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Increased NO-concentration contributing to the enhancement of radio wave absorption following geomagnetic storms

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Abstract. The increase of the NO-concentration in the lower ionosphere following geomagnetic storms is considered as an additional factor in the development of the after-effects in ionospheric absorption. These mid-latitude phenomena are mainly due to excess ionization produced by precipitating electrons. However, analyses of ionization rates determined for 85 km altitude have confirmed that at this height the enhanced day-time ionization might partly originate from increased NO-concentration. Satellite and rocket observations and data derived from ground-based measurements are used. It is suggested that Meira's NO-profile might be representative of disturbed periods rather than normal conditions.

Key words: Geomagnetic activity – Lower ionosphere – Electron precipitation – Increased NO-concentration – Ionization rates – Absorption after-effect

Introduction

The enhancement of radio wave absorption observed at middle latitudes following geomagnetic storms has generally been attributed to electrons precipitating from the outer radiation belt of the magnetosphere into the lower ionosphere (e.g. Lauter and Knuth, 1967). The precipitation is due to an interaction between trapped electrons and plasmaspheric ELF waves (Spjeldvik and Thorne, 1975). On the basis of satellite and ground-based measurements, Larsen et al. (1976) showed, with experimental evidence, that the excess ionization in the *D*-region after geomagnetic disturbances is a consequence of particle precipitation. Results indicating some relations between after-effects in ionospheric absorption and Pc 1-type pulsations also confirmed the importance of these processes in the generation of the phenomenon (Märcz and Verő, 1977).

Nevertheless, other factors are also believed to be involved into the development of increased ionization at *D*-region heights following geomagnetic disturbances. Belrose (1964) supposed that changes in atmospheric composition originating at auroral latitudes during magnetic storms can be transferred towards lower latitudes. Thus transport processes should also be involved in the occurrence of delayed ionization enhancements at mid-latitudes. Thomas (1971) concluded that both the anomalies occurring in the *D*-region during winter and the effects following certain magnetic storms might in part arise from changes in concentrations of minor neutral constituents.

Rocket observations of the lower ionosphere in winter (Aikin et al. 1977) have confirmed the contribution of increased NO-concentration to the enhancement of electron density which was, however, predominantly caused by energetic electrons precipitated into the mesosphere after a geomagnetic storm. Björn et al. (1979) reported a rocket observation at high latitude during an auroral absorption event. They derived the NO-concentrations for heights between 80 and 100 km by measuring the energy spectrum of energetic (40–800 keV) electrons and the ion composition. The high NO-concentration around 80–85 km was attributed to an efficient downward transport of NO molecules mainly produced above 90 km by interaction of precipitating energetic electrons with the neutral atmosphere.

In the present study it is accepted that the excess absorption of radio waves following certain geomagnetic storms can be generated mainly by processes of magnetospheric origin. In addition to this basic idea, however, the paper applies several previously published results in order to consider the influence of certain atmospheric changes in the development of the after-effect.

Ionization rates at 85 km

Ionization rates determined at middle latitudes both for normal conditions and for periods with after-effects will be studied at a height of 85 km, as this seems to be suitable for certain comparisons. Namely that the following favourable circumstances can be assumed (Taubenheim et al., 1975):

a) the number of negative ions is negligible

b) the total number density of positive ions can be taken equal to the electron density

c) the dissociative recombination of the various species of positive ions with electrons seems to be the main loss process (which can be characterized by an effective recombination coefficient: α_{eff})

d) O_2^+ and NO^+ become the predominant ions, and the role of water-cluster ions diminishes.

Additionally, precipitating electrons of energies >40 keV can reach this height, where an excess ionization is consequently produced.

Normal conditions

During normal day-time conditions the main sources of ionization in the *D*-region are

– Lyman α (1,215.7 Å), ionizing neutral nitric oxide,

Table 1. Ionization rates at 85 km due to XUV-radiation

Ionizing radiation component	Ionized atmospheric constituent	Ionization rate at 85 km ($\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$)	Symbol
Lyman-α ($\sim$1216 Å)	NO nitric oxide	4.0 (a) 10.0 (b)	$q_{L\alpha}$
X-rays ($<$100 Å)	several	1.9 ($<$10 Å) 0.1 ($>$10 Å) 2.0 (Σ)	q_x
UV ($\sim$1108 Å)	$O_2\,(^1\Delta_g)$ metastable oxygen	1.5	q_m

(a) NO profile by Brasseur and Nicolet (1973)
(b) NO profile by Meira (1971)

- Solar UV (around 1,108 Å) ionizing metastable oxygen,
- Solar X-rays ($<$100 Å),
- Galactic cosmic rays.

At 85 km the latter component is negligible in comparison with the other ionization sources. Table 1 shows the ionization rates due to the three main components of the ionizing radiation. The values are given for high solar activity and summer at $\chi = 40°$ solar zenith angle, on the basis of Taubenheim et al.'s (1975) results.

In Table 1 the rate of ion production due to Ly-α depends on the NO-density distributions applied in the calculations. The ionization rate with Brasseur and Nicolet's (1973) theoretical model is smaller than that based on Meira's (1971) rocket profile. Ionization by hard ($<$10 Å) and soft ($>$10 Å) X-rays together amounts to half of the production by Ly-α in the case of NO distributions according to Brasseur and Nicolet. The radiation component, ionizing metastable oxygen, has the lowest share in the total ionization (Q_o) at 85 km. Q_o is calculated as the sum of the individual components:

$$Q_o = q_{L\alpha} + q_x + q_m \tag{1}$$

Depending on the $q_{L\alpha}$ value applied, two different approximations can be given for Q_o: 7.5 and 13.5 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. The possible sources of this large discrepancy will be discussed later. Initially the smaller Q_o value (based on Brasseur and Nicolet's NO distributions) will be used. Meira's profile has been mentioned as anomalous at heights below 90 km (Mitra and Rowe, 1974) and this may be true even if an improved NO γ band emission rate factor (Witt et al. 1976) reduces Meira's results to a certain extent.

Periods with after-effects

During periods with after-effects in radio wave absorption, an excess ionization appears in the *D*-region which should also be indicated by the ionization rates determined for the 85 km height. There are only sparse direct measurements of precipitating particles which generate the excess ionization. On the basis of coordinated satellite and ground-based measurements, Larsen et al. (1976) have derived ionization rates due to precipitating electrons for *D*-region heights. By calculating the median value from six individual measurements we have determined an approximate ionization rate (Q_p) for 85 km: 35.5 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. This can be accepted both for day and night.

In day-time, however, the rate of ion pair production by ionizing radiations is different, as shown above. Thus the total ionization for periods with after-effects is the sum of two components: $Q_o + Q_p$. Consequently the day-time ($\chi = 40°$) ionization rate for 85 km amounts to 43 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ in the case where Q_o is derived using Brasseur and Nicolet's NO distributions.

Ionization rates for periods with after-effects on the basis of electron density data

Around noon a quasi-stationary equilibrium between ion production and recombination loss can be assumed in the *D* region. This is simply described by

$$Q_o \approx \alpha_{eff}\, N_{eo}^2 \tag{2}$$

where Q_o is the total ionization rate due to ionizing radiations during normal conditions, N_{eo} is the electron density determined during normal conditions and α_{eff} is the effective recombination coefficient (at 85 km practically equal to α_D, the dissociative recombination coefficient). Transport effects are not considered in the simplified equation of continuity given above as, in the *D*-region, the ions have too short a life-time for transport to be effective.

Extending these considerations to periods with after-effects, another continuity equation is valid

$$Q_a \approx \alpha_{eff}\, N_{ea}^2 \tag{3}$$

where Q_a is the total ionization rate due to both ionizing radiation and precipitating electrons, N_{ea} is the electron density determined in the case of after-effects and α_{eff} is the effective recombination coefficient, assummed to be not greatly different from that for normal conditions.

By combining Eqs. (2) and (3) it is possible to determine a further approximate value of the ionization rate during after-effects (Q_a), however, this time on the basis of electron density data:

$$Q_a = Q_o \frac{N_{ea}^2}{N_{eo}^2} \tag{4}$$

At 85 km Q_o is known, as shown above. For high solar activity and summer conditions the normal day-time ($\chi = 40°$) electron density (N_{eo}) at 85 km is taken from Taubenheim et al. (1975). For day-time ($\chi = 40°$), however, we could not find electron density data determined for an after-effect. Montbriand and Belrose (1976), published electron densities determined in case of $\chi = 70°$ both for normal condition (N'_{eo}) and for after-effect (N'_{ea}). If N'_{ea} is the electron density produced by ionizing radiation accompanied by electron precipitation and N'_{eo} is the electron density due solely to ionizing radiation then the difference ΔN_e between these data can be regarded as an approximate value of electron density due purely to the effect of precipitating electrons. Assuming that electron precipitation is rather constant during the day, the total electron density during after-effects can also be determined for another solar zenith angle (e.g. $\chi = 40°$) in the following way: $N_{ea} = N_{eo} + \Delta N_e$. Finally, the ionization rate (Q_a) during after effects (at $\chi = 40°$) is calculated on the basis of Eq. (4).

In Table 2 the actual values of the parameters discussed their sources and denotations and some further remarks, are presented in order to give a review of the preceding considerations. The procedure applied yields an ionization rate (56 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$) substantially larger than that

Table 2. Actual values for parameters applied and deduced in the text

Publication	Ionization rate Source* Denotation	Electron density Source* Denotation	Solar zenith angle (χ)	Remarks
Taubenheim et al. 1975	$7.5\ \text{cm}^{-3}\ \text{s}^{-1}$ IR Q_o	$5.5 \times 10^3\ \text{cm}^{-3}$ IR N_{eo}	40°	NO-model (Brasseur and Nicolet, 1973)
Montbriand and Belrose, 1976		$2.0 \times 10^3\ \text{cm}^{-3}$ IR N'_{eo}	70°	
		$1.15 \times 10^4\ \text{cm}^{-3}$ IR + EP N'_{ea}	70°	
Present work		$9.5 \times 10^3\ \text{cm}^{-3}$ EP ΔN_e		$\Delta N_e = N'_{ea} - N'_{eo}$
		$1.5 \times 10^4\ \text{cm}^{-3}$ IR + EP N_{ea}	40°	$N_{ea} = N_{eo} + \Delta N_e$
	$56\ \text{cm}^{-3}\ \text{s}^{-1}$ IR + EP Q_a		40°	$Q_a = Q_o \frac{N_{ea}^2}{N_{eo}^2}$

* IR = Ionizing radiation; EP = Electron precipitation

(43 ion pairs $\text{cm}^{-3}\ \text{s}^{-1}$) determined in another way ($Q_o + Q_p$) in the previous section.

Enhanced ionization rate and radio wave absorption due to increased NO-concentration following geomagnetic storms

The difference between the total ionization rates for after-effects, determined in two ways may originate from several sources. The value deduced first ($Q_o + Q_p$) should approach the second (Q_a) if the ionization rate due to precipitating electrons (Q_p) were larger than that used (35.5 ion pairs $\text{cm}^{-3}\ \text{s}^{-1}$). Potemra and Zmuda (1970) determined ionization rates in the nighttime *D* region for different conditions on the basis of model spectra of precipitating electrons (>40 keV). For disturbed conditions the ionization rate due to precipitating electrons was approximately 25 ion pairs $\text{cm}^{-3}\ \text{s}^{-1}$ at 85 km. Unfortunately data on this rate are rather sparse. After all, it can be seen that the Q_p value applied in the present work is quite large when compared with that of Potemra and Zmuda (1970). Thus it is not reasonable to increase Q_p further.

There is, however, another possibility. Namely, that the Q_o value used is rather small, or to be more exact the ionization produced by radiation might be higher for some reason during disturbed periods than under normal circumstances. Q_o is the sum of three components and among them the ionization of NO by Lyman-α is potentially the most important source as shown in Table 1. After geomagnetic disturbances, a considerable change in the Ly-α flux cannot be expected, thus the increase of ionization due to this component may originate from an abundant NO-concentration.

Results mentioned in the introduction have shown that the NO-concentration can really increase at the top of the mesosphere following geomagnetic disturbances. Recently an experiment on the Atmosphere Explorer C(AE-C) satellite indicated an enhancement of the NO-concentration at the base of the thermosphere (Cravens and Stewart, 1978). A clear latitude dependence of the enhancement was found for a height of 105 km, with the largest increase at high latitudes and a more restrained one at low latitudes. Independently of magnetic activity, the NO-density seemed to be almost stable in the equatorial region. According to Cravens and Stewart (1978) a horizontal transport of NO away from the auroral source could account for the latitudinal variation. Moreover, an efficient vertical transport in combination with enhanced lifetime of NO is assumed by Björn et al. (1979) to explain the high concentration of nitric oxide observed in the height range from 80 to 100 km during an auroral absorption event.

On the basis of the AE-C measurements (Cravens and Stewart, 1978) the mid-latitude NO-density in the lower thermosphere can be about three times higher after storms than in normal conditions. Taking into account the foregoing considerations it may be supposed that the increased NO-density results in a higher Lyman-α ionization rate at 85 km, too. The $q_{L\alpha}$ component can generally be written as

$$q_{L\alpha} = n_{\mathrm{NO}} \, J_{L\alpha}$$

where n_{NO} is the number density of neutral nitric oxide at the height considered and J_{L_α} is a function of height depending on the Ly-α photon flux above the atmosphere and its atmospheric absorption given by the optical depth. During storms a change in $J_{L\alpha}$ above the lower thermosphere should not be assumed thus $q_{L\alpha}$ is to be dependent on n_{NO}. Consequently for disturbed conditions the total ionization rate due to all radiations (Q'_o) will be higher and can be described as

$$Q'_o = q_{L\alpha} + \Delta q_{L\alpha} + q_x + q_m \qquad (5)$$

where $\Delta q_{L\alpha}$ is an additional term representing the surplus ionization associated with the increase in n_{NO}, while the remaining terms are those given above.

In the case of a three times higher NO-density during storms, the ionization rate by Lyman-α radiation ($q_{L\alpha} + \Delta q_{L\alpha}$) will be 12 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ at 85 km, when referring to the appropriate NO-concentration given by Brasseur and Nicolet (1973). Thus on the basis of Eq. (5), an approximate ionization rate due to radiation can be determined for periods with after-effects in radio wave absorption (by using $q_{L\alpha} = 4$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ and $\Delta q_{L\alpha} = 8$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$, as well as $q_x = 2$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ and $q_m = 1.5$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$). The calculated $Q'_o = 15.5$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ is about twice as high as that given above for normal conditions. The total ionization rate at 85 km is the sum of Q'_o and Q_p (35.5 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$, which is the share of precipitating electrons during after-effects). At mid-latitudes an ionization rate of 51 ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ can be expected at 85 km in day-time if both the increased NO-density and the particle precipitation is taken into account following geomagnetic disturbances. This value is rather similar to that determined on the basis of electron concentration data ($Q_a = 56$ ion pairs $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$), the discrepancy being about 10%.

Discussion

Using some recently published results, the present paper confirms a contribution from certain atmospheric changes to the development of the after-effect in radio wave absorption. Results deduced here have indicated that a rather enhanced day-time ionization at 85 km may be connected with different kinds of processes following some geomagnetic disturbances. An example has been discussed when 70% of the total ionization might be due to precipitating electrons and the remaining 30% originated from ionizing radiation. Half of the latter portion should be ascribed to the enhanced NO-density following magnetic storms.

Based on the observations of the AE-C satellite (Cravens and Stewart, 1978), an NO-density three times higher than in normal conditions can be expected for the mid-latitude lower ionosphere following geomagnetic storms. Consequently, calculations taking into account this degree of NO-density enhancement yield an ionization rate similar to that deduced from electron density data. In practice, the ionization due to Lyman-α radiation is highly dependent on the NO-distribution applied in the calculations. This is clearly shown in Table 1 where $q_{L\alpha}$ is 2.5 times higher when the NO-density for 85 km is chosen according to Meira's profile instead of that given by Brasseur and Nicolet. It is remarkable that the degree of discrepancy between the two distributions at 85 km and the degree of NO enhancement following magnetic storms (in relation to normal conditions) are quite comparable.

Considering this and knowing that Mitra and Rowe (1974) assumed some irregularities in the lower part of the Meira-profile, we suggest that Meira's profile might be typical for NO-densities associated with geomagnetic effects. Meira (1971) has compiled his profile by means of two rocket measurements. The first rocket was launched on 31 January 1969 and the second one on 6 February 1969 at mid-latitude (Wallops Island, $\varphi = 37.8°$N). The daily ΣK_p values around these days show a rather enhanced geomagnetic activity on some days preceding both launches and even on the start day of the second rocket. Consequently NO-densities measured by these rockets should be more characteristic for periods with after-effects in radio wave absorption than for normal conditions. For that very reason the ionization rate due to Lyman-α radiation, if calculated on the basis of Meira's profile, has approached the value determined by using Brasseur and Nicolet's model with an additional correction ($q_{L\alpha} + \Delta\, q_{L\alpha}$). The latter takes into account the enhancement of NO-density following geomagnetic storms.

It is to be mentioned that increased NO-density may also be taken into account when interpreting another *D*-region phenomenon known as the winter anomaly, which is the enhancement of HF radio wave absorption during winter in the altitude range 75–95 km. Recently a detailed analysis of the winter anomaly has been given by Offermann et al. (1982) on the basis of results of the Western European Winter Anomaly Campaign carried out in 1975/1976. Their model explains the main characteristics of the winter anomaly by combined action of temperature, turbulent downward transport of nitric oxide and horizontal transport of nitric oxide by winds. According to their study the measurements of Meira (1971) were taken in moderately disturbed winter conditions. Based on measurements during that campaign, Arnold and Krankowsky (1979) have shown that NO-densities in the mid-latitude *D*-region may be higher by factors up to about 4–8 on winter anomalous days. Consequently, these NO enhancements are more abundant than supposed for after-effect conditions in the present paper.

Finally, it can be concluded that, although the enhancements in radio wave absorption following geomagnetic disturbances are mainly due to precipitating electrons, earlier ideas considering changes in atmospheric parameters (e.g. Belrose, 1964) as the origin of the after-effects may also be valid to some extent. In the present paper these ideas have been supported by combining several results and showing that, at mid-latitudes, the increased NO-concentration can really contribute to the day-time enhancement of radio wave absorption after certain geomagnetic storms.

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