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LOG Id: LOG_0017
LOG Titel: Solar electron fluxes, increased geomagnetic activity and ionospheric absorption following selected flares
LOG Typ: article

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J. Geophys. 45, 91–100, 1978

Journal of Geophysics

Solar Electron Fluxes, Increased Geomagnetic Activity and Ionospheric Absorption Following Selected Flares

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Abstract. Investigations on the after-effect in ionospheric absorption following selected solar flares are presented for the interval 1966–1969. By a superposed epoch analysis a significant after-effect was detected in night absorption data at 245 kHz on the circuit Kalundborg/Denmark – Kühlungsborn/GDR by using days of important flares (CFI = 9–16) with intense electron fluxes (> 40 keV) as key days. Further analyses have revealed some specific details, namely that the most outstanding after-effects are related to central-zone flares (30° E-30° W) of high importance, even when the associated electron fluxes were lower than in case of outer-zone 30°–90° W-flares of similar importance. An inverse test has implicitly confirmed these results, and has also proved that not all of the intense geomagnetic disturbances are followed by a significant after-effect.

Key words: Solar flares – Comprehensive Flare Index (CFI) – Flare position – Flare-associated electrons – Geomagnetic activity – Lower ionosphere – Absorption after-effect.

1. Introduction

Enhanced electron densities in the lower ionosphere (particularly in the D-region) result in increased absorption of reflected radio waves. The anomalous increase of absorption in winter-time may be attributed to electron enhancements of "meteorological" type as it was first suggested by Dieminger (1952). The after-effect, i.e., another type of increase of radio wave absorption at mid-latitudes following certain geomagnetic storms has been attributed to energetic electrons (> 50 keV) precipitating from the earth's outer radiation belt into the lower ionosphere (e.g., Lauter and Knuth, 1967).

A recent study (Märcz and Verö, 1977) has found some connections between after-effects in ionospheric absorption and Pc 1-type micropulsations. The latter results are in agreement with explanations invoking the resonant scattering

0340-062X/78/0045/0091/$02.00

by ELF waves as a reasonable mechanism responsible for the precipitation of energetic electrons at mid-latitudes (e.g., Spjeldvik and Thorne, 1975).

The connection between electron precipitation and increased ionization in the D-region has also been verified by coordinated experiments using satellite measurements of electron fluxes and ground-based partial reflection data obtained at Ottawa (Larsen et al., 1976).

In our earlier studies (Märcz, 1971, 1973) – devoted to the latitude dependence of the after-effect in ionospheric absorption as well as to the role of the frequency differences of radio waves used – the superposed epoch analyses of absorption data were carried out by selecting key days on the basis of high geomagnetic activity. This had been a common procedure, also applied in other investigations (e.g., Bourne and Hewitt, 1968) studying the phenomenon on a statistical basis. The superposed epoch method has also been used in the present study, key days, however, were selected according to other criteria. Some additional aspects were considered, too.

As first step of these analyses days of occurrence of certain solar flare events have been chosen as key days and expected variations have been traced both in geomagnetic activity and in absorption during the post-flare period. We intended to check whether any differences in the solar source of the magnetic activity would be reflected in the appearance, or in any other parameters of the absorption after-effect. Two main factors have been considered:

(a) The importance of the flare regarding both its electromagnetic and particle radiation

(b) the position of the flare on the Sun's visible disk.

Investigations carried out according to these aspects, as well as their results will be presented in the following sections.

2. Solar Flares and Associated Electron Fluxes

Dodson and Hedeman (1971) have elaborated a system to characterize the flare on the basis of the associated electromagnetic radiation. Their Comprehensive Flare Index (CFI) is equal to the sum of five components:

$$\mathrm{CFI} = A + B + C + D + E$$

where, A = importance of ionizing radiation as indicated by the accompanying Short Wave Fadeout (SWF), or other SIDs (scale 1–3),

B = importance of H_α flare (scale 1–3),

C = characteristic of the log of ~ 10 cm flux in units of $10^{-22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$,

D = dynamic spectrum events: type II = 1, continuum = 2, type IV = 3,

E = characteristic of the log of ~ 200 MHZ flux in units of $10^{-22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$.

The CFI can reach about 15–17 for flares which are outstanding in all aspects of electromagnetic flare radiation. The flare-associated increase of ionizing electromagnetic radiation (directly affecting the ionosphere) is taken into account by the A-component.

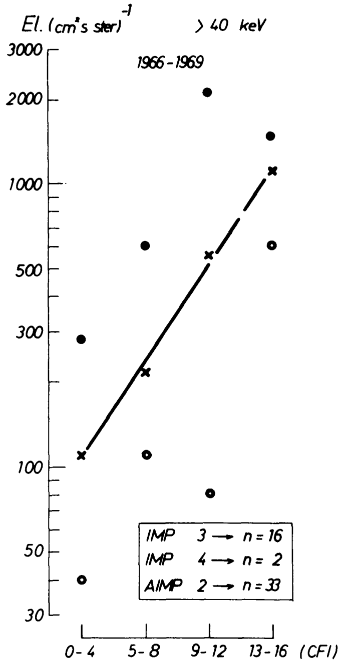

Fig. 1. Median values (crosses) of flare-associated electron (>40 keV) fluxes $(\mathrm{cm}^2\mathrm{s\ ster})^{-1}$ measured by IMP-3, IMP-4 and AIMP-2 satellites during 1966–1969 as a function of Dodson-Hedeman indices (CFI). The appropriate lower quartiles (circles), upper quartiles (dots) and number of observations (n) by the individual satellites are also indicated

During solar flares, however, the Sun is also a source of increased particle streams of different energies. Švestka and Simon (1975) compiled a catalog of solar particle events for the interval 1955–1969. Their particle data for the second half of the sixties were mainly measured on spacecrafts beyond the magnetosphere. The data coverage of this part of the catalog is sufficiently complete due to the improved instrumentation of IMP satellites. Thus, in our investigations we have used the data from 1966 to 1969.

For the forthcoming analyses the selection of suitable key days was based on the following main condition: a flare should be taken into account only if in addition to the increased electromagnetic flare radiation (experienced by different ground-based flare monitoring) the associated particles had also been observed on spacecraft at the near-earth space. In order to have a possible homogeneous material only those events containing also electrons of >40 keV energies were chosen. The CFI-index of the flare, i.e., the importance of the associated electromagnetic radiation was also taken into account, as follows. The electron fluxes selected from the catalog were grouped according to the CFI-value of the corresponding flare. Four flare groups with the given ranges of CFI have been established:

Group 1:	CFI = 0–4,	weakly active (9),
Group 2:	CFI = 5–8,	moderately active (21),
Group 3:	CFI = 9–12,	quite active (17),
Group 4:	CFI = 13–16,	highly active (4).

The values in brackets give the number of flares in the individual groups – in cases of available electron flux data – for the interval 1966–1969. Finally, median values of the appropriately grouped flux data have been determined, they are presented as a function of CFI in Figure 1.

The median values of electron fluxes (>40 keV) lie approximately on a straight line. (The broken line towards high CFI-values indicates the scarcity of cases). Thus there is a logarithmic increase of electron fluxes with increasing flare-associated electromagnetic radiation characterized by CFI. (To represent the scatter of individual data, the upper and lower quartiles are given for each group by dots and circles, respectively, in Fig. 1, where the number of flux data from each satellite is also noted).

Figure 1 yields a rough estimation of flare-associated electron fluxes (>40 keV) on the basis of CFI-indices. Taking into account this empirical connection, the key days of the forthcoming analyses can be selected according to the CFI-values, and by setting appropriate CFI-ranges the dependence of the absorption after-effect on the flare importance can be traced.

3. Geomagnetic Activity and Ionospheric Absorption Following Solar Flare Events

3.1. Dependence on Flare Importance

The particle effects can be detected more easily in the night absorption data, since electron precipitation more frequently occurs in the midnight sector of the auroral oval. Furthermore, the influence of the Sun's electromagnetic radiation on absorption vanishes after sunset, thus mixed effects can be restrained when using night data. Therefore our analyses have also been based on night-time ionospheric absorption data (Geophysikalische Meßreihen, Kühlungsborn, 1966–67, and HHI Geophysikalische Beobachtungsergebnisse, 1968–69). The ΣKp-values (Geomagnetic Planetary Indices, Göttingen, 1966–69) were applied to characterize geomagnetic activity. In order to investigate the dependence on flare importance, the data covering the interval 1966–69 were arranged into two sets, and two independent superposed epoch analysis were carried out.

First, days of weakly and moderately active solar flares (CFI = 0–8) with associated electron fluxes were chosen as key days (0-days). In the left part of Figure 2, the lower curve shows the changes in geomagnetic activity on and around the selected key days. On the average the maximum activity occurs on the third day following the flare. It surpasses the reference level by about 30%. In case of the ionospheric night absorption (upper curve) the mean departures from the appropriate monthly medians are small and they fluctuate around the reference level, i.e., do not show a significant effect.

There is, however, a drastic change in the picture when days with solar flares qualified as quite active and highly active (cf. Section 2) are set as key days in the superposed epoch analysis. (These solar flares of CFI = 9–16 were associated with intense electron fluxes. During the intervals after key days further smaller flares only occasionally occurred, but they were not accompanied by electron fluxes). In the right part of Figure 2 the peak of geomagnetic activity appears again on the third day following the selected flare events. The ΣKp-

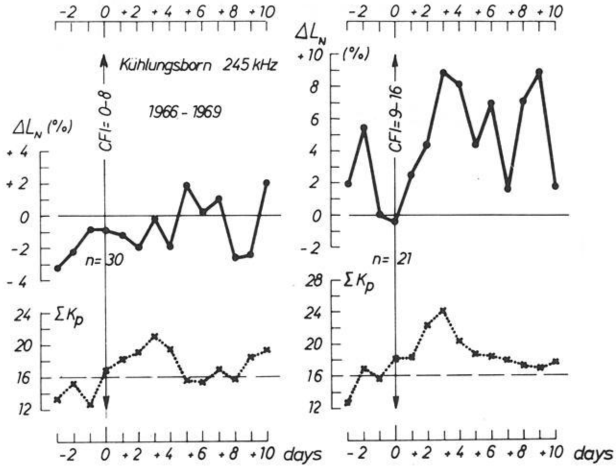

Fig. 2. Mean departures of ionospheric night absorption (245 kHz, Kühlungsborn: $\varphi_{\text{geogr.}} = 54°03'$N, $\lambda_{\text{geogr.}} = 11°46'$E; GDR) from the corresponding monthly medians given in percentages (dots with full lines) around key days (O) selected on the basis of solar flares associated with electron fluxes (>40 keV); as well as changes of the ΣKp mean values (crosses with dotted lines). Horizontal broken line indicates the ΣKp-average for the interval 1966–1969. *In the left part*: the solar flares ($n=30$) were weakly, or moderately active (CFI = 0–8) and were associated with small electron fluxes. *In the right part*: the solar flares ($n=21$) were quite active, or highly active (CFI = 9–16) and were associated with intense electron fluxes

average is about 50% higher than the reference value. A simultaneous maximum in ionospheric absorption corresponds to the "primary storm effect". A few days later, the geomagnetic activity approaches its normal level, but the ionospheric night absorption remains above normal. This can be interpreted as an after-effect most likely caused by particle precipitation (Lauter and Knuth, 1967). It should be mentioned, however, that increased concentrations of NO^+ (at the expense of hydrated ions) could also be observed in the D-region during a certain post-magnetic storm period in winter (Aikin et al., 1977). Thus composition changes might occasionally contribute to the post-storm increase of electron density, although electron precipitation should be regarded as the dominant factor.

The confidence of the latter results was checked by a χ^2-test. As null hypothesis it was assumed that the number of positive and negative departures from the median is equal. The observed distribution of absorption departures determined for all intervals following the key days (between days "+1" and "+10") have been checked against this null hypothesis by the χ^2-test. The positive departures for the ionospheric night absorption (245 kHz) in the right part of Figure 2 proved to be significant at the 99% confidence level.

3.2. Dependence on Flare Position

A connection of the great magnetic storms with the longitudinal position of the intense flares on the visible solar disk has been known since several decades

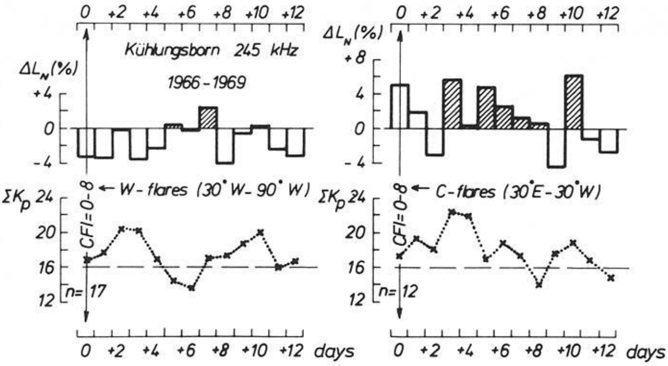

Fig. 3. Mean departures of the ionospheric night absorption from the corresponding monthly medians (in percentages) on and following days with flares of lower importance (CFI = 0–8). Shaded columns indicate the period with primary storm effect and after-effect. Changes of the ΣK_p mean values are shown by crosses with dotted lines. *In the left part*: the solar flares were located in the western outer-zone on the visible solar disk (30°W–90°W). *In the right part*: the solar flares were located in the central-zone on the visible solar disk (30°E–30°W)

(e.g., Newton, 1944). The association has been found to be much closer in case of central-zone flares than in case of outer-zone flares.

The analyses to be presented in this section intended to clarify whether a dependence of magnetic activity on flare position would be transferred into certain changes of the absorption after-effect. Therefore, magnetic and absorption data investigated in the previous section were additionally grouped on the basis of the longitudinal position of flares. Flare position has been depicted in relation to the Sun's central meridian, wherein three zones (east, central and west) have been distinguished. Each zone covers a longitude range of 60°. Consequently, the flares are denoted within the zones as

90° E to 30° E: E-flares
30° E to 30° W: C-flares
30° W to 90° W: W-flares.

According to this classification, the 51 flare events used for setting key days in the previous section (cf., Fig. 2), have included only 2 E-flares, but 20 C-flares and 29 W-flares. Excluding the two E-flares, the absorption and magnetic data analyzed in Section 3.1 were divided into two subsets (central, or west). This was separately done for flares of lower (CFI = 0–8) and of higher (CFI = 9–16) importance.

The results of superposed epoch analyses carried out with these four groups of data are presented in Figure 3 (for CFI = 0–8) and Figure 4 (for CFI = 9–16). C-flares of lower importance can be followed by a rather moderate absorption increase, while no effect occurs in case of the corresponding W-flares, as shown in Figure 3. It becomes obvious that central-zone flares of high importance (Fig. 4) – associated with high geomagnetic activity – play the major role in the significant absorption after-effect found in the right part of Figure 2 (As proved

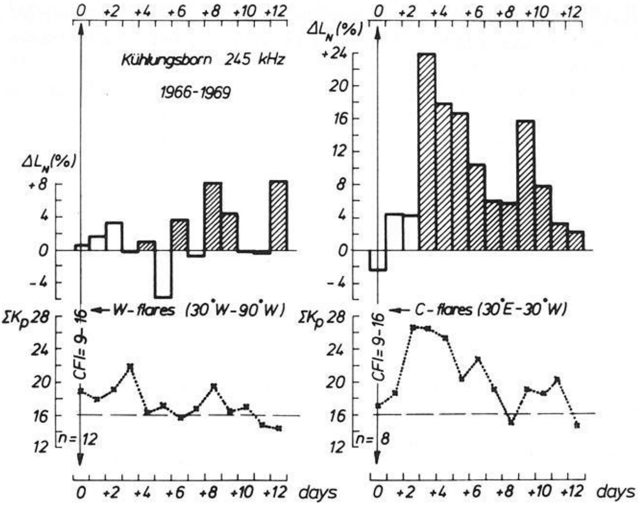

Fig. 4. Same as Figure 3, but for flares of higher importance (CFI = 9–16)

by a χ^2-test, the positive departures in the right part of Fig. 4 are only significant at the 90% confidence level, this, however is conceivable because of the smaller number of data, $n = 8$, compared with those in the right part of Fig. 2).

4. Summary and Discussion

Before summarizing the results of this study and presenting additional ones some basic ideas should be advanced. We accept that the absorption after-effect can be attributed to excess ionization which is most likely caused ba particle precipitation following the enhanced geomagnetic activity, as found by earlier investigations (e.g., Lauter and Knuth, 1967). Furthermore, for the interpretation of our results we also would like to use the considerations about the mechanism of electron precipitation (e.g., Spjeldvik and Thorne, 1975) including the radial diffusion of electrons towards lower L-values after an appropriately intense geomagnetic disturbance, as well as wave-particle interactions. As regards the solar flare electrons (> 50 keV) it is known that they can enter the magnetosphere along connected (interplanetary and geomagnetic) field lines and appear in the tail of the magnetosphere with little delay after the flare (Anderson, 1970).

The present analyses have provided some informations on the flare-associated characteristics of the absorption after-effect, as additional factors with respect to the solar source of both the particles and the magnetic activity have also been taken into account.

Following important flares (CFI = 9–16) a significant absorption after-effect has been shown in the right part of Figure 2 (On the basis of earlier experiences this result could have been expected in advance.) Actually, more complex analyses have also revealed that the characteristics of the absorption after-effect depend – besides the flare importance – on flare position as well (Figs. 3 and 4). In case of C-flares, e.g., the after-effect is preceded by a primary storm

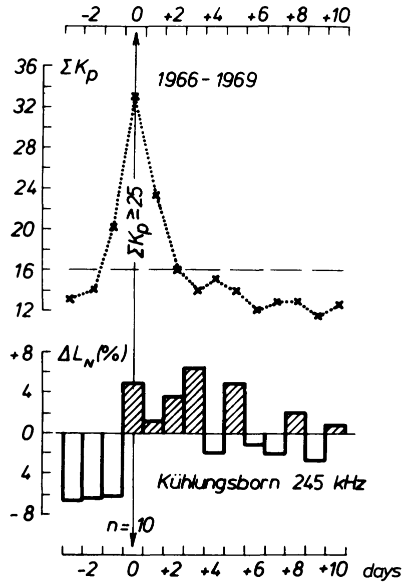

Fig. 5. The ΣK_p mean values on and around selected geomagnetic disturbances (crosses with dotted lines), and mean departures of the ionospheric night absorption from the corresponding monthly medians in percentages. Shaded columns indicate the period with primary storm effect and after-effect

effect. Furthermore, it appears that the major magnetic disturbances attached to central-zone flares (and especially to the important ones) result in the most effective particle precipitation which consequently causes a significant after-effect in ionospheric absorption. (Important W-flares – CFI = 9–16 – are followed by a rather moderate after-effect). Thus in case of central-zone flares, we can suggest a certain proportionality in the sequence of processes, namely between those originating from the solar source and the terminal ones causing the effect in the lower ionosphere.

The latter results seem to be in contradiction with some earlier findings which have indicated that particle precipitation is not always connected to the major geomagnetic disturbances (Lauter and Knuth, 1967; Märcz, 1973). As the following test should confirm both versions might be true, depending on different circumstances.

The test is based on key days chosen from the same 1966–1969 interval, for their selection, however, a geomagnetic criterion was prescribed: $\Sigma \mathrm{Kp} \geqq 25$. Additionally, in order to have an independent test, days with particle events of the catalog of Švestka and Simon (1975) were excluded. Altogether 10 major magnetic disturbances have fulfilled the selection criteria. Mean departures of the ionospheric absorption (245 kHz) from the corresponding monthly median are shown on and around the selected key days in the lower part of Figure 5. For the rather moderate after-effect the following explanation can be given. Seven out of the ten selected magnetic disturbances were preceded by corresponding solar flares of importances of Sb, 1b, 3b, or 2n (according to the dual-importance scheme adopted by the International Astronomical Union). In any case, only two flares out of them were located in the central-zone of the solar disk and all remaining ones were observed in the outer-zones. Thus, the results

Table 1. Classification of flare-associated electron fluxes (>40 keV) observed on spacecrafts between 1966 and 1969. (The flux data were selected from the catalog of Švestka and Simon, 1975)

Flare position	90° E–30° E East-flare	30° E–30° W Central-flare	30° W–90° W West-flare	Flare importance
Number of cases	1	12	17	CFI = 0–8
El. $(cm^2\ s\ ster)^{-1}$ median value	(600)	200	160	
Number of cases	1	8	12	CFI = 9–16
El. $(cm^2\ s\ ster)^{-1}$ median value	(100)	325	1750	

of the test implicitly hint at the outstanding role of the central-zone flares in the after-effect. In addition, the results have shown that the intense magnetic disturbances are not always followed by a significant absorption after-effect. Certainly, this also occurred in cases included in the test as the increased magnetic activity was connected with outer-zone flares.

Finally, Table 1 presents some parameters of the 51 flares with electron fluxes (>40 keV) investigated in the previous sections. Both flare position and flare importance have been taken into account for the classification. The scarcity of observed electron fluxes in case of E-flares is due to the general spiral structure of the interplanetary magnetic field which guides the flare particles. Consequently, electrons emitted from the eastern outer-zone on the solar disk have only a little chance to encounter the earth. The opposite is true for the western outer-zone flares, what is confirmed by the corresponding number of cases in Table 1. Median values of electron fluxes connected with important flares (CFI = 9–16) are rather different; they depend on the flare position as shown in Table 1. After all, although the fluxes were more intense in case of W-flares than in case of C-flares, the geomagnetic activity was higher and the absorption after-effect more significant following C-flares (cf. Fig. 4). This stresses again the clear relationship between events connected with central-zone flares and the investigated effect.

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Received April 27, 1978 / Accepted July 26, 1978