Delayed ionospheric absorption events following enhanced geomagnetic activity

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Superposed-epoch methods have been used to investigate absorption levels (using \(f_{\text{min}}\) values) in the hours before and after hours of high AE index for some auroral, sub-auroral and high mid-latitude stations. It is shown that absorption occurs preferentially in the sunrise period for auroral stations, and in both sunrise and sunset periods for other stations. The absorption can extend up to 3 days after high geomagnetic activity for auroral-zone stations and is observed at progressively longer delays as stations further from the auroral zone are considered. Other plots have been made for a number of stations using days of high \(f_{\text{min}}\) as controls to consider AE-index levels in the hours before and after the centre times for these controls. Results were found to be consistent with those found when high AE indices were used as controls. There is some discussion on the characteristics of some geophysical parameters which could be associated with these delayed absorption effects.

1 Introduction

Published hourly values of \(f_{\text{min}}\) obtained from ionograms have been used in this paper to investigate relationships between geomagnetic activity (as determined by the AE indices) and ionospheric absorption at stations located in auroral, sub-auroral and high mid-latitude regions. Of particular interest are delayed effects such as those reported by Lauter and Knuth\(^1\) for a high mid-latitude station (see also Bourne and Hewitt\(^2\)). Lauter and Knuth\(^1\) found most delayed absorption occurred about 3 days after geomagnetic activity although some effects were recorded with delays as long as 10 days. It is important to note (because of the results to be presented here) that the delayed absorption seemed to be concentrated in the sunrise and sunset periods (see also Belrose and Thomas\(^3\)). Besides absorption similar delayed occurrences have been reported for other geophysical phenomena including mid-latitude spread-F. These other phenomena are mentioned (with references) by Bowman\(^4\), where the delayed occurrence of spread-F following increased geomagnetic activity is examined in some detail. This analysis involving spread-F is considered further in another paper\(^5\).

Since these early investigations into delayed absorption effects, it has been shown in a number of papers\(^6\)\(^-\)\(^9\) that the absorption results from the precipitation of electrons into the D-region. The sequence of events which leads to the delayed absorption is summarized by Spjeldvik and Thorne\(^10\) who write “Throughout the storm recovery the electrons radially diffuse to lower L and decay slowly ...”. Precipitation loss during the storm recovery is shown to be a major D-region ionization source responsible for storm after-effects at middle latitudes. Within the plasmasphere, electron precipitation results primarily from resonant pitch angle scattering with naturally occurring ELF whistler mode turbulence. Furthermore their theoretical calculations\(^10\) show that “Enhanced D-region ionization should persist for approximately a week following the storm, consistent with electron precipitation lifetimes.”

It has been known for some time\(^7\)\(^-\)\(^11\) that two types of auroral-zone precipitation are found to be associated with increased geomagnetic activity. One type is recorded around midnight. The other type, thought for many years to result from an eastward drift of electrons deposited into the radiation belt in the midnight sector, is recorded in the early morning hours. Kremser \(et\ al\)\(^8\) have called the precipitation around midnight “direct precipitation” and they have used the term “drift precipitation” for the early morning events. However recently Hargreaves and Devlin\(^12\) have presented results not consistent with these ideas. Concerning morning-sector precipitation events they state “... it is shown that the spectrum is most energetic at the maximum of the event and softens subsequently. The observations cannot
be explained by simple gradient-curvature drift of
trapped electrons." Also, earlier Berkey et al. commented "The observations cannot all be understood
in terms of gradient and curvature drift of electrons
from a small area of injection only."

For the analyses performed for this paper any AE
index $\geq 276$ nT (approximately $\geq 5$ on the $K_p$
scale) was regarded as a high AE index. High values
which were used as controls in superposed-epoch
analyses were determined in sets for each hour of the
day (universal time, UT) from July 1957 to Decem-
ber 1960. Sets of controls for each hour were also
determined for very low geomagnetic activity
(AE index $\leq 75$ nT or $K_p \leq 1$). The superposed-
epoch analyses not only investigated $f_{\text{min}}$ levels rela-
tive to high AE controls but in addition the var-
iations in AE indices (hourly values) were consid-
ered relative to times of high $f_{\text{min}}$ occurrence at three
mid-latitude stations. Any day when the value of $f_{\text{min}}$
was greater than 1.3 times the medium value for the
month, for any of the hours (local time, LT) 1300 to
1700 (inclusive) was called an $f_{\text{min}}$ control day.
These $f_{\text{min}}$ control days were determined for

Corrected geomagnetic coordinates have been
used. Details of the ionosonde stations used in the
analyses are listed in Table 1.

### 2 Methods of analysis

Superposed-epoch analyses for each hour of the
day (UT) have been performed to determine the sig-
nificance of $f_{\text{min}}$ variations (hour by hour) relative to
the high AE-index controls which apply to each anal-
ysis. This section of the investigation involved 96
separate analyses (i.e. $4 \times 24$) since four stations
(College, Campbell Island, Uppsala and Christch-
urch) were used. Although the number of AE-index
controls varied for each hour of the day the average
for the 24 sets of controls (from July 1957 to Decem-
ber 1960) was 349. The array of values resulting
from each analysis was quite large as it extended
from minus 1200 hourly values to plus 1200 values
either side of the control hour, so that 2401 values
resulted from each analysis. A second set of 2401
values was obtained by using very low AE-index
controls (equal in number to the high controls).
Each of these values was subtracted from a corre-
sponding value in the first set, thus producing a set
of values representing displacements from average
conditions. Thus some compensation is made for
the diurnal variation of $f_{\text{min}}$ at each station. The
mean of the set of values obtained after subtraction
was determined along with the standard deviation
(SD) of the set. Finally each analysis output was nor-
malized so as to show each value of the final set in
terms of its SD displacement from the mean. Thus
an indication is available of the significance of any
particular value judged from its SD displacement
from the mean.

The investigation of AE-index values relative to
$f_{\text{min}}$ controls was performed in a similar manner ex-
cept that (unlike the use of AE controls) only one set
of controls was used. In addition each analysis re-
sulted in 1601 values, 800 before and 800 after the
control time. The control time used was 0100 UT
on the day of high $f_{\text{min}}$ as defined in Sec. 1. Thus the
centre time for these superposed-epoch plots is
1300 LT for Christchurch and Auckland and 1100
LT for Brisbane (see Table 1), these being the
stations used in this part of the investigation.

### 3 Results

#### 3.1 AE-index controls

In the superposed-epoch plots presented in this pa-
per, 24 h periodicities appear in the $f_{\text{min}}$ distri-
butions. Figure 1 represents the result of an analysis to
investigate whether or not these are produced by
24 h periodicities in the tabulated AE indices. A su-
perposed-epoch analysis (again having an output
of 2401 values) has been performed on AE indices
relative to hours of high AE-index values for 9 sets

![Fig. 1](image_url)

**Fig. 1**—Level of the AE index for several days on either side of
hours which experience high AE indices. High values for each
hour from 1500 to 2300 UT (inclusive) have been used for the
period 1957-60.
of controls (for hours 1500 to 2300 UT inclusive), in all involving 3416 controls. Although the control sets are for different hours, the distributions for each set were shifted hour by hour so that the final output represented occurrence relative to high AE indices irrespective of the hour of each set of controls. Figure 1 shows that although (as expected) conservation of geomagnetic data exists for a few days either side of the hour of high AE index, nevertheless there is no tendency for the high activity to peak at 24 h intervals.

The centre sections (which are the sections of interest) of the SD-displacement outputs using sets of controls for particular hours of the day are presented in Fig. 2. Outputs for the hours (from the 24 sets) which recorded maximum absorption at the time of high AE index were chosen for College and Campbell Island while the control hours used for Uppsala and Christchurch were chosen arbitrarily. Figures 2(a) and 2(b) show that at times before and after the control hour (0800 LT and 0500 LT respectively) there is a marked preference for absorption to occur in the sunrise period. Because of the conservation of geomagnetic activity (Fig. 1), the level of activity either side of the central hour is expected to be symmetrical. The fact that this is not so seems to suggest that the significant asymmetry which is observed results from the precipitation of charged particles which were trapped earlier at the control hour. Thus it seems likely that charged particles injected into the trapping region at times of high AE index are responsible for some of the delayed absorption (on following days) which occurs at these auroral stations. This absorption is centred on the sunrise period for up to 2 days after the time of injection. Both Uppsala and Christchurch (sub-auroral and high mid-latitude stations respectively) show, as Figs 2(c) and 2(d) indicate, a preference for excessive absorption to occur not only in the sunset period but also in the late afternoon (around 1500 LT). For Uppsala the absorption is concentrated within a day or so of the control hour with however weaker delayed absorption effects extending out to about 4 days. The reverse is true for Christchurch where there is little or no absorption near the control hour. Here the significant absorption occurs around +2.5, +3.5 and +4.5 days. These observations are consistent with the earlier results of Lauter and Knuth and Belrose and Thomas who reported delayed absorption events in sunrise and sunset periods (see Sec. 1). Twenty-four sets of controls (one set for each hour of the day) were used to produce a similar number of plots related to Christchurch $f_{min}$ occurrence.

![Fig. 2—Plots showing the significance of $f_{min}$ levels relative to specified hours of high AE index for College, Campbell Is., Uppsala and Christchurch for the period 1958-60](image-url)
ence. Figure 2(d) illustrates some of the results (distribution points close to the central hour) from one of these plots. For these 24 plots maximum absorption effects were usually found around +3.5 and +4.5 days. However these plots also show isolated peaks in absorption recorded out as far as +9 days. For example, on one particular plot a peak of 3.4 \( \sigma \) occurs at 1200 LT for a delay of about 8.5 days. For each plot SD displacements were averaged 3 days at a time (in local time hours) starting with the group (-3, -2, -1) days and finishing with the group (+7, +8, +9) days. The averages of 24 such 3-day groups (one for each control hour) are shown in Fig. 3 where it can be seen that there is a shift in times of occurrence as the delay times increase. Although the average absorption effects are close to sunrise and sunset for days +1, +2 and +3, in subsequent days there is a movement of times of occurrence towards midday. For example the absorption which is centred around 1600 LT for days +1, +2 and +3 [Fig. 3(b)] is shown to move to 1300 LT on days +7, +8 and +9 [Fig. 3(d)]. The local time of midnight closest to the control hour (expressed in UT) was taken as the point separating the negative delays from the positive delays.

From the 24 plots for College which use sets of controls for each hour of the day, the centre sections of 3 particular plots (for the hours of 2000 LT, 0000 LT and 1400 LT) are presented in Fig. 4. Figure 2(a) shows a similar plot for 0800 LT. The conservation of geomagnetic activity (illustrated by Fig. 1) means that because the plots in Fig. 4 are statistical results, a relatively high level of geomagnetic activity can be expected for at least 2 days either side of the control hours in Figs 4(a), 4(b) and 4(c). As in the case for Figs 2(a) and 2(b) the absorption shown in the 3 diagrams of Fig. 4 is concentrated around the sunrise period. This occurs even though the level of absorption is sometimes not very pronounced at the times of high AE index [Fig. 4(a)]. However it is important to note that although conservation alone would predict symmetry with respect to the centre time, there is [as with Fig. 2(a)] a definite bias indicating additional levels of absorption at positive delays out to +3 days. As proposed previously [for Figs 2(a) and 2(b)], it seems likely that this additional absorption results from the precipitation (from the radiation belt) of particles trapped sometime earlier. The level of maximum absorption shown in Fig. 4 in the sunrise period (a maximum value of 7.0 \( \sigma \)) is somewhat lower than that absorption recorded [11.0 \( \sigma \); Fig. 2(a)] when the AE index is high in the sunrise period. When the AE index is high at local midnight and a superposed-epoch analysis performed [Fig. 4(b)] the SD displacement \( \sigma \) is given as 5.5 whereas at 0800 LT on the morning following it is 6.9 \( \sigma \). Also
Figure 5—Centre-time displacements of $f_{\text{min}}$ levels relative to high AE indices from plots related to each hour of the day for College, Campbell Is., Uppsala and Christchurch.

for high AE indices at 2000 LT [Fig. 4(a)] the central hour SD displacement is 2.5 and at 0800 LT on the morning following it is 6.3 \(\alpha\). These observations are thus supportive of the results of Hargreaves and Devlin\(^{12}\) (mentioned in Sec. 1).

Figure 5 shows the centre-time SD displacements for the 24 plots (one for every hour of the day) for the 4 stations used for Fig. 2. Because of the way hourly values of the AE index are defined the values shown in Fig. 2 will actually relate to geomagnetic
activity averaged over the 60 min prior to the hour of listing of the AE index. Consistent with the results discussed in the previous paragraph, it is shown for the two auroral-zone stations [Figs 5(a) and 5(b)] that the highest level of absorption (at least as measured by $f_{\text{min}}$ values) occurs when the AE index is high in the sunrise period. Statistically the sub-auroral station Uppsala [Fig. 5(c)] experiences some absorption at times of high AE index but there is no well-defined preference for this to occur at any particular time of the day. For the high mid-latitude station, Christchurch [Fig. 5(d)], there is little evidence of absorption at the times of high AE index. As shown by Figs 2(d) and 3, for this station the significant absorption effects are delayed.

3.2 $f_{\text{min}}$ controls

The results of analyses, which used high $f_{\text{min}}$ values as controls (discussed previously), are presented in this sub-section. Figure 6 shows that for Christchurch (CG lat. = 50.8°) significant AE-index values are found between -3.5 and -5 day positions. This result is consistent with the results shown by Fig. 2(d). In addition isolated peaks in occurrence can be seen at earlier times (i.e. between -6 and -7 day positions). The analysis for Auckland (CG lat. = 43.2°) indicates (Fig. 7) high AE-index values between -7 and -11.5 days with the peak activity centred around -10 days. For Brisbane (CG lat. = 36.6°) longer delays between high AE-index values and $f_{\text{min}}$ enhancements (due to further radial diffusion) which might be expected, are not recorded, at least out to -16 days (Fig. 8). However unexpectedly there is a peak in the AE-index displacement at -3 days and another peak around +1 day. These results are interesting but outside the scope of the present investigation. Further work needs to be done on these unusual Brisbane results. Absorption effects due to solar flares (which usually precede high geomagnetic activity) may explain the high values after the centre time shown in Fig. 8.

4 Discussion

As explained in Sec. 1 the observations of delayed absorption in sub-auroral and high mid-latitude regions seems to be well understood. This analysis has shown [see Figs 2(a) and 2(b)] that even for auroral latitudes (where the injection occurs) delayed absorption centred on the sunrise period is recorded for 2 and perhaps 3 days following days of high AE index. For lower latitude stations it has been shown that for Auckland (CG lat. = 43.2°) enhanced absorption is found delayed by as long as 11 days (Fig. 7). However absorption delayed by more than 11 days was not found for Brisbane (CG lat. = 36.6°). These mid-latitude results are consistent with the theoretical calculations of Spjeldvik and Thorne who found that the precipitation of electrons which is responsible for the absorption is expected to be insignificant below an invariant latitude of 45°.

It is interesting to consider the enhanced upper-atmosphere neutral-particle densities associated with auroral electrojet activity, which many investi-
gators have examined. In particular, altitude regions from 155 to 250 km have been studied by Forbes and Marcos, 240 to 350 km by Prolss, and 400 to 1000 km by Taeusch et al. Taueusch et al. found 12 and 24 h periodicities in their data of density changes with effects extending right up to equatorial regions. They state "There is a striking periodicity to the atmospheric response throughout the storm. Most of the high-latitude density maximum occur near 0600 or 1800 MT ...". The results by Prolss may also have some relevance to the results presented here. This paper states "... the magnitude of the temperature increase is significantly larger in the morning than in the afternoon/evening local time sector". These observations are for latitudes from the auroral zone to at least 40° CG lat. Equatorward winds are thought to be responsible for these mid-latitude effects. Thus it has been shown that during the progress of magnetic storm enhanced neutral-particle densities at F-region levels are more likely to occur in the morning sector. If these effects extend to lower ionospheric levels (e.g. the D layer) the possibility exists that this enhanced neutral-particle density may in some way be associated with the enhanced absorption, at least in the auroral-zone regions for a day or two after high AE index values [see Figs 2(a) and 2(b)].

Baker et al. have considered the loss process for energetic particles which are produced by substorm acceleration and injection mechanisms. The basic process involves magnetospheric waves interacting resonantly with electrons and ions to scatter the particles, thus perturbing their pitch-angle distributions. Satellite measurements of the increase and decay of electron populations during substorms are shown to be closely associated with ground-level absorption. It is found that strong pitch angle diffusion at L = 6.6 is most probable from 0000 to 0800 LT. The equatorial chorus as considered by Tsurutani and Smith, which is dominant in the early morning hours, is identified as the relevant ELF magnetospheric waves responsible for the pitch angle diffusion, leading to the precipitation of charged particles.

The sub-auroral and high mid-latitude delayed absorption is well understood in terms of radial diffusion and pitch-angle diffusion. However the reasons why this absorption is concentrated in sunrise and sunset periods are not known with any certainty. Also, the movement of the absorption at these times towards midday for longer delays (Fig. 3) is interesting and needs further investigation.

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References