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Reevaluation of thermosphere heating by auroral electrons

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Abstract

This paper presents a new calculation of neutral gas heating by precipitating auroral electrons. It is found that the heating rate of the neutral gas is significantly lower than previous determinations below 200 km altitude. The neutral gas heating arises from the many exothermic chemical reactions that take place from the ions and excited species created by the energetic electrons. The calculations show that less than half the energy initially deposited ends up heating the neutral gases. The rest is radiated or lost in the dissociation of O_2 because the O atoms do not recombine in the thermosphere. This paper also presents a new way of calculating the heating rate per ionization that can be used for efficient determination of the overall neutral gas heating for global thermosphere models. The heating rates are relatively insensitive to the neutral atmosphere when plotted against pressure rather than altitude coordinates. At high altitudes, the heating rates are sensitive to the thermal electron density and long-lived species. The calculations were performed with the Field Line Interhemispheric Plasma (FLIP) model using a 2-stream auroral electron precipitation model. The heating rate calculations in this paper differ from previous heating rate calculations in the treatment of backscattered electrons to produce better agreement with observed flux spectra. This paper shows that more realistic model auroral electron spectra can be obtained by reflecting the up going flux back to the ionosphere at the upper boundary of the model. In this case, the neutral gas heating rates are 20%–25% higher than when the backscattered flux escapes from the ionosphere.

Keywords: Aurora; Precipitation; Heating; Efficiency; Thermosphere; Ionosphere

1. Introduction

Energetic electron precipitation is a significant source of thermospheric heating at high latitudes. The energy is initially stored as ionization and excitation energies of the neutral species. Subsequently the energy is converted into translational energy of the neutral particles through a myriad of exothermic chemical reactions. Above ~100 km, only about half of the energy that is initially deposited ends up heating the neutral gases. The rest of the energy is radiated out of the thermosphere from excited species or is lost through dissociation of O_2 because the O atoms must diffuse down below ~100 km before releasing the energy of dissociation in 3-body reactions. Each dissociation event results in 5.08 eV being stored in the O atoms and consequently lost to the thermosphere.

After the auroral energy is deposited into the thermal gases additional energy losses occur through collisional excitation and subsequent radiation from O fine structure at 63μ, NO at 5.3μ, and CO_2 at 15μ. These processes are not part of the heating efficiency calculation because they relate to processes that occur after the auroral energy is deposited in the neutral gases. Thermal electron cooling also produces O fine structure excitation, which results in a small amount of neutral gas heating because O quenching is probably too fast to permit substantial radiation of this energy (Iwagami and Ogawa, 1982). This paper presents a new determination of the auroral electron heating of the neutral gas using updated reaction rates and including some additional processes. A full calculation of the neutral heating rate by energetic electrons is not practical for global ionosphere–thermosphere models. Therefore, the

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heating efficiency concept has been employed in the past (Singh and Gerard, 1982; Rees et al., 1983). Newer models such as the National Center for Atmospheric Research (NCAR) models parameterize the ionization rate profile as a function of energy flux and mean energy, and then derive species-specific ionization rates, dissociation rates, chemical processes, neutral, electron, and ion heating rates explicitly based on this ionization rate. Thus, a heating efficiency approximation is not directly employed (Stan Solomon private communication, 2011).

The neutral heating efficiency at a particular altitude is defined as the rate of energy transferred to the neutral gas divided by the energy deposition rate at that altitude. The heating efficiency can be conveniently parameterized because it is relatively insensitive to the precipitating auroral electron characteristics and variations in the thermosphere composition.

2. Model

The field line interhemispheric plasma (FLIP) model has been developed over a period of more than 30 years as a tool specifically designed to improve our understanding of the physics and chemistry of the ionosphere (Richards et al., 1998; Richards and Wilkinson, 1998; Richards, 2001, 2002, 2004). It incorporates the basic chemical scheme that was developed from the Atmosphere Explorer satellite mission but is continually updated as more information becomes available. The reaction rates in the FLIP model are listed in the Appendix. The ion chemistry in the FLIP model has been validated against Atmosphere Explorer satellite data (Richards, 2002; Richards et al., 2010a). The FLIP model solves for the vibrational distribution of N_2 because the $O^+ + N_2$ loss rate is greatly enhanced for vibrational levels greater than one. It is also an important channel for neutral gas heating. In addition to the exothermic reactions listed in the Appendix, we have included the translational energy from dissociation of molecular nitrogen. From laboratory measurements Cosby (1993) found that N_2 dissociation leads to neutral dissociation fragments with discrete energy peaks at 0.7, 1.2, and 2 eV for impacting electron energies between 18.5 and 148.5 eV. For calculating the neutral gas heating in this paper we have assumed that the dissociation fragments have an average energy of 1 eV. We assume 2 eV for the translational energy of the fragments from dissociative ionization based on the measurements of Deleanu and Stockdale (1975). The translational energy from all N_2 dissociation processes constitutes about 3% of the total neutral gas heating rate.

The FLIP model is a one-dimensional model that calculates the plasma densities and temperatures along entire magnetic flux tubes from below 100 km in the Northern Hemisphere through the plasmasphere to below 100 km in the Southern Hemisphere. The flux tubes can also move under the influence of zonal electric fields. 3-D coverage can be obtained by solving many flux tubes. The model uses a tilted dipole approximation to the Earth's magnetic field.

The equations solved are the continuity and momentum equations for O^+, H^+, He^+, and N^+ and the energy equations for ion and electron temperatures. To solve the equations, we use a flux-preserving formulation together with a Newton iterative procedure (Torr et al., 1990a,b). Secondary ion production and thermal electron heating due to photoelectrons is provided by a solution of the two-stream photoelectron flux equations using the method of Nagy and Banks (1970). The photoelectron solutions have been extended to encompass the entire field line on the same spatial grid as the ion continuity and momentum equations. Chemical equilibrium densities are obtained for NO^+, O_2^+, N_2^+, $O^+(^2P)$, and $O^+(^2D)$ ions below 500-km altitude in each hemisphere. The densities of minor neutral species NO, $N(^2D)$, $N(^4S)$, and vibrationally excited N_2 are obtained by solving continuity and momentum equations in each hemisphere.

The FLIP model calculates photoionization rates and photoelectron fluxes using the high-resolution solar EUV irradiance model for aeronomic calculations (HEUVAC) (Richards et al., 2006). The HEUVAC model is a high-resolution version of EUVAC model (Richards et al., 1994) that also includes the irradiances below 50 Å that are important for photoelectron production. Recent solar EUV irradiance measurements from the SNOE and TIMED satellites support the basic HEUVAC irradiances (Richards et al., 2006; Bailey et al., 2000; Solomon et al., 2001). The FLIP model can also use measured solar EUV irradiances when available.

The auroral model, which uses the same type of 2-stream model as the photoelectron model, has been described by Richards and Torr (1990). The 2-stream technique compares well with other methods such as the diffusion equation formulation and the Monte Carlo technique. Cicerone et al. (1973) found good agreement between three methods in the transport dominated topside ionosphere. Lejeune (1979) showed that the 2-stream method gives excellent agreement with the much more complicated solution of Mantas and Walker (1976) for the Boltzmann coupled differential equations with full angular resolution. Solomon (2001) found very good agreement between the 2-stream method and Monte Carlo methods in a study of auroral precipitation. Richards and Peterson (2008) recently found very good agreement between FAST data and modeled precipitating and backscattered photoelectrons for energies between 10 and 250 eV using the same basic parameters as the auroral code.

Prior to 2006, the FLIP model used the MSIS-86 neutral atmosphere (Hedin, 1987) neutral densities and temperatures. Recently the MSIS model has been revised and this has primarily affected the O_2 densities (Picone et al., 2002). The new NRL Mass Spectrometer, Incoherent Scatter Radar Extended (NRLMSISE) model O_2 densities are not much different at solar minimum but they are a factor of 2 smaller than in previous MSIS models at solar maximum.

There are several factors that support the new O_2 densities. First, the new O_2 densities agree well with densities