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6. AUTHOR(S) W. Swider, T.J. Keneshea*				
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# The Quiet Sunrise *E* Region: Enhancements at High Latitudes in Winter Due to Increased Nitric Oxide

W. SWIDER AND T. J. KENESHEA<sup>1</sup>

*Geophysics Directorate, Phillips Laboratory, Hanscom Air Force Base, Massachusetts*

*E* region electron concentrations derived from European Incoherent Scatter Facility observations at 70°N were found to be much larger than normal for high solar zenith angles during 23 of 32 days in winter. Electron concentrations computed with the Keneshea code are compatible with the observations if nitric oxide concentrations are about  $10^7$  cm<sup>-3</sup> at 100–110 km. For these altitudes near ground sunrise, it is shown that numerically, the nitric oxide concentration approximately equals the square of the electron concentration.

## 1. INTRODUCTION

Nitric oxide is a minor, but important, constituent of the atmosphere up to approximately 150 km. This ubiquitous gas helps destroy ozone in the stratosphere and is an important IR emitter in the lower thermosphere, and its photoionization creates the undisturbed *D* region.

In the *E* region, NO has two clear roles. In the quiet nadday *E* region, nitric oxide converts O<sub>2</sub><sup>+</sup> ions into NO<sup>+</sup> ions by the charge transfer process, O<sub>2</sub><sup>+</sup> + NO → NO<sup>+</sup> + O<sub>2</sub>. This reaction increases the mean recombination coefficient of the *E* region, but only slightly, as the dissociative recombination rate coefficient of NO<sup>+</sup> is about twice that of O<sub>2</sub><sup>+</sup> and as the electron concentration is inversely dependent upon the square root of this coefficient. These two ions are the only significant ones in the nonsporadic *E* layer. By day, they have comparable abundances [Keneshea *et al.*, 1970]. At night, NO<sup>+</sup> is by far the more dominant ion, arising principally from the above charge transfer process, with O<sub>2</sub><sup>+</sup> produced mainly from the photoionization of O<sub>2</sub> by scattered solar H Ly β photons. Some NO<sup>+</sup> is generated by the photoionization of NO by scattered H Ly α radiation. (See Strobel *et al.* [1980] for a more detailed analysis of the various faint nighttime ionization sources, including starlight.)

The role of nitric oxide is far more significant in the *E* region at twilight [Swider, 1965; Swider and Keneshea, 1968], the present subject. Near ground sunrise (or sunset), the solar H Ly α flux is unattenuated as it penetrates into the central *E* region, 110–100 km, in contrast to the bulk of the daytime radiation (EUV + X rays) which ionizes O, O<sub>2</sub>, and N<sub>2</sub>. Thus, for a short span of solar zenith angles χ near ground sunrise (or sunset) the dominant ionization source of the *E* region is NO + H Ly α → NO<sup>+</sup> + e. For this reason, the ratio of NO<sup>+</sup> to O<sub>2</sub><sup>+</sup> ions is greatest at twilight [Swider and Keneshea, 1968; Keneshea *et al.*, 1970].

## 2. CALCULATIONS

Time-dependent computations of electron concentrations [*e*] were accomplished with the same code [Keneshea, 1967]

<sup>1</sup>Now at Visidyne, Incorporated, Burlington, Massachusetts.

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used for the first time-dependent model of the *E* region [Keneshea *et al.*, 1970]. Results were presented [Swider *et al.*, 1976] but were never submitted previously for publication. Neutral concentrations and temperatures were taken from the 1966 U.S. Standard Atmosphere Supplements for fall–spring at 45°N with a 1000°K exospheric temperature. Calculations were performed for this latitude at zero solar declination (equinox). Our NO profile is based mainly on the observations by Meira [1971] for 85–105 km, with extrapolation to higher altitudes by diffusion, and henceforth will be denoted as the baseline profile. It will be illustrated later in the text for comparison with other profiles. The NO concentrations are 0.9, 1.0, and 0.9 in units of 10<sup>8</sup> cm<sup>-3</sup>, at 100, 105, and 110 km, respectively, the best altitudes for comparing our model with the European Incoherent Scatter Facility (EISCAT) data. Incidentally, our baseline profile closely matches a one-dimensional model for NO with an auroral electron flux of 0.5 ergs cm<sup>-2</sup> s<sup>-1</sup> [Barth, 1992].

As before [Keneshea *et al.*, 1970], scattered intensities for H Ly α and H Ly β at night are 1% and 0.4% of their respective noon (χ = 45°) values. Strobel *et al.* [1974] used more detailed scattering profiles, but their work is more pertinent to the nighttime *E* layer. These scattered intensities are of little significance at sunrise but only establish the nighttime levels of the electron concentrations prior to sunrise. All other photon intensities also are as before, except that X ray intensities were reduced by a factor of 4. The proper level of X ray intensities remains somewhat controversial [cf. Siskind *et al.*, 1990; Clancy *et al.*, 1992]. This problem is not of concern here, as X rays are negligible in the lower twilight *E* region because of their attenuation.

Rate coefficients were updated from those listed by Keneshea *et al.*, [1970], and in particular, the rate coefficient for the charge transfer process O<sub>2</sub><sup>+</sup> + NO → NO<sup>+</sup> + O<sub>2</sub> was lowered slightly from 6 to 4.6 × 10<sup>-10</sup> cm<sup>3</sup> s<sup>-1</sup>. However, since the ion chemistry of the lower *E* region at twilight is reduced basically to the photoionization of NO followed by the dissociative recombination of NO<sup>+</sup> ions, only the dissociative recombination coefficient of NO<sup>+</sup>, *k*, is significant. The value adopted for *k* was 4 × 10<sup>-7</sup> cm<sup>3</sup> s<sup>-1</sup> (300/T). Application of the most recent value for the rate coefficient would have minimal impact on the calculations as it differs little from that used here, and as the electron concentration is a function of the inverse square root of *k*.

Production rates for NO<sup>+</sup> at twilight from solely the photoionization of NO by H Ly α, *q*(NO, H Ly α), are

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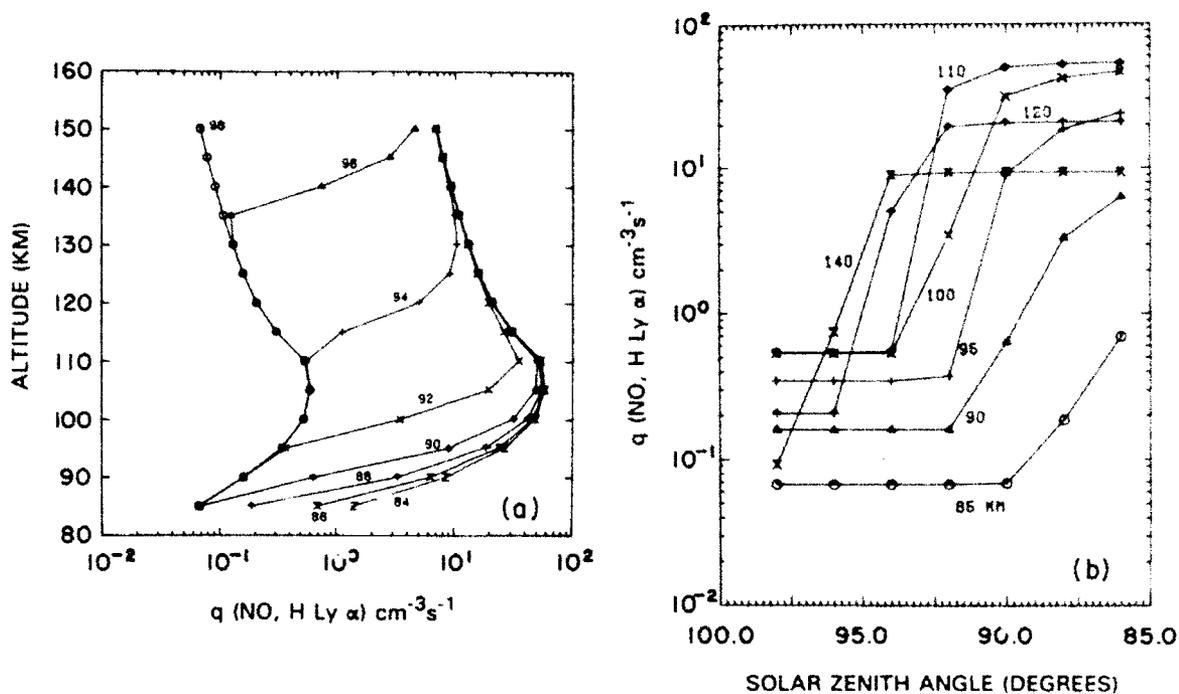


Fig. 1. Production rates for  $\text{NO}^+$  at twilight from the photoionization of NO by H Ly  $\alpha$  versus (a) altitude for solar zenith angles in  $2^\circ$  intervals and (b) solar zenith angle for selected altitudes. (Ten times the baseline NO concentrations used in the calculations are given in Figure 3.)

displayed in two formats in Figure 1. Figure 1b shows that at 110 km, H Ly  $\alpha$  sunrise begins (sunset ends) near  $\chi = 94^\circ$ , and by  $\chi = 90^\circ$ ,  $q(\text{NO}, \text{H Ly } \alpha)$  has almost attained its maximum value. At 95 km, H Ly  $\alpha$  sunrise occurs at  $92.5^\circ$ , and  $q(\text{NO}, \text{H Ly } \alpha)$  attains nearly its maximum value by  $87.5^\circ$ . The changes in  $q(\text{NO}, \text{H Ly } \alpha)$  are quite abrupt, almost step functions.

The ionization coefficient for NO,  $\sigma_1 I_0$ , is  $6 \times 10^{-7} \text{ s}^{-1}$ , the product of the photoionization cross section,  $\sigma_1$ , and a nominal photon flux of  $3 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$  for  $I_0$ , the intensity of H Ly  $\alpha$ . The maximum ionization rate of NO by H Ly  $\alpha$  is  $\sigma_1 I_0 [\text{NO}]$ . At 105 km, for example, the product is  $60 \text{ cm}^{-3} \text{ s}^{-1}$ . This  $\text{NO}^+$  production rate is a factor of 5 higher than that calculated by Swider and Keneshea [1968], since they used values of  $3.2 \times 10^7 \text{ cm}^{-3}$  for  $[\text{NO}]$  and  $2 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$  for  $I_0$ , or a value of 0.21 lower for  $I_0 [\text{NO}]$ . This lower value for  $I_0$  is more appropriate for solar minimum.

### 3. COMPARISONS WITH EXPERIMENTAL DATA

The EISCAT radar has provided evidence of an enhanced E layer during quiet conditions for  $\chi < 93^\circ$  [Kirkwood, 1991]. The layer was present on 80% of 32 winter days. Electron concentrations  $[e]$  from EISCAT observations are compared in Figure 2 with  $[e]$  profiles computed with our baseline NO profile (Figure 2a) and with NO concentrations 10X (Figure 2b) and 100X (Figure 2c) greater. From comparison of Figure 2a with Figure 1a, the other ionization sources (EUV + X rays) become important above 110 km as  $\chi$  decreases below  $90^\circ$ . For Figure 2c, ionization of NO is the dominant ionization mechanism at all altitudes. Note that near 100–110 km, computed  $[e]$  increases by a factor of 3 for an  $[\text{NO}]$  increase of a factor of 10 at altitudes where  $q(\text{NO}, \text{H Ly } \alpha)$  is the dominant ionization source, since, as shown later,

$[\text{NO}]$  is roughly proportional to  $[e]^2$ . The NO concentrations appropriate to the EISCAT measurements are estimated from Figures 2b and 2c to reach concentrations slightly above  $10^9 \text{ cm}^{-3}$  at 100–110 km, i.e., about a factor 15–30 times greater than our baseline levels for nitric oxide. For 85–95 km, the increase in  $[\text{NO}]$  is a factor of 10 or less greater than our baseline nitric oxide concentrations.

The functional relationships for NO are better understood if we consider a simple, steady state solution, permissible because of the slow rate of change of the solar zenith angle,  $1.5^\circ/\text{min}$ , appropriate to the EISCAT data:  $70^\circ\text{N}$ ; mid-November:  $\chi = 87^\circ$ . The steady state solution for NO is

$$[\text{NO}] = \frac{k[e]^2}{\sigma I_0 \exp(-\tau)} \quad (1)$$

where  $\tau = \sigma_A [\text{O}_2] \text{H Ch}(\chi, X)$ . By happenstance, this equation simplifies to

$$[\text{NO}] = [e]^2 \exp(\tau) \quad (2)$$

since the ionization coefficient for NO,  $\sigma_1 I_0$ , is  $6 \times 10^{-7} \text{ s}^{-1}$ , as noted above, and since  $k = 6 \times 10^{-7} \text{ cm}^{-3} \text{ s}^{-1}$ ,  $T$  averaging about  $210^\circ\text{K}$ . The absorption cross section of  $\text{O}_2$  at 121.6 nm (H Ly  $\alpha$ ),  $\sigma_A$ , is  $10^{-20} \text{ cm}^2$ . The average scale height  $H$  at 85–110 km is 5.8 km. The Chapman function,  $\text{Ch}(87^\circ, X)$ , is about 15.6 for  $X = (z + R)/H$ , where  $z$  (mean) = 95 km and  $R$  (Earth) = 6370 km.

Using the EISCAT results for  $[e]$ , equation (2) was solved for  $[\text{NO}]$  at 85, 90, 95, 100, 105, and 110 km. The solutions, lower bounds compared to the time-dependent solutions, are plotted as a smooth line labeled  $87^\circ$  in Figure 3 in conjunction with our baseline  $[\text{NO}]$  distribution. Lower  $[\text{NO}]$  is calculated if  $T$  and/or  $I_0$  are greater, according to equation (1). Different models of the atmosphere mainly would shift the

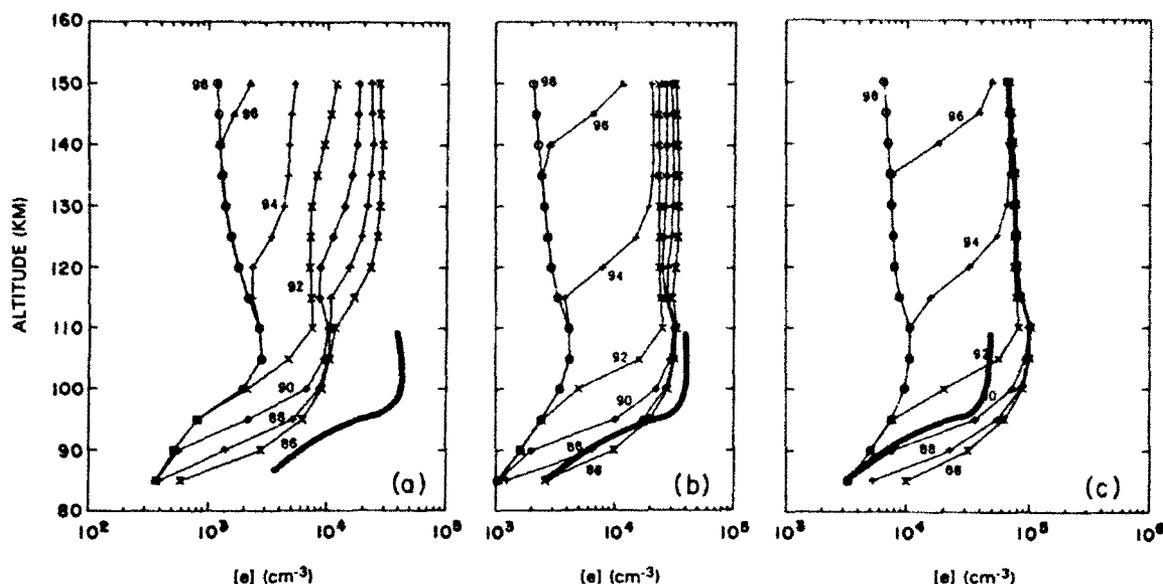


Fig. 2. Electron concentrations  $[e]$  versus altitude obtained from EISCAT observations (bold curve) at  $\chi = 87^\circ$  [Kirkwood 1991], compared with computations of  $[e]$  performed with various NO concentrations: (a) baseline [NO] and with [NO] increased by factors of (b) 10 and (c) 100 times the baseline values. (Ten times the baseline concentrations are plotted in Figure 3.)

entire computation up or down a km or two. It should be particularly noted that for the altitudes 100–110 km, the solution is trivial, as the attenuation of H Ly  $\alpha$  is negligible. Equation (2) is reduced to merely

$$[\text{NO}] = [e]^2 \quad (3)$$

Kirkwood [1991] calculated an electron concentration of  $4 \times 10^3 \text{ cm}^{-3}$  for 100 km at  $\chi = 87^\circ$  for  $[\text{NO}] = 9.5 \times 10^7 \text{ cm}^{-3}$ , a value taken from Witt *et al.* [1976], whose  $[\text{NO}]$  for 100–110 km are within 20% of our baseline concentrations. She calculated  $[e] = 9 \times 10^3 \text{ cm}^{-3}$  by increasing Witt *et al.*'s NO concentration by a factor of 5. The increase from 4 to 9

is in line with the simple theory above (equation (3)). However, we calculate  $[e] = 9 \times 10^3 \text{ cm}^{-3}$  for our baseline NO profile (Figure 2a), suggesting that her computations involve excessive attenuation of H Ly  $\alpha$ . We estimate that Kirkwood's [1991] computations would require NO values near  $10^{10} \text{ cm}^{-3}$  to match the EISCAT data at 100–110 km.

#### 4. DISCUSSION AND CONCLUSIONS

We proposed over a decade ago [Swider *et al.*, 1976, 1977] that analysis of the high-latitude quiet E region at sunrise might yield enhanced concentrations of nitric oxide. The EISCAT results reported by Kirkwood [1991] appear to support this prediction. Both our time-dependent and rough steady state calculations indicate that NO concentrations reach  $1\text{--}3 \times 10^9 \text{ cm}^{-3}$  at 100–110 km. This enhancement provides for an augmented E region at sunrise since H Ly  $\alpha$  photons essentially penetrate these altitudes without any attenuation for solar zenith angles near  $90^\circ$  [Swider and Keneshea, 1968]. We have shown that near ground sunrise,  $\chi = 90^\circ$  the nitric oxide concentration approximately equals (numerically) the square of the electron concentration at 100–110 km. This relationship is true for all latitudes under quiet conditions, providing the nitric oxide concentration is not too low, i.e., that  $\text{H Ly } \alpha + \text{NO} \rightarrow \text{NO}^+ + e$  is the dominant ionization mechanism.

In the polar regions, all other factors being equal, NO concentrations are greatest in winter, when photodissociation of NO is inoperative. Nitric oxide concentrations derived from satellite  $\gamma$  band observations [Rusch and Barth, 1975] show  $[\text{NO}]$  enhanced in the polar regions during winter. The main surprise in the EISCAT observations may be that the  $[\text{NO}]$  enhancements were present 72% of the time, 23 of 32 cases [Kirkwood, 1991]. Nitric oxide concentrations derived from satellite measurements of the NO  $\gamma$  band [e.g., Fesen *et al.*, 1990; Barth, 1992] appear to be lower, on average, than those estimated here and those

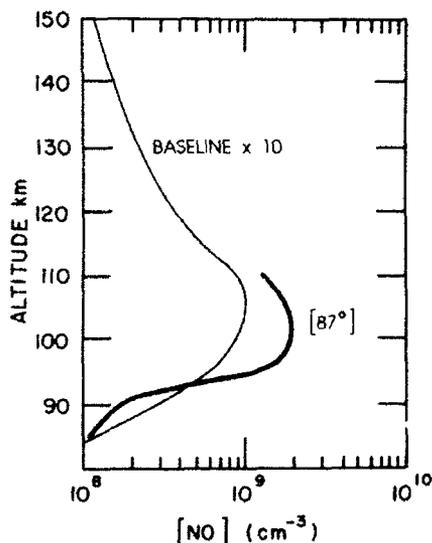


Fig. 3. Nitric oxide concentrations (bold curve) estimated from EISCAT electron concentrations at  $\chi = 87^\circ$  using equation (2). The thin curve is the baseline  $[\text{NO}]$  profile used in our computations increased by a factor of 10.

derived from in situ auroral ion composition measurements [Swider and Narcisi, 1977]. Although, in the latter study, in at least three of the eight auroral events considered, [NO] equaled  $10^9 \text{ cm}^{-3}$  at 100 km. In part, the lower values for the satellite-based data may be attributable to their being averaged over a much wider area than either the EISCAT- or the rocket-based data.

We have not presented any sunset profiles because their interpretation is more complex. Perturbations by sporadic *E* and aurora are more difficult to discriminate from the normal daytime *E* region behavior in comparison to the low background conditions prior to sunrise. However, the late afternoon data from EISCAT are quite similar [Kirkwood, 1991] to the early morning data depicted here.

Other mechanisms for an enhanced *E* region at sunrise are thought less likely. There is no evidence, for example, of enhanced layers of meteoric ions at high latitudes, although the data base is meager [Swider, 1984].

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- W. Swider, PL/GPS, Hanscom AFB, MA 01731.

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