

The northern auroral region as observed in nitric oxide

C.A. Barth, D.N. Baker, and K.D. Mankoff

Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder

S.M. Bailey

Center for Atmospheric Sciences, Hampton University, Hampton, VA

Abstract. The distribution of thermospheric nitric oxide in the northern polar region has been measured from the Student Nitric Oxide Explorer (SNOE). A polar image of a one-year average at 106 km shows the maximum density lies between 60° and 70° N geomagnetic latitude. The density around this auroral oval varies as a function of longitude with the larger densities occurring at western geomagnetic longitudes. A polar image of a second year of observations demonstrates the same latitudinal-longitudinal density distribution indicating that the asymmetry is a persistent property of the auroral region. For a period of high geomagnetic activity, the nitric oxide observations indicate that the flux of precipitating electrons at 90° W geomagnetic longitude was 75% larger than the flux at 90° E geomagnetic longitude. We suggest that this asymmetry is caused by the longitudinal variation in the magnetic field strength around the auroral oval.

Introduction

The concept of an auroral oval originated from the analysis of all-sky camera images of the visible aurora obtained during the International Geophysical Year (IGY) [e.g., *Akasofu, 1977; Feldstein and Galperin, 1985*]. The auroral oval is the region where the maximum flux of precipitating electrons interacts with the atmosphere producing ionization, luminosity, and heating. This region is usually described using magnetic local time coordinates (MLT) with the earth and its geographic features rotating below the auroral oval. Satellite images of the ultraviolet aurora measure the entire oval instantaneously [e.g., *Frank and Craven, 1988*]. A sequence of these images shows the auroral oval fixed in space with continents rotating beneath the oval. A survey of over 17,000 images obtained with the Polar UVI instrument shows the most intense auroral emissions occurring near 2230 MLT and 68° N geomagnetic latitude [*Liou et al., 1997*]. A large survey (1.5×10^8 events) of electron precipitation data shows the maximum probability of observing an electron aurora occurs near a magnetic local time of 2100 and a geomagnetic latitude of 67° N [*Newell et al., 1996*].

Nitric oxide is produced in the auroral region by electrons precipitating into the atmosphere in the 1-10 keV range. The maximum density of nitric oxide occurs in the 100-110 km altitude region where precipitating electrons produce the maximum rate of ionization. This paper presents two years

of measurements of nitric oxide in the northern polar region. The density distribution of nitric oxide at 106 km is used to determine the flux of precipitating electrons that produce the observed nitric oxide. Since the time constants for the production and loss of nitric oxide are long (0.8 days), the nitric oxide density is a measure of the amount of electron precipitation that has taken place during the previous day.

Observations

Nitric oxide is measured in the auroral regions from the Student Nitric Oxide Explorer (SNOE) polar-orbiting satellite [*Barth et al., 1999*]. The nitric oxide density is determined from the fluorescence scattering of ultraviolet sunlight by nitric oxide, which is measured with an ultraviolet spectrometer (UVS). The satellite is in a nearly circular, sun-synchronous orbit at an altitude of 556 km with an orbital period of 96 minutes and an inclination of 97.75 degrees. Using the spinning motion of the satellite, the UVS telescope scans the limb five times per minute, producing altitude profiles of the nitric oxide density between 90 and 170 km. The nitric oxide is measured on the daylight portion of the orbit at a local time of 10:30 AM.

Global images have been made of the distribution of nitric oxide in the northern auroral region for a variety of time periods and geophysical conditions. The global image shown in Figure 1 displays the average nitric oxide density at 106 km altitude for a one-year period starting at the spring equinox, March 20, 1998. Data from over a half a million individual limb observations are included in this image. The measurements are sorted into 18 latitude bins and 15 longitude bins.

Nitric oxide is produced in the thermosphere both by auroral particles and by the action of solar soft x-rays on the atmospheric gases. The nitric oxide produced by the solar x-rays has its maximum in the tropics but extends poleward toward the auroral region particularly during the solstices. In Figure 1, the contribution of the nitric oxide from the solar x-rays has been removed from the nitric oxide measured by the SNOE UVS instrument. A photochemical model was used to calculate the amount of nitric oxide produced by the solar soft x-rays using the flux measured by the SNOE solar soft x-ray photometer [*Bailey et al., 1999*]. The calculated nitric oxide for this one-year period was summed and the average subtracted from the observed nitric oxide. The resulting image in Figure 1 shows the yearly average of nitric oxide that is attributed to auroral electron precipitation.

Figure 1 has the north geomagnetic pole (81.5° N, 82.5° W geographic coordinates) in the center of the image. The grids drawn on this image are in corrected geomagnetic coor-

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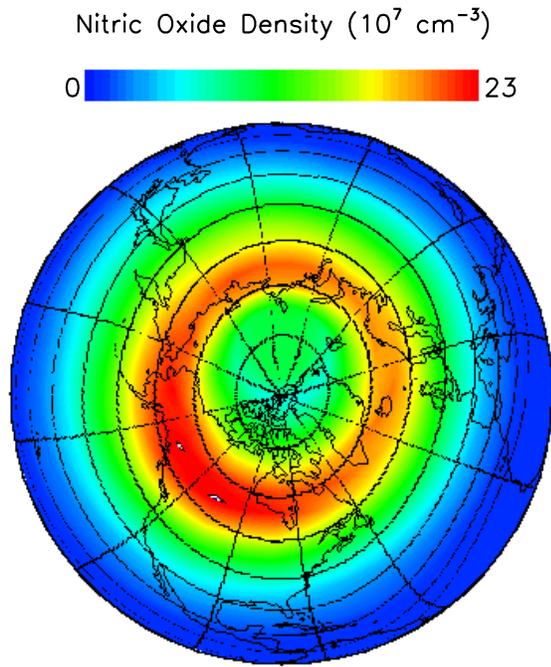


Figure 1. Polar image of nitric oxide density at an altitude of 106 km determined from one year of SNOE observations, March 20, 1998 - March 20, 1999. The largest nitric oxide density is located between 60°-70° N geomagnetic latitude. The grid lines indicate geomagnetic latitude and longitude (CGM). The 0° longitude line crosses the east coast of the United States near the bottom of the image.

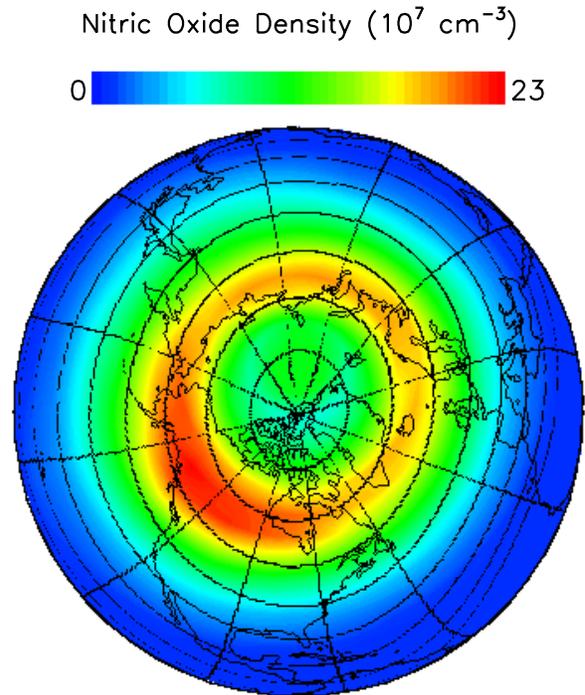


Figure 2. Polar image of nitric oxide density at an altitude of 106 km determined from one year of SNOE observations, March 20, 1999 - March 20, 2000. Both Figure 1 and 2 show the same asymmetric longitudinal distribution of nitric oxide.

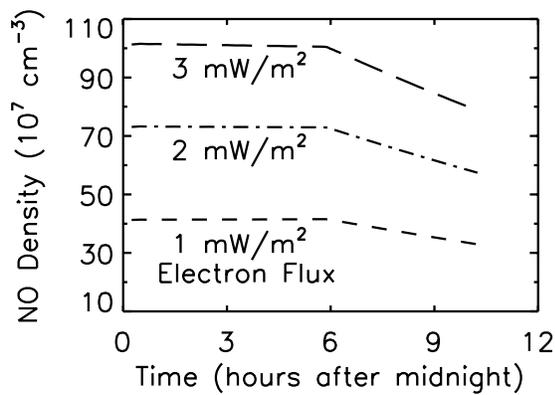


Figure 3. Calculations of the density of nitric oxide at 106 km at 65° N for the period from midnight until 10:30 AM in the morning when the SNOE measurements are made. In the time-dependent model calculation, electron fluxes of 1, 2, and 3 mW/m² were turned on at 6 PM and then turned off at midnight. All three curves show the decrease in nitric oxide that occurs after dawn.

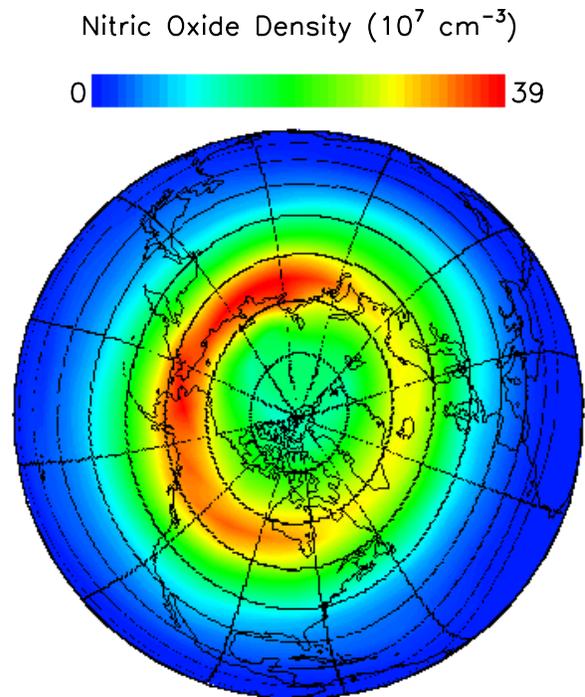


Figure 4. Polar image of the density of nitric oxide at 106 km for the equinox periods between March 20, 1998 and March 20, 1999. These observations were made on those days when the geomagnetic activity index A_p was greater than 12. The grid lines are in geomagnetic coordinates (CGM). The 0° longitude line crosses the east coast of the United States near the bottom of the image. The density of nitric oxide in the auroral oval is larger at longitude 90° W than at 90° E.

dinates (CGM). The maximum nitric oxide density lies approximately between 60° and 70° N geomagnetic latitude. The distribution of nitric oxide has the appearance of an oval because of the shape of the lines of geomagnetic latitude on this orthographic projection. However, the nitric oxide density is not uniform around the auroral oval indicating that the flux of precipitating electrons is not uniform. The density and, hence, the electron flux is larger near a geomagnetic longitude of 90° W and smaller near a geomagnetic longitude of 90° E. The low-latitude boundary of the region of high density extends equatorward of 60° N geomagnetic latitude near 90° W and lies poleward of 60° N near 60° E.

Since the major contribution to the enhanced nitric oxide density during a one-year period is from dozens of geomagnetic storms, the question arises, "Is the spatial distribution of auroral nitric oxide observed in this one-year period (Spring 1998 to Spring 1999) typical or does the distribution vary randomly from year to year"? To explore this question, another one-year period starting March 20, 1999 was analyzed in the same way as the Year One data set. The Year Two data, which are presented in Figure 2, show a distribution of auroral nitric oxide that is nearly identical to the results in Figure 1. The maximum density also occurs between geomagnetic longitudes 60° W and 90° W. The smallest densities occur between longitudes 60° E and 90° E. This comparison suggests that the distribution of auroral nitric oxide shown in Figures 1 and 2 is typical. This further suggests that the asymmetric distribution of precipitating electron flux that is inferred from the nitric oxide distribution is controlled by some intrinsic property of the magnetic field.

Model Calculations

The density of nitric oxide in the auroral region may be correlated to the flux of precipitating electrons with the aid of a thermospheric model [Barth, 1992]. Auroral primary electrons with a characteristic energy of 4 keV penetrate to the 100-110 km level of the thermosphere. These 4 keV electrons ionize the major constituents, N_2 , O, and O_2 and produce nitric oxide. The loss process for nitric oxide is the photodissociation of nitric oxide by ultraviolet solar radiation which has a time constant of 1.6 days. Because the atomic nitrogen produced in the photodissociation of nitric oxide also destroys nitric oxide, the effective time constant for the loss of nitric oxide is 0.8 days (19 hours).

A time-dependent calculation of the production and loss of nitric oxide during an auroral electron precipitation event was performed for the conditions present in the auroral region at a latitude of 65° N geomagnetic latitude. The time chosen for this model calculation was the time of the equinox when there are equal periods of solar illumination and darkness. The auroral electron flux was turned on for a 6 hour period of darkness in the evening starting at 6:00 PM. At midnight, the auroral flux was turned off. The results are shown in Figure 3 for three values of the auroral electron flux starting at midnight just after the electron flux is turned off. During the period of darkness following the end of the electron precipitation, the nitric oxide density remains almost constant. When the atmosphere is illuminated starting at dawn, the nitric oxide density decreases. In the four and a half hour period between dawn and 10:30 AM, the nitric

oxide density decreases by 20% for all values of energy flux. These calculations illustrate how the measurement of nitric oxide at a local time of 10:30 AM may be related to the production of nitric oxide in darkness twelve hours earlier. The amount of nitric oxide produced during the electron precipitation is proportional to the flux of precipitating electrons and the length of time of the precipitation event.

Geomagnetic Activity

To further explore the role of precipitating electrons in the production of nitric oxide, the distribution of nitric oxide in the polar region for varying levels of geomagnetic activity was investigated. The equinox periods between March 20, 1998 and March 20, 1999 (equinox ± 45 days) were chosen for this investigation to allow the use of the results of the model calculation in Figure 3. Nitric oxide densities for those days when the Ap index was greater than 12 were summed and are displayed in Figure 4. The color scale for Figure 4 is set 70% higher than the color scale for Figure 1 so that both figures may use the full range of the color scale. During this 183 day period, there were 70 days of geomagnetic activity greater than 12. The nitric oxide density in Figure 4 was processed the same way as in Figure 1. This image shows that the precipitating electrons create the largest amount of nitric oxide in the auroral oval between 60° and 70° N geomagnetic latitude. However, there is again an asymmetry in the longitudinal distribution of nitric oxide. In the latitude band between 60° and 70° N geomagnetic latitude, the largest amount of nitric oxide is at a geomagnetic longitude of 90° W and the smallest amount at 90° E as in Figures 1 and 2.

The calculations shown in Figure 3 were used to develop an algorithm to convert nitric oxide density into the flux of precipitating electrons that is capable of producing the observed density. This algorithm was applied to the equinox observations at high geomagnetic activity (Figure 4). At 65° N, 90° W, the maximum flux is 1.27 mW/m^2 and at 65° N, 90° E the latitudinal maximum is 0.57 mW/m^2 . The ratio of the maximum to the minimum flux in the auroral oval is 1.75. This means that during the 70 days of high auroral activity ($Ap > 12$) during the 1998-9 equinox periods the electron flux precipitating into the auroral oval was 75% greater at 90° W than at 90° E.

Magnetic field control of electron precipitation

As discussed in the Introduction, auroral luminosity is clearly associated with strong electron precipitation: Both of these physically related phenomena tend to maximize in the premidnight local time sector and are associated with magnetospheric substorms and enhanced geomagnetic activity [see Baker *et al.*, 1996 for a review of substorm models]. In this paper we have made the further association of nitric oxide production in the lower thermosphere with auroral electron precipitation. If local time were the only controlling factor in NO production, we would expect to see a rather uniform distribution of NO around the Earth in geomagnetic longitude. However, when SNOE data are averaged over seasonal and annual time scales, we find a clear geomagnetic, rather than local time, asymmetry in NO production. This suggests that asymmetries in the Earth's magnetic field, and

its extension to the high-latitude atmosphere and magnetosphere, play a clearly discernible role in long-term electron precipitation and resultant NO production.

An obvious candidate for such control is the offset, tilted dipole magnetic field of the Earth [e.g., *Roederer*, 1970]. The Earth's field may be well approximated by a magnetic dipole that is tilted by 11° and offset by ~ 500 km from the center of the Earth [e.g., *Olsen et al.*, 2000]. The tilt of the dipole is well accounted for in the CGM coordinate system discussed in the Observations section of this paper. The offset of the dipole leads to a weaker magnetic field at low altitudes in the south Atlantic region. Electrons mirroring at large mirror field strengths and drifting (eastward) into the south Atlantic region from the west see a weak magnetic field (*Roederer*, 1970). Such particles move further down toward the Earth in order to reach their appropriate mirror magnetic field strength. However, in doing so these electrons enter into the denser atmosphere and are absorbed into the lower thermosphere. This "windshield wiper effect" depletes the electrons throughout the anomaly region. On the east side of the weak magnetic field region, where a higher magnetic field strength again occurs, the electrons can again be replenished by pitch angle scattering of near-equatorial electrons that are produced by substorm and other acceleration effects. We suggest, therefore, that in the present SNOE northern hemisphere observations of NO, we are seeing "normal" electron precipitation west of the weak magnetic field region, but much weakened precipitation of electrons in the weak magnetic field region and eastward of it. Of course, in any particular active interval, local time effects and auroral substorm processes will dominate the auroral luminosity, electron precipitation, and NO production. However, over the long term, averaging over many event intervals, the magnetic field asymmetry signal in the NO density will emerge clearly.

Summary

Nitric oxide that is produced in the auroral region by precipitating keV electrons may be used to deduce the flux of auroral electrons. The observed nitric oxide density is a measure of the amount of precipitation that has occurred during the previous 19 hours. Satellite observations of the northern auroral region show the largest density of nitric oxide in a band between 60° and 70° N geomagnetic latitude centered on the north magnetic pole. However, the density of nitric oxide around the auroral zone is not uniform with the densities at western geomagnetic longitudes being greater than those at eastern longitudes. Satellite observations for two successive one-year periods show a similar distribution of nitric oxide suggesting that the 1998 and 1999

observations are typical and that there is a true, persistent asymmetry in the longitudinal distribution of nitric oxide. Satellite observations of nitric oxide during periods of high geomagnetic activity show an even larger west-east asymmetry in the distribution of nitric oxide around the auroral oval. Using an algorithm derived from a model calculation, the calculated flux of precipitating electrons at 90° W geomagnetic longitude is 75% larger than the electron flux at 90° E.

We suggest that the longitudinal asymmetry in the flux of precipitating electrons is caused by the longitudinal variation of the magnetic field strength around the auroral oval. The electron flux is depleted east of the longitude where the magnetic field strength is weaker.

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C.A. Barth, D.N. Baker, and K.D. Mankoff Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309-0590. (e-mail: charles.barth@lasp.colorado.edu)

S.M. Bailey, Center for Atmospheric Sciences, Hampton University, 23 Tyler Street, Hampton, VA 23668. (e-mail: scott.bailey@hamptonu.edu)

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