On the mechanism of the post-midnight winter $N_mF_2$ enhancements: dependence on solar activity

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Abstract. The mechanism of the $N_mF_2$ peak formation at different levels of solar activity is analyzed using Millstone Hill IS radar observations. The $h_mF_2$ nighttime increase due to thermospheric winds and the downward plasmaspheric fluxes are the key processes responsible for the $N_mF_2$ peak formation. The electron temperature follows with the opposite sign the electron density variations in this process. This mechanism provides a consistency with the Millstone Hill observations on the set of main parameters. The observed decrease of the nighttime $N_mF_2$ peak amplitude with solar activity is due to faster increasing of the recombination efficiency compared to the plasmaspheric flux increase. The $E \times B$ plasma drifts are shown to be inefficient for the $N_mF_2$ nighttime peak formation at high solar activity.

Key words: Ionosphere (ionosphere–atmosphere interactions; mid-latitude ionosphere; plasma temperature and density)

Introduction

Nighttime $N_mF_2$ enhancements (pre-midnight and post-midnight) are a typical phenomenon for the mid- to low-latitude F2-region which has long been observed both in $N_mF_2$ and TEC (Arendt and Soicher, 1964; Evans, 1965, 1974; Da Rosa and Smith, 1967; Titheridge, 1968, 1973; Bertin and Papet-Lepine, 1970; Young et al., 1970; Tyagi, 1974; Davies et al., 1979; Kersley et al., 1980; Jakowski et al., 1986, 1991; Balan and Rao, 1987; Joshi and Iyer, 1990; Jakowski and Förster, 1995). A morphological study by Mikhailov et al. (2000) of the $N_mF_2$ nighttime enhancements on the latitudinal chain of the Eurasian ionosonde stations has revealed systematic variations with season and solar activity in the occurrence probability of the peaks, their amplitude and timing. In particular, the second (post-midnight) peak shows a well-pronounced seasonal variation in the occurrence probability with the peak to be more frequent in winter compared to summer both at solar minimum and maximum. The largest amplitudes of the peak take place in winter, the amplitudes being small for other seasons. The amplitude of winter $N_mF_2$ enhancements is larger during solar minimum compared to solar maximum. There is a tendency for the amplitude to increase with latitude. A pronounced seasonal variation in the timing of the peak occurrence is also observed with winter peaks being later than summer ones.

The revealed morphological features require physical interpretation. Fluxes of thermal plasma from the plasmasphere into the nocturnal F2-region are considered as a commonly accepted mechanism to explain the effect (Förster and Jakowski, 1986, 1988; Jakowski and Förster, 1995). However, there are problems with model simulation of such nighttime $N_mF_2$ increases as well as with its physical mechanism. The total flux required to produce the observed nighttime electron density increase was estimated to be $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ by Davies et al. (1979) for winter solar minimum conditions. Jakowski et al. (1991) estimated necessary fluxes as $(3-5) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ for similar winter solar minimum conditions. More moderate fluxes of the order of $(1-2) \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ are given by Bertin and Papet-Lepine (1970), Standley and Williams (1984), and Jain and Williams (1984). Direct observations at Millstone Hill (Evans, 1974, 1975) gave plasmaspheric fluxes of the order of $10^7-10^8 \text{ cm}^{-2} \text{ s}^{-1}$ with the most probable average nighttime value of $3 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$. Although the accuracy of nighttime observations is not high when electron concentration is low (Evans et al., 1978), it is difficult to consider large fluxes as real, at least during low solar activity. The scatter mentioned in the required flux estimates reflects the difference in the $O^+$ ion recombination rates for the nighttime F2-region accepted by different authors. Our model calculations for the January 06–12, 1997, CEDAR period, (Mikhailov and

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Förster, 1999) have shown that the strong $N_mF_2$ post-midnight enhancements observed at Millstone Hill can be explained with O' plasmaspheric fluxes equal to (1–2) $\times$ 10$^8$ cm$^{-2}$ s$^{-1}$ in accordance with the Millstone Hill IS radar observations. The variety of nighttime $N_mF_2$ variations observed during this period was shown to reflect the balance between plasma influx and the total number of recombinations in the F$_2$-region ionospheric column controlled by the linear loss coefficient $\beta = \gamma_1[N_2] + \gamma_2[O_2]$. The efficiency of recombination strongly decreases when the F$_2$-layer is uplifted by the nighttime equatorward thermospheric wind and even moderate fluxes of the order of (1–2) $\times$ 10$^8$ cm$^{-2}$ s$^{-1}$ from the plasmasphere appear to be sufficient to produce an essential enhancement in $N_mF_2$. Night-to-night variations was related in our approach with the plasma compression/decompression mechanism under the action of the observed $E \times B$ drift moving plasma from higher L shells to lower ones and squeezing it into the F$_2$-region. In contrast, Richards et al. (2000) when analyzing the same January 06–12, 1997, period came to the conclusion that the nighttime plasmaspheric heat flux variation drives the nighttime ionospheric density variation. However, they could not explain the reason for night-to-night plasmaspheric heat flux variation and their calculated nighttime fluxes of O' ions at 400 km are around 3 $\times$ 10$^8$ cm$^{-2}$ s$^{-1}$ being by a factor of two larger than the observed ones.

Our aim here is the further analysis of the physical mechanism responsible for the $N_mF_2$ nighttime enhancements using Millstone Hill IS radar observations. Among many features of the $N_mF_2$ nighttime enhancements revealed by our morphological study (Mikhailov et al., 2000), the dependence of the winter post-midnight $N_mF_2$ peak amplitude on solar activity will be analyzed.

Morphology of the American sector

It was stressed by Mikhailov et al. (2000) that the results of different morphological studies of the $N_mF_2$ nighttime enhancements in various longitudinal sectors were controversial to a great extent. This may be due to either real longitudinal differences in the occurrence of this effect, or may reflect differences in the method of analysis used. As we are considering Millstone Hill observations, an additional morphological study was made for the American sector. All available ionosonde $f_0F_2$ observations at Boulder (40.0°N, 254.7°E, $L = 2.3$) were analyzed for the years of solar maximum (1957–1959, 1968–1970, 1979–1981, 1989–1990) and solar minimum (1953–1954, 1964–1965, 1975–1976, 1985–1986) using the same method as was applied to the Eurasian sector by Mikhailov et al. (2000). The selected years correspond to the periods around solar maxima and minima of the last four solar cycles. The presence of nighttime peaks was checked in $N_mF_2$ daily variations for the years in question. The absolute minimum was searched in $N_mF_2$ values within the period after sunset to 02 LT, and this value was called $N_{min}$. The amplitude of the peak, $N_{peak}/N_{min}$ and the local time of its occurrence were found for each case. A plateau of 2–3 $N_mF_2$ hourly values was referred to as a peak with its maximum in the middle of the plateau. Several maxima are possible after midnight. Therefore, the largest post-midnight maximum was found and treated as the peak. Only quiet days with $Ap \leq 12$ were analyzed to exclude storm effects, although nighttime $N_mF_2$ increases are frequent during storm periods. The results of the post-midnight (second) peak occurrence are given in Fig. 1 for Boulder.

In general the results are similar to those obtained for the Eurasian sector by Mikhailov et al. (2000). There is a well-pronounced seasonal dependence in the occurrence probability of the peak. As with the Eurasian sector the peak is most frequent in winter (November–February, 70–80% of all quiet days), the summer probability being about 40%. Seasonal differences are larger in the Eurasian sector, (80–90% and 10–30%) for winter and summer periods, respectively. It should be stressed that the seasonal pattern is the same regardless the solar activity. This contradicts the results of Jakowski et al. (1991) for Havana, Cuba, who found an inversion of the seasonal pattern with the largest peak occurrence in summer at high solar activity. Similar to the Eurasian sector, the winter nighttime enhancements are the largest with amplitudes being higher during solar minimum (Fig. 1, bottom). The mechanism of this solar activity dependence for the peak amplitude is analyzed below. Like the Eurasian sector there is a clear dependence in the timing of the peak: winter peaks are later in local time than equinoctial and summer ones (Fig. 1, middle panel). This also contradicts the results of Jakowski et al. (1991) who revealed no seasonal variations in the timing of the peak occurrence during solar minimum and are an inverse to our results showing seasonal dependence during solar maximum with summer peaks to be the latest. Perhaps additional analysis is needed for lower-latitude stations (close to Havana, Cuba) in the American sector to clear up the reason for these differences.

Summarizing the results of the morphological study we may conclude, that there are no substantial differences between the Eurasian and the American sectors in the post-midnight peak occurrence at least for stations with $L$-parameter close to 3. This is important for the further analysis of the Millstone Hill ($L = 3.13$) observations. We must be sure that cases of nighttime $N_mF_2$ enhancement chosen for the analysis reflect the typical situation for the given geophysical conditions.

Millstone Hill observations

Nighttime $N_mF_2$ enhancements are most pronounced during winter conditions. This is the outcome of the morphological study as reviewed in the previous section. Solar activity dependence of the peak amplitude is clearly seen in the observations (Fig. 1, bottom). Therefore, three January nights with Millstone Hill IS radar observations were chosen for the analysis. Solar minimum conditions are presented by January 08, 1997,