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Letter to the Editor

Effects of hot oxygen in the ionosphere: *TRANSCAR* simulations

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Abstract. Recent studies of the ion energy balance in the mid-latitude ionosphere have led to the suggestion that hot neutral atomic oxygen may play a significant role; the presence of a population of hot O could explain some of the problems met in balancing the ion energy budget for Incoherent Scatter (*IS*) observations. The aim of the present study is to look at such effects by using numerical simulation. The *TRANSCAR* model is a time-dependent, 13-moment ionosphere model developed for high latitude studies. It was first adapted for mid-latitude conditions. In a first step the model was calibrated and cross-checked with St. Santin *IS* measurements for the winter case of 27 January 1972 around noon using, in particular, the *MSIS* neutral atmosphere model. This provides a reference diurnal variation of the ionosphere. The second step investigated the influence of a maxwellian population of hot neutral atomic oxygen introduced in addition to the standard neutral atmosphere. The paper describes the initial comparison between the model and St. Santin *IS* data, and then the effects induced by a hot atomic oxygen population.

Key words. Ionosphere (ionosphere-atmosphere interactions; ion chemistry and composition; mid-latitude ionosphere)

1 Introduction

There is more and more evidence that a hot part of the oxygen velocity distribution exists and plays an important role in thermosphere-ionosphere interactions. The first evidence was the discrepancy between the oxygen density inferred from incoherent scatter data and that measured by *OGO 6*: Hedin and Alcaydé (1974) showed individual conjunction agreements for daytime measurements, but significant discrepancies between *OGO 6* and St. Santin diurnal variations, in particular, around sunrise and sunset. Another indication was suggested after studies of the collision frequency

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ν_{O^+-O} between ion O^+ and the neutral atomic oxygen O, using either the energy balance or momentum balance equation (Oliver and Glotfelty, 1996). These two methods lead to as much as 60% different solutions for the collision frequencies. Oliver (1997) showed that the inclusion of a small fraction of hot oxygen can bring the results of these two methods into agreement. Despite the lack of direct measurements of the hot O component in the upper thermosphere, strong indications of a high-energy non-maxwellian tail with equivalent temperatures ranging from 4000 to 6000 K have been inferred from airglow measurements (Yee et al., 1980; Cotton et al., 1993). A recent study of the 630nm airglow emission (Shematovich et al., 1999) led to the conclusion that hot O(1D) emissions have to be taken into account for accurate neutral temperature measurements in the thermosphere. Oliver and Schoendorf (1999) inferred hot oxygen variations from incoherent scatter data, and Schoendorf et al. (2000) used a simple method of deriving hot O profiles from its mass and energy conservation equations. These previous studies motivated the current work to quantitatively model the effect of the hot oxygen component on the ionosphere. These simulations have been made using the *TRANSCAR* ionosphere model (Blelly et al., 1996). The effects of an additional small fraction of hot O, added to the *MSIS* atmosphere model (Hedin, 1987, 1991) on the ion energy balance, is self-consistently modelled. Finally, the resulting effects are shown on the method used to determine the exospheric temperature and the oxygen density from the incoherent scatter data.

2 Method of *n*[O] and exospheric temperature determination

The ion energy balance equation for an altitude profile is solved in order to determine the neutral parameters. These parameters are the oxygen density as a function of altitude and the exospheric temperature, which, with the assumption of a Bates profile shape, gives the complete description of the

thermosphere. The ion energy equation taken in the steady state is

$$L_{ei} = L_{in} \tag{1}$$

where L_{ei} represents the heat given by the electrons to the ions and L_{in} the losses of energy from the ions to the neutrals. This equation can admit a simplified form for altitudes where the only ion is O^+ and the main neutral component is atomic oxygen (above 280 km for mid-latitudes)

$$L_{in} = \frac{3}{2} n_i k (T_i - T_n) \nu_{O^+-O}, \tag{2}$$

$$L_{ei} = 3 n_e k (T_e - T_i) \nu_{ei}, \tag{3}$$

where n_e, n_i are the ion and electron densities (charge neutrality implies $n_e = n_i$), T_e and T_i the electron and ion temperatures and T_n the neutral temperature; ν_{O^+-O} is the resonant energy-dependent collision frequency, ν_{ei} is the classical electron-ion coulomb collision frequency, and k is the Boltzman constant. Substituting Eq. 2 and 3 in Eq. 1 leads to

$$\nu_{O^+-O} (T_i - T_n) = 2 \nu_{ei} (T_e - T_i) \tag{4}$$

with, following Banks (1966),

$$\nu_{O^+-O} \propto n[O] \sqrt{T_i + T_n}, \text{ and } \nu_{ei} \propto n_e T_e^{-1.5}. \tag{5}$$

From Eq. 4–5, one can express T_i as a function T_i^* which depends on the altitude profiles of the neutral temperature and atomic oxygen concentration $n[O]$, and on measured ionospheric parameters, T_e , T_i and n_e

$$T_i^* = \frac{T_n + \kappa T_e}{1 + \kappa}, \text{ with } \kappa \propto \frac{T_e^{-1.5} n_e}{\sqrt{T_i + T_n} n[O]}. \tag{6}$$

If one assumes that in the upper atmosphere (above 300 km altitude), the neutral temperature has reached its asymptotic exospheric value T_∞ and furthermore, that the thermal atomic oxygen is in diffusive equilibrium, then T_i^* can be fitted to T_i using two free parameters, namely the exospheric temperature T_∞ and the atomic oxygen concentration at a reference altitude (Bauer et al., 1970; Alcaydé and Bauer, 1977).

## 3 *TRANSCAR* use to check the method

TRANSCAR modelling can introduce in a complete way the complex interactions between the ionosphere and neutral atmosphere. *TRANSCAR* uses the 13-moment approximation of ionosphere transport (see Blelly and Schunk (1993) for a complete description of the set of equations, and Blelly et al. (1996) for a description of the model). The ion energy equation can be written as a general time-dependent equilibrium of energy exchanges resulting from electron-ion collision L_{ei}, ion-neutrals collisions L_{in}, friction between ions and neutrals and transport effects

$$n_i k \frac{\partial T_i}{\partial t} = L_{ei} - L_{in} + L_{\text{Frict}} + L_{\text{Transp}}. \tag{7}$$
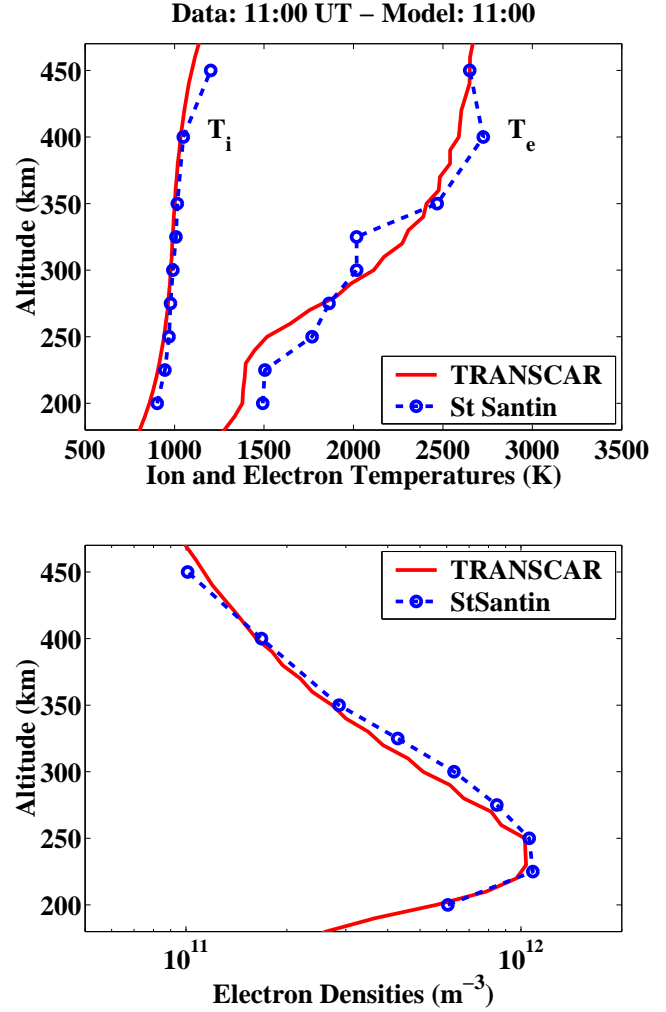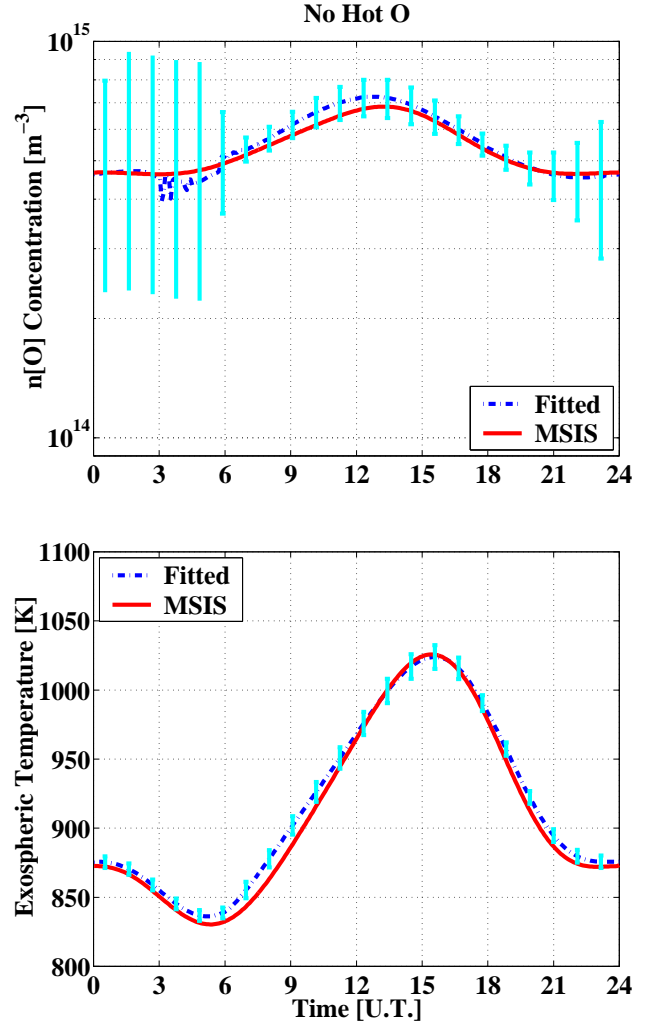

Fig. 1. Altitude profile of electron densities (bottom panel), electron and ion temperatures (top panel) observed by the St. Santin Incoherent Scatter on 27 January 1972 (symbols and broken lines), and *TRANSCAR* simulation results.

TRANSCAR assumes as external inputs (for mid-latitude conditions) a solar *EUV* flux indexed to the *10.7* cm radio flux index, the neutral atmosphere model provided by *MSIS* (Hedin, 1987, 1991), and the neutral wind model provided by *HWM* (Hedin et al., 1991) for ion-neutral frictional effects. Chemical equilibrium is assumed in the lower boundary (90 km), while at the upper boundary a downward electron heat flux is injected for adjusting observed electron temperature profiles. All other ion and electron parameters (concentrations, field-aligned velocities, temperature and heat flow) are solved vs. time and altitude. Figure 1 shows the model results for the Solar, Local Time and Seasonal conditions that were observed by the St. Santin Incoherent Scatter facility observations of 27 January 1972 (11:00 UT). The only purpose of this comparison is to show that *TRANSCAR* can adequately model the mid-latitude ionosphere observed above St. Santin, and the good agreement between data and model in Fig. 1 gives confidence to the model results. Now, given
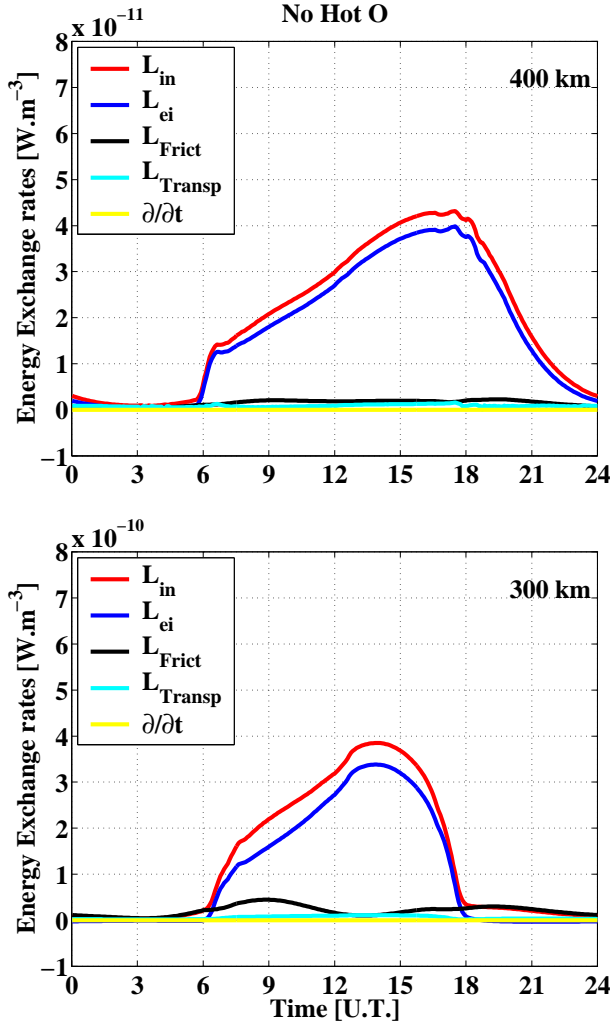
Fig. 2. Energy equation terms (see text and Eq. 7) extracted from the *TRANSCAR* outputs at 400 km (top panel) and 300 km (bottom panel) altitudes.

Fig. 3. Altitude profiles of n_e, T_e and T_i given by *TRANSCAR* outputs were fitted to infer the exospheric temperature (bottom panel) and the atomic oxygen concentration at 300 km altitude (top panel). The *MSIS* model temperatures and concentrations that were used in the *TRANSCAR* model are shown for comparison. Case with no additional hot oxygen population.

diurnal *TRANSCAR* results, one can evaluate the various terms entering Eq. 7, in order to a-posteriori test the method of deducing neutral parameters by fitting with Eq. 6. Figure 2 shows the time variation of the various terms of Eq. 7, extracted from *TRANSCAR* results at 300 and 400 km. This figure shows that the $L_{ei} = L_{in}$ approximation can be considered good but not perfect. Diurnal discrepancies between the two terms appear to be essentially due to neutral wind (frictional) effects and not surprisingly, are more sensitive at 300 km than at 400 km. But the discrepancy appears to be 10%, at most. With *TRANSCAR* profiles one is then able to use the fitting procedure of Eq. 6 in order to check the resulting estimates of the exospheric temperature and n[O] concentration (results are shown in Fig. 3). Error bars are calculated by placing an estimated error on the model T_i profile of 1% (i.e. 10 K for a 1000 K ion temperature). The resulting errors on the exospheric temperature are approximately 15 K. Figure 3 shows that most of the T_∞ diurnal variation inferred from the

fits agrees quite well with the *MSIS* model which was used in the simulations. The same holds also for the inferred n[O] densities, with estimated errors of 10%, which correctly take into account the model-fitted density discrepancies. This is true during most of the daytime while at night and around dusk and dawn, the energy balance of Eq. 4–5 is ensured by the trivial equation $T_e = T_i = T_n$. These dusk, night and dawn periods had therefore to be considered as safe for T_∞ determination but not reliable for n[O]. The next step is now to introduce an extra population of hot oxygen in the *TRANSCAR* simulations and to check its effects upon the previous results. This will be done by using these new *TRANSCAR* results and applying the n[O] and T_∞ fit, but ignoring the presence of hot O.
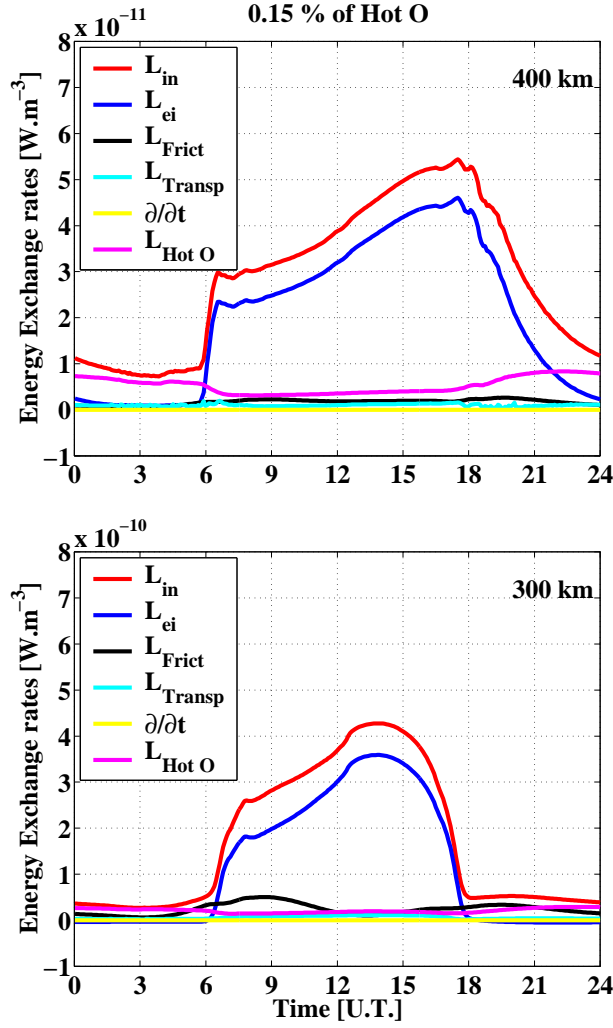
Fig. 4. Same as Fig. 2, but a population of hot O has been added to the standard *MSIS* neutral atmosphere: Hot O concentration is kept constant vs. time such that at noon $\{n[\mathrm{O_{Hot}}]/n[\mathrm{O}]\}_{400\mathrm{km}} = 0.15\%$; its altitude profile is defined with an equivalent exospheric temperature of 4000 K.

Fig. 5. Same as Fig. 3, but a population of hot O has been added to the standard *MSIS* neutral atmosphere: Hot O concentration is kept constant vs. time such that at noon $\{n[\mathrm{O_{Hot}}]/n[\mathrm{O}]\}_{400\mathrm{km}} = 0.15\%$; its altitude profile is defined with an equivalent exospheric temperature of 4000 K. However, $n[\mathrm{O}]$ and T_∞ fits are done ignoring the presence of this minor neutral constituent.
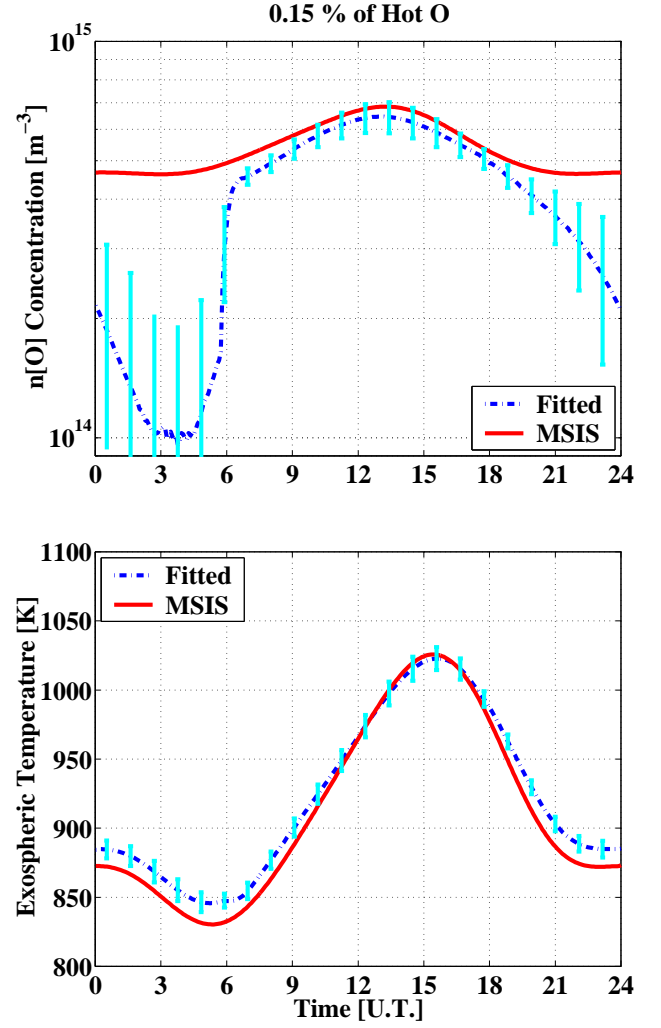
4 Introducing a hot oxygen population

As the rate of ion heat exchange depends on temperature differences (Eq. 4), even a small fraction of hot oxygen O* can imply significant energy exchanges. Assuming an extra population of suprathermal oxygen with a maxwellian distribution with characteristic temperature $T_{\mathrm{O}*}$, Eq. 4 should be rewritten

$$\nu_{\mathrm{O^+-O}}\,(T_i - T_n) = 2\,\nu_{ei}\,(T_e - T_i)$$
$$+ \nu_{\mathrm{O^+-O^*}}\,(T_{\mathrm{O^*}} - T_i) \qquad (8)$$

with, similarly to Eq. 5,

$$\nu_{\mathrm{O^+-O^*}} \propto n[\mathrm{O^*}]\,\sqrt{T_i + T_{\mathrm{O^*}}}\,. \qquad (9)$$

In the case where the O* component has a temperature higher than the ion temperature, the last term in Eq. 8 turns to be

positive and acts as a net heat source for the ions. Hence, neglecting this source term requires that the sink term be reduced accordingly by underestimating $n[\mathrm{O}]$ to balance the ion heat inflow and outflow. Again *TRANSCAR* was used to quantitatively study this effect. In a first step, a population of hot oxygen was added to the standard neutral atmosphere model in the following way. As the purpose is only to demonstrate the effects of a small fraction of hot O in the thermosphere, only a simple altitude profile of hot oxygen was used, and that profile was kept constant throughout the day. Hot O was assumed to be in diffusive equilibrium with a scale height appropriate to a temperature of 4000K, and its density at 400 km altitude was set to be between 0.15% and 0.5% of the thermal O density at noon. This fractional hot O population is taken into account in *TRANSCAR* by its

collisional effects (Eq. 9) in the momentum, energy and heat flux equations. Figure 4 is similar to Fig. 2 with now the additional term L_{HotO} computed from the new *TRANSCAR* results with 0.15% hot O at 400 km at noon. The presence of the small fraction of hot O at 300 and 400 km implies a significant increase of the electron-ion L_{ei} and ion-neutral L_{in} energy exchanges. Note that L_{ei} increases because hot O heats the electrons as well the ions. While L_{HotO} appears to be negligible around noon at 300 km altitude, its influence increases with increasing altitude because of the large hot O scale height, and becomes greatest near and after sunset. Sources from hot neutrals play a large role and are comparable to sources from thermal neutrals at night. If one tests again the atomic oxygen fitting method applied on these new *TRANSCAR* results, but ignores in the fitting procedure the presence of the hot O population, then one obtains the results displayed in Fig. 5. This figure shows that the resulting exospheric temperatures are still in reasonable agreement with the initial model, but with systematic errors of about 20 K, i.e. larger than the inferred statistical errors. However, the inferred atomic oxygen concentrations present, as expected, important disagreements, especially well before sunset and after sunrise, and throughout the night. Increasing the fraction of hot O obviously makes the situation worse. These results confirm that, as suggested by Oliver (1997), neglecting the presence of the hot O may be a major drawback in the incoherent scatter data fitting.

5 Discussion and conclusion

The simulations with *TRANSCAR* show that even a small fraction of hot O has a significant impact on the ion energy balance, and affects O determination greatly at certain times of day while the exospheric temperature determination is only modestly affected. Particular deviations are found near sunset/sunrise periods for the densities, even with small fractions of hot O. As suggested by Oliver (1997), if one assumes that *MSIS* model's cold O values are reliable and the heat balance analysis with the hot O terms are included, this becomes a candidate method to infer hot O concentration instead of cold O but the sensitivity of the method to neglected terms and assumptions needs to be checked carefully. In particular, our study shows frictional effects to be of a similar order of magnitude as hot O effects. Also, the shape of the hot O profile is largely unknown and the assumptions made for that shape may affect the hot O density deduction substantially. Finally, whether one can separate the dusk-night-dawn uncertainties on $n[\mathrm{O}]$ determination from hot O effects is certainly challenging. These investigation can be aided by the use of *TRANSCAR* as a quantitative tool and will be the subject of future studies.

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