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To cite this version:
A. Litvin, W. L. Oliver, Christine Amory-Mazaudier. Hot O and nighttime ionospheric temperatures. Geophysical Research Letters, American Geophysical Union, 2000, 27 (17), pp.2821-2824. <hal-00968641>
Hot O and nighttime ionospheric temperatures

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Abstract. By analysing a large set of St. Santin F region Incoherent Scatter (IS) radar data for low solar activity we find nighttime ion temperature ($T_i$) on average to be apparently slightly higher than electron temperature ($T_e$). We show that this difference is a bias incurred by the IS spectral analysis procedure owing to the neglect of $H^+$ ions in the 300-500 km altitude region. Further, we show $T_e$ and $T_i$ to depart from the neutral temperature $T_n$ with increasing altitude. We perform a simulation of ion and electron temperatures and show that the difference between $T_n$, $T_e$, and $T_i$ can be caused by the presence of a small amount of hot oxygen. Using our simulation we estimate the ratio of hot oxygen to cold oxygen density to be 0.13% on average at 400-km altitude for low solar activity.

1. Introduction

During nighttime at midlatitudes the electron ($T_e$) and ion ($T_i$) temperatures are often assumed to approach the neutral temperature due to the weakness of the nighttime heat sources. Nevertheless, we have noticed in St. Santin Incoherent Scatter (IS) radar data that during nighttime $T_i$ and $T_e$ depart from the characteristic Bates shape of the neutral temperature profile. In this work we explain this feature of the observed nighttime $T_e$ and $T_i$ profiles by the presence of an additional heat source usually neglected in ionospheric heat balance considerations, namely, hot oxygen.

A survey of hot O studies is given by Oliver [1997]. It is believed that the typical hot O density is on the order of 1% of the cold ambient O density at the exobase and the temperature of hot O is about 4000 K. There is no agreement regarding the shape of the altitude profiles of hot O. The investigated shapes of the altitude profiles of hot O are the Chapman-like shape proposed by Cotton et al. [1993], one in diffusive equilibrium at the hot O temperature of 4000 K, and one in diffusive equilibrium at the cold O temperature.

In order to investigate the possible effect of hot O on the $T_i$ and $T_e$ at night, we perform a simplified modeling of these temperatures using heat balance equations, assuming that the only heat source for both electrons and ions is hot O. We assume further that the hot O profile has the Cotton et al. [1993] Chapman layer shape, which has peak density around the exobase. We compare the simulated $T_i$ and $T_e$ profiles with data obtained with the St. Santin IS facility.

2. Data

The $T_i$ and $T_e$ profiles used in this study are the medians calculated from all available St. Santin IS radar data (Nancay receiver) from 1968 to 1981. This period was chosen because in-situ measurements of neutral O density were made by satellites during this period, which ensures that the neutral O density model (MSIS-86, Hedin [1987]) used in this work is unbiased. The radar functioned in the altitude-by-altitude scanning mode, and IS spectra measured at different altitudes correspond to different times. We used cubic spline interpolation in time to obtain the temperature profiles at half-hour intervals.

In order to get a homogeneous yet the biggest possible set of data, we picked only those profiles which had complete data at a specific set of altitudes: 300, 325, 350, 400, 450 and 500 km. We chose only data from 0 to 3 LT to try to ensure that the chosen profiles were well between local sunset and sunrise and any upper-boundary heat source had ceased.

Prior to calculation of the median profiles the data were split into groups for low and high solar activities with $F_{10.7} = 147$ chosen to divide the groups. For low solar activity we found that $T_i$ was apparently lower than $T_e$. We argue in the section that this resulted from a neglect of $H^+$ ions in the original data analysis. A correction brings $T_e$ and $T_i$ into better agreement. For high solar activity $T_e$ was higher than $T_i$ by approximately 30 K at all altitudes. This difference indicates that a selective heat source was present for the electrons for high solar activity. Possible sources can be photoelectrons coming from the conjugate hemisphere or heat conducted from the overlying magnetic flux tubes, which may fill more fully and leak heat into the ionosphere longer into the night of solar maximum. These processes are difficult to model, and in the rest of this work we limit our considerations to low solar activity.

Median nighttime $T_e$ and $T_i$ profiles for low solar activity are shown in Figure 1a. The error bars represent the uncertainty of the medians. $T_i$ apparently rises much higher than the neutral temperature ($T_n$), which should remain almost constant above 300 km. This points out the presence of a heat source for the electrons or ions during the night.

3. Correcting observed temperatures for the $H^+$ effect

Let us consider the median $T_e$ and $T_i$ profiles shown in Figure 1a. Apparently $T_i$ is bigger than $T_e$. This is inconsistent with the traditional view of heat balance that the electrons heat the ions and the ions subsequently heat the neutrals, such that $T_e < T_i < T_n$.
We believe that this apparent \( T_i > T_e \) condition is largely a bias caused by the assumption of only O\(^+\) ions in the radar spectral analysis. Small amounts of H\(^+\), He\(^+\) or molecular ions could cause this bias. Molecular ions were shown to be unimportant above 260 km [Oliver, 1975]. The effect of He\(^+\) is weaker than the effect of H\(^+\) because of the lower content and bigger atomic mass of the former. To test a possible H\(^+\) effect, we derived simple relations for ion and electron temperature deductions as a function of assumed ion composition. After calculating an IS spectrum using different values of \( p = [\text{H}^+] / [\text{e}] \), we fitted a spectrum calculated without H\(^+\) (\( p = 0 \)) to it and calculated functions \( F_i(p) \) and \( F_e(p) \) giving the ratio of the temperature used in the calculation of the spectrum with composition \( p \) to the temperature obtained for the best-fitting spectrum with \( p = 0 \). Knowing these two functions allows us to correct temperatures for the H\(^+\) effect if the composition \( p \) is known. The corrected value of ion temperature is calculated as \( T_i(p) = T_i(p=0) F_i(p) \). When \( p \) ranges from zero to 0.05, \( F_i(p) \) and \( F_e(p) \) are approximated as

\[
F_i(p) = -0.922 \cdot p^2 - 1.53 \cdot p + 1 \\
F_e(p) = 0.790 \cdot p^2 - 0.929 \cdot p + 1
\]

To approximate the H\(^+\) level, we assumed chemical equilibrium in the reversible charge-exchange process \( \text{O}^+ + \text{H} \rightarrow \text{H}^+ + \text{O} \), which is valid when diffusion is slow. Derieut et al. [1975] showed that it is true most of the time in the altitude range from 400 to 500 km. Thus, the composition \( p \) can be calculated using

\[
p \approx \frac{[\text{H}^+]}{[\text{O}^+] + [\text{H}^+]} = \frac{[\text{H}]}{[\text{O}] + [\text{H}]}
\]

The MSIS-86 model values for [H] and [O] are used to calculate \( p \) for each data profile. Using (1) and (2), we corrected the measured \( T_i \) and \( T_e \) and calculated the new median profiles as shown in Figure 1b. The H\(^+\) correction brings the deduced \( T_i \) and \( T_e \) profiles closer together, placing them within the uncertainty limits except for the lowest altitude of 300 km. It confirms our supposition that the \( T_i \) and \( T_e \) separation is caused mainly by the neglect of H\(^+\) ions.

4. Study of the hot O effect

As we mentioned before, the presence of hot O can provide a heat source for ions and electrons, elevating their temperatures above the cold O temperature. To test this hypothesis, we performed a theoretical calculation of \( T_i \) and \( T_e \) assuming that the only heat source is hot O.

We restricted our simulation in several ways: single ion plasma (O\(^+\)); all charged particle motions are restricted to be field aligned; and the ion and electron energy balance equations can be written as

\[
-\sin^2 \theta \frac{\partial}{\partial z} \left( \frac{K}{\partial T} \right) = \sum P - \sum L
\]

were \( I \) is the magnetic dip angle, \( T \) is the ion or electron temperature, \( K \) is the ion or electron thermal conductivity, and \( \sum P \) and \( \sum L \) are the sums of all energy production and loss rates, respectively. We should take into account that the use of a single ion plasma model introduces an error in the estimated hot O density. H\(^+\) fractions of total ion densities are less than 5% between 300 and 500 km and the ion energy balance in this altitude range is dominated by heat transfer from hot O to the ions, frictional heating and cooling by cold O. The corresponding heat transfer rates for H\(^+\) and O\(^+\) differ maximally by the order of 4. Thus we estimate the related error in hot O density to be less than 20%.

We are interested primarily in the altitude range 300-500 km, but we solve the heat balance equation from 200 to 2000 km in order to be able to use simple boundary conditions. The temperature changes are assumed fast enough to neglect time variations.

In order to calculate heat production and loss rates we make the following assumptions:

1) The neutral temperature profile is given by the Bates profile

\[
T_n(z) = T_\infty - (T_\infty - T_0) e^{-z/a} \quad (z=120 \text{ km})
\]

where the parameters \( T_\infty \), and \( a \) are obtained from the MSIS-86 model using mean conditions for the set of data considered (August, UT=1, \( F_{10.7} = 120 \), and \( Ap = 14 \)). \( T_\infty \) was chosen to give best agreement with \( T_i \) and \( T_e \) below 350 km (Figure 1b).
2) Hot O has the temperature 4000 K and its density follows the Cotton et al. [1993] layer shape with its peak around 500 km. The profile is parameterised by the fraction of hot O to the total neutral O density at 400 km.

3) Heat transfer between electrons and ions takes place through Coulomb collisions only. The only external heat source for electrons is hot O.

4) The ions are heated by hot O and ion-neutral friction. The friction term is estimated using a coarse estimate of relative ion-neutral velocity.

5) The only ion local heat sink is collisions with neutral cold O atoms.

6) The heat sinks for electrons are: cooling due to elastic collisions with neutral cold O atoms; cooling due to neutral cold O fine structure excitation.

7) The neutral cold O density profile is calculated by averaging the MSIS-86 cold O profiles corresponding to each of the profiles in the data set.

We estimated the relative ion-neutral velocity to be about 100 m/s from the model of ion drift by Richmond et al. [1980], the model of neutral horizontal wind by Hedin et al. [1988], and St. Santin parallel ion drift measurements.

The scheme of local energy flows used in our simulation is shown in Figure 2. The expressions for heat transfer rates and thermal conduction coefficients are given by Schunk [1978], Banks [1966], and Banks [1967].

The heat balance equations we wish to solve are two second-degree differential equations where all coefficients depend non-linearly on temperature (Schunk [1978], Banks [1966], and Banks [1967]). We use a recursive method to solve those equations. The upper boundary condition ($z_{max}=2000$ km) is: $\partial T_i/\partial z|_{z=z_{max}} = \partial T_e/\partial z|_{z=z_{max}} = 0$. This condition is appropriate for our assumptions about the heat sources as the density of the only heating agent (hot O) approaches zero as the upper boundary becomes large. We set the upper limit of our simulation to 1500 km and also to 2500 km to test its influence on the simulated profiles of $T_i$ and $T_e$. These tests gave temperatures which differed by less than 0.5 K below 600 km. We show here results with the upper boundary set to 2000 km. At 200 km $T_i$ and $T_e$ are controlled by the balance between local heat sources and sinks.

In Figure 1b we compare the simulated $T_i$ and $T_e$ profiles with the data profiles. We set $[O_{hot}]/[O_{cold}]$ to 0.13% at 400 km in order to get the simulated $T_i$ profile as close as possible to the observed $T_i$ profile. Good agreement is achieved in the whole altitude range where the data are available. This result shows that only a small amount of hot O is needed to explain the observed $T_i$ departure from $T_e$. The adopted hot O fraction (0.13%) is of the same order of magnitude as that obtained using the technique of Oliver [1997] for daytime data. From Figure 1b and our calculated heating rates we find that the difference between $T_i$ and $T_e$ below 400 km (about 10 K) is caused primarily by frictional heating, in agreement with Mazaudier and Bauer [1976], while at higher altitudes hot O comes into play, leading to departure of $T_i$ from $T_e$. We also note that the calculated difference of the order of 20 K between $T_i$ and $T_e$ at 300 km is of the same order as that obtained by Mazaudier and Bauer [1976] from thermal balance considerations. According to that paper and our simulation, the higher electron heat conduction is responsible for $T_e$ being lower than $T_i$ at 300 km. We conclude by noting that the observed difference of 40 K between corrected $T_i$ and $T_e$ at 300 km is bigger than that predicted by our simulation. This difference may be caused by the uncertainties in our correction technique.

In our simulations we neglect electron cooling due to vibrational excitation of N₂, which is important only below 300 km, and electron cooling rates due to elastic collisions with N₂ and O₂, which are much lower than other heat sink rates for electrons. For ions we neglect cooling rates due to collisions with N₂ and O₂, which are much lower than other cooling rates for ions. We also calculated the diffusion term in the electron and ion energy equations for the highest possible mean diffusion velocities. The resulting diffusion terms are much smaller than other terms throughout the region of simulation. We confirmed the negligible influence of the neglected terms by including them into our simulation.

Our findings have an important implication for traditional methods based on the energy balance equation used for the derivation of exospheric temperature $T_0$ (Bauer et al. [1970]) from IS data. Let us imagine the analysis of the data profiles (Figure 1a), uncorrected for H⁺ effect, using the technique described by Bauer et al. [1970]. Since $T_i \approx T_e$, the calculated heat flux from ions to neutrals is zero and $T_\infty$ is determined by fitting a Bates $T_\infty$ profile directly to the $T_i$ data yielding the dotted line in Figure 1a. The fit gives the value 933 K for $T_\infty$, which differs by $\approx 40$ K from the approximation of the true value of $\approx 890$ K (see Figure 1b).

5. Conclusion

The purpose of this paper has been to show that the presence of a small amount of hot O can raise $T_i$ and $T_e$ above $T_0$ during nighttime, in good agreement with what is observed in St. Santin IS radar data. A simplified modeling of $T_i$ and $T_e$ was performed, and the agreement between modeled and measured temperatures was good up to 500 km with hot O density 0.13% of cold O density at 400 km.
This result shows that a small amount of hot O can produce a substantial ionospheric temperature effect at night. This amount of hot O is of the same order as that obtained using the energy balance analysis technique applied to daytime data.

The \( T_i \) and \( T_e \) elevation above \( T_o \) due to the presence of hot O has a direct consequence on \( T_o \) derivation from IS data as used in the MSIS model development. Our results show that using traditional methods for \( T_o \) derivation can incur errors on the order of 40 K.

Acknowledgments. This work was supported through grant ATM-9700162 from the National Science Foundation to Boston University. The extension of the CNET incoherent scatter facility at Saint Santin to a quadristatic configuration was supported by the Institut d'Astronomie et de Geophysique and by the Direction des Recherches et Moyens d'Essais. The facility is operated with financial support from the Centre National de la Recherche Scientifique.

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(Received March 27, 2000; revised June 6,2000; accepted June 23, 2000.)