengths are also of the same magnitude as those evaluated by *Olson and Pfitzer* [1982] for the initial phase of the magnetic storm on July 29, 1977, which

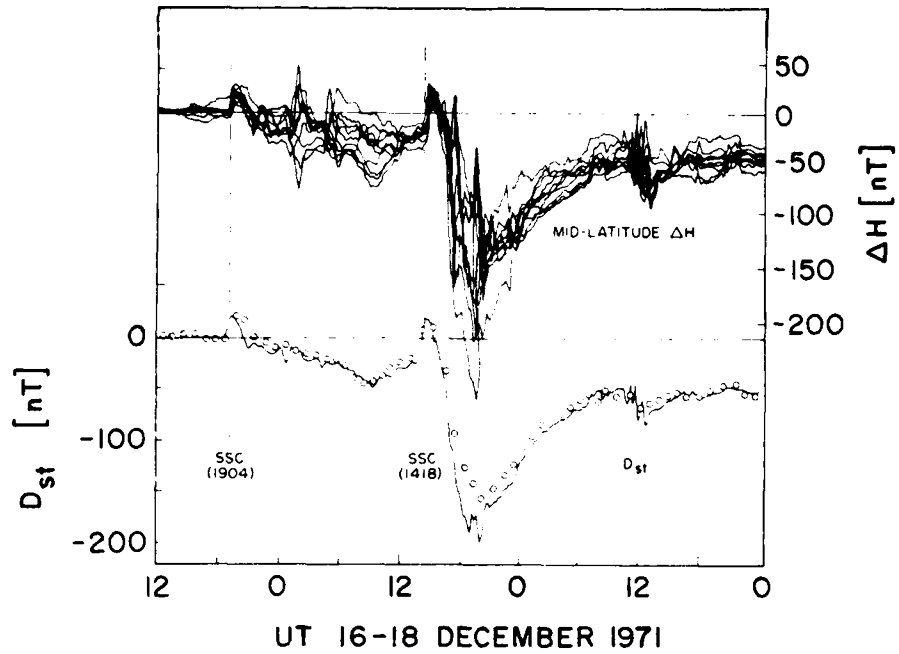

Fig. 6. The superposed *H* component records from 10 mid-latitude observatories (top) and the 5-min (solid line, derived from data of 10 observatories) and hourly (circles, derived from data of four observatories) *Dst*. Figure adapted from *Kamide* [1976].

was very similar to the initial phase of the storm considered in this analysis.

5. SUMMARY AND CONCLUSIONS

A procedure is presented which enables remote sensing of disturbances in the distant geomagnetic field to estimate the intensity of the ring current and of the magnetopause currents during the initial phase of a magnetic storm based on the *Dst* index and on the cosmic ray cutoff rigidity changes observed at approximately 55° geomagnetic latitude. The method has been applied to the magnetic storm on December 17, 1971, using the cutoff rigidity changes as observed at Kiel. It was found that at 1530 UT the contribution to $Dst \approx$ 20 nT due to the ring current was about −60 nT whereas the contribution due to the magnetopause currents was about 80 nT. These results are in agreement with those obtained by *Olson and Pfitzer* [1982] for the initial phase of the July 29, 1977, magnetic storm.

We thus conclude from our analysis that also during the December 17, 1971, magnetic storm the intensities of the ring current and of the magnetopause currents were increased significantly immediately after the ssc at 1418 UT and that therefore during the compression phase of the magnetic storm the time profile of the *Dst* index does certainly not reflect the intensification of the ring current as it does later in the event.

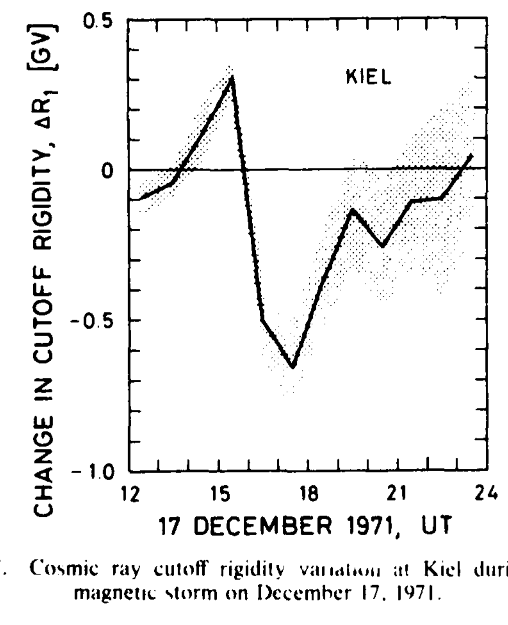

Fig. 7. Cosmic ray cutoff rigidity variation at Kiel during the magnetic storm on December 17, 1971.

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