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An updated model of $O^+(^2P)$ 7320 Å dayglow emission

P Thirupathaiah, Maneesha Dharwan & Vir Singh[$,*]

Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247 667, Uttarakhand, India
[$]E-mail: virphfph@iitr.ac.in

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A comprehensive model is developed using the updated rate coefficients and transition probabilities to study the $O^+(^2P)$ 7320 Å dayglow emission. The solar extreme ultraviolet (EUV) fluxes, calculated using the Solar Irradiance Platform (SIP), are incorporated into the model. The neutral atmospheric parameters are adopted from the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE-00) model. The ionospheric parameters are adopted from the International Reference Ionosphere (IRI-07) model. The measurements as provided by instruments onboard Atmosphere Explorer-C satellite, Dynamics Explorer-2 spacecraft and Upper Atmosphere Research Satellite are used to validate the model results. It has been found that the emission rates computed using the present model are in good agreement with the measurements. It is also found that the present model results are in better agreement with the measurements in comparison with the earlier models. The model results show that the updated rate coefficients and transition probabilities are quite consistent with each other and may be used in the aeronomical studies.

Keywords: Airglow emission, Solar EUV radiation flux, $O^+(^2P)$ 7320 Å dayglow emission, Rate coefficient, Transition probability

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1 Introduction

The 7320 Å emission is produced in the radiative transitions from metastable state $O^+(^2P)$ to $O^+(^2D)$. In general, this emission occurs in the thermosphere between 200 and 300 km altitude region. The 7320 Å dayglow emission can be observed in the airglow as well as in aurora. It was first observed by Carlson & Suzuki[1] in the twilight and night airglow. The identified production sources of $O^+(^2P)$ 7320 Å dayglow emission are the photoionization excitation of ground state atomic oxygen by solar EUV radiation (λ<666 Å), and the photoelectron impact ionization of ground state atomic oxygen[2,3]. The production rate of $O^+(^2P)$ state due to these two sources depends strongly on atomic oxygen number density. Mcdade *et al.*[4] have demonstrated in their study that twilight observations of 7320 Å airglow emission can be inverted to infer atomic oxygen number density and unattenuated $O^+(^2P)$ ionization frequency, which depends on solar EUV flux. In inversion technique, the column emission rate along the appropriate line of sight of 7320 Å airglow emission can be expressed in terms of atomic oxygen number density. More details of the inversion technique are presented by Mcdade *et al.*[4]. Yee & Abreu[5] have developed a technique to deduce exospheric temperature from 7320 Å emission measured by the visible airglow experiment onboard the Atmosphere Explorer-E satellite. According to Yee & Abreu[5], the exospheric temperatures can be deduced by monitoring changes in vertical brightness of 7320 Å dayglow emission with respect to solar zenith angle. The details of the technique are presented by Yee & Abreu[5].

The 7320 Å dayglow emission has a very limited observational database reported in the literature[6-15]. Consequently, a numbers of limited model studies have been reported in the literature on the 7320 Å dayglow emission. Torr *et al.*[16] have developed first mid-latitude inter-hemispheric model to study 7320 Å airglow emission. This model used the neutral number density from MSISE-86 model and the calculation of the excited and loss rates of $O^+(^2P)$ state were performed using the model of Torr & Torr[17]. This model presented a 3-dimensional picture of 7320 Å volume emission rate (VER) in the peak emission rate (PER) region under solar minimum conditions. However, these results could not be validated using experimental observations. Singh & Tyagi[18] developed a model for 7320 Å dayglow emission by using the solar EUV fluxes from Hinteregger *et al.*[19] and Tobiska[20] flux models. Singh & Tyagi[18] used one available Wind Imaging Interferometer (WINDII) measured emission rate profile of 7320 Å dayglow emission to validate their model. They found that the emission rates obtained using Tobiska flux model are in good agreement above 220 km and the emission rates obtained using Hinteregger flux model are in good agreement below 220 km with the WINDII measurements. Consequently, none of the above solar flux models could explain the measured emission rates at all altitudes. The model of Singh & Tyagi[18] was further modified by Sunil & Singh[21] by incorporating the solar EUV fluxes from the SOLAR2000 model[22]. Sunil & Singh[21] have used the measurements as provided by Visible Airglow Experiment (VAE) onboard Atmosphere Explorer-C (AE-C) satellite to validate their model. The model of Sunil & Singh[21] is reasonably in good agreement with the measurements above 240 km altitude. Recently, Shepherd *et al.*[23] have presented results of the 7320 Å airglow emission measured by WINDII onboard Upper Atmosphere Research Satellite (UARS). Shepherd *et al.*[23] have compared WINDII results with Canadian Ionosphere and Atmosphere model (C-IAM)[24,25]. It has been found that the C-IAM model overestimates quite significantly the results of WINDII measurements. The C-IAM model uses the neutral densities from MSISE-86 and the solar fluxes from Richards *et al.*[26]. It is worth mentioning here that Sunil & Singh[21] and Shepherd *et al.*[23] have used transition probabilities for $O^+(^2P\text{-}^2D)$ transition from Seaton & Osterbrock[27]. Further, the quenching of $O^+(^2P)$ by thermal electrons has not been included in the C-IAM model. On the other hand, Sunil & Singh[21] have included the reaction rate coefficient for the quenching of $O^+(^2P)$ by thermal electrons from Henry *et al.*[28]. The values of transition probabilities and reaction rate coefficient used by Sunil & Singh[21] are outdated. However, these transition probabilities and reaction rate coefficient have been revised by Wiese *et al.*[29] and McLaughlin & Bell[30], respectively. These revised values reported in the literature differ quite significantly from those used by Sunil & Singh[21]. Consequently, the model of Sunil & Singh[21] needs to be updated accordingly.

In the present paper, a comprehensive model is developed by incorporating the revised transition probabilities and reaction rate coefficients to study the 7320 Å dayglow emission. The solar EUV fluxes obtained from the Solar Irradiance Platform[31] (SIP v2.36) are incorporated into the model. The measurements as provided by the instruments onboard Atmosphere Explorer-C (AE-C) satellite, Dynamics Explorer-2 (DE-2) spacecraft and Upper Atmosphere Research Satellite (UARS) are used to validate the model.

2 Model

The transition $O^+(^2P\text{-}^2D)$ produces doublet lines at 7320 and 7330 Å in the dayglow spectrum.

$$O^+(^2P) \rightarrow O^+(^2D) + h\upsilon(7320-7330\text{Å}) \qquad \dots (1)$$

The energy level diagram of O^+ for $O^+(^2P)$ doublet lines at 7320 and 7330 Å is shown in Fig. 1. The $O^+(^2P)$ is primarily produced in the atmosphere through the following reaction:[4,8,13,14,17,20,32,33]

$$O + h\upsilon(\lambda < 666\text{Å}) \rightarrow O^+(^2P) \qquad \dots (2)$$

The production rate of $O^+(^2P)$ from the photoionization of atomic oxygen can be calculated as:

$$P_1(z,\alpha) = [O]\sum_{\lambda} I_z(\lambda,\alpha)\sigma_{O^+(^2P)}(\lambda) \qquad \dots (3)$$

Here, [O], is the atomic oxygen density; $I_z(\lambda,\alpha)$, the solar EUV flux at wavelength λ and solar zenith angle α; and $\sigma_{O+(2P)}(\lambda)$, the photoionization cross-section of $O^+(^2P)$ state. The atomic oxygen density is adopted from the NRLMSISE-00 model[34]. The electron number densities and temperatures are adopted from the IRI-07 model[35]. The solar EUV fluxes are

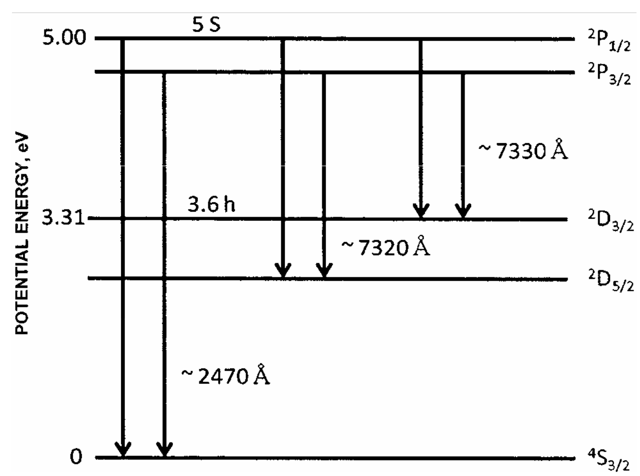

Fig. 1 — Energy level diagram of O^+ which contains different spectroscopic transitions from ^2P and ^2D states

obtained from the Solar Irradiance Platform[31,36] (SIP v2.36). The photoionization cross sections of $O^+(^2P)$ state are obtained from Fennelly & Torr[37].

The secondary production source of $O^+(^2P)$ is the photoelectron impact ionization of ground state atomic oxygen. Several studies[4,8,13,14,21,32,33] confirmed that this secondary source contributes less than 20% to the total production of $O^+(^2P)$ in the atmosphere.

$$O + e_{ph} \rightarrow O^+(^2P) + 2e \qquad \text{… (4)}$$

The production rate of $O^+(^2P)$ associated with the above source can be expressed as:

$$P_2(z,\alpha) = [O]\int_{E_{th}}^{\infty} \phi(E,z,\alpha)\sigma_e(E)dE \qquad \text{…(5)}$$

Here, $\sigma_e(E)$, is the total excitation cross-section of $O^+(^2P)$ state due to photoelectron of energy E; $\Phi(E, z, \alpha)$, the photoelectron flux as a function of photoelectron energy E, altitude z and solar zenith angle α; and E_{th}, the threshold energy for the production of $O^+(^2P)$. The total excitation cross sections are taken from Jackman *et al.*[38]. The photoelectron fluxes are obtained using the model of Richards & Torr[39] with updates to the electron impact cross sections for O and O_2. The total cross section for O_2 excitation is taken from Kanik *et al.*[40].

The total production rate of $O^+(^2P)$ due to the said two production sources can be written as:

$$P[O^+(^2P)] = P_1(z,\alpha) + P_2(z,\alpha) \qquad \text{…(6)}$$

The $O^+(^2P)$ produced is lost by radiative decay and quenched through collisional deactivation by N_2, O and thermal electrons (e_{th}).

$$O^+(^2P) \xrightarrow{A_7} O^+(^2D) + h\upsilon(7320\text{Å}) \qquad \text{… (7)}$$

$$O^+(^2P) \xrightarrow{A_8} O^+(^2D,^4S) + h\upsilon(total) \qquad \text{…(8)}$$

$$O^+(^2P) + N_2 \xrightarrow{k_9} O^+ + N_2^* \qquad \text{… (9)}$$

$$O^+(^2P) + O \xrightarrow{k_{10}} O^+(^2D,^4S) + O \qquad \text{… (10)}$$

$$O^+(^2P) + e_{th} \xrightarrow{k_{11}} O^+(^2D,^4S) + e_{th} \qquad \text{… (11)}$$

The quenching factor (Q) of $O^+(^2P)$ due to the above mentioned loss processes can be given by the equation:

$$Q = \frac{A_7}{A_8 + k_9[N_2] + k_{10}[O] + k_{11}[e_{th}]} \qquad \text{… (12)}$$

The transition probabilities (A_i) and reaction rate coefficients (k_i) incorporated in the model are listed in Table 1. The total volume emission rate of 7320 Å dayglow emission can be expressed as:

$$V_{7320} = Q \times P[O^+(^2P)] \qquad \text{… (13)}$$

3 Results and Discussion

The 7320 Å dayglow emission is a very weak emission. It is extremely difficult to measure 7320 Å emission during daytime from the ground because of bright sunlight background due to Rayleigh scattering in the atmosphere. The Visible Airglow Experiment (VAE) onboard Atmosphere Explorer (AE) satellites provided the first observational data on the volume emission rate profiles of 7320 Å dayglow emission[41,42]. The second observational data of volume emission rate profiles of 7320 Å dayglow emission has been provided by Fabry-Perot interferometer (FPI) onboard Dynamics Explorer-2 (DE-2) spacecraft[13,43]. The most recent observations of the volume emission rate profiles of 7320 Å dayglow emission have been provided by Wind Imaging Interferometer (WINDII) onboard Upper Atmosphere Research Satellite (UARS)[23]. The measurements as provided by AE-C satellite[10], DE-2 spacecraft[13,43] and WINDII[23] are used to validate the present model. A comparison is made between the present modeled results and the

Table 1 — Reaction rate coefficients and transition probabilities

Reaction	Transition probabilities A_i (s^{-1})/ Rate coefficients ki, $cm^3\ s^{-1}$	References
$O^+(^2P) \rightarrow O^+(^2D) + h\upsilon$ (732.0 nm)	$A_7 = 0.09907$	Wiese *et al.*[29]
$O^+(^2P) \rightarrow O^+(^2D, ^4S) + h\upsilon$ (total)	$A_8 = 0.22587$	Wiese *et al.*[29]
$O^+(^2P) + N_2 \rightarrow O^+ + N^*$	$k_9 = 4.8 \times 10^{-10}$	Chang *et al.*[14]
$O^+(^2P) + O \rightarrow O^+(^2D, ^4S) + O$	$k_{10} = 5.2 \times 10^{-11}$	Stephan *et al.*[33]
$O^+(^2P) + e_{th} \rightarrow O^+(^2D, ^4S) + e^-$	$k_{11} = 2.143 \times 10^{-7}(300/T_e)^{0.5}$	McLaughlin & Bell[30]

measurements of AE-C satellite in Fig. 2. The earlier model results of Sunil & Singh[21] are also shown in Fig. 2. Figure 2(a) shows the results for upleg of AE-C orbit 669 on 14 February 1974, and Fig. 2(b) shows the results for AE-C orbit 1959 on 8 June 1974. It is noticed from Fig. 2 that the present model reproduces the measured emission rate profiles quite well. The present results are in good agreement with the measurements. It is further noticed from Fig. 2(a) that the present results are in better agreement (within 5%) with the measurements in comparison with the model results of Sunil & Singh[21] in the region of peak emission rate. A comparison is made between the present results and the measurements of DE-2 spacecraft in Fig. 3. Figure 3(a) shows the results for DE-2 orbit 1306 on 30 October 1981, and Fig. 3(b) shows the results for DE-2 orbit 7125 on 18 November 1982. It is noticed from Fig. 3 that the present model reproduces the measured profiles very well. It is further noticed from Fig. 3 that the present results are in very good agreement (within 8%) with the DE-2 data in the PER region. A comparison is made between the present modeled results and the WINDII measurements[23] in Fig. 4. The Canadian Ionosphere and Atmosphere Model (C-IAM) results of Shepherd *et al.*[23] are also shown in Fig. 4. The results shown in Fig. 4 are zonally averaged volume emission rates of 7320 Å dayglow emission for the equatorial latitude band 20° S to 20° N. Figure 4(a) shows the results of 21 October 1992, and Fig. 4(b) shows the results of 8 September 1993. It is noticed from Fig. 4 that the present results are in better agreement with the WINDII measurements in comparison to the C-IAM results in the region of peak emission rate.

One can notice from Fig. 2(a) and Fig. 4 that the model of Sunil & Singh[21] and C-IAM model overestimate the measurements quite significantly for a wide range of altitudes respectively. The transition probabilities used in the present model are smaller than the transition probabilities adopted by the other two models. The temperature dependent reaction rate coefficient k_{11} [in Eq. (11)] is used in the present model, which is not included in the model of Sunil & Singh[21]. Thus, the inclusion of updated transition probability and the temperature dependent reaction

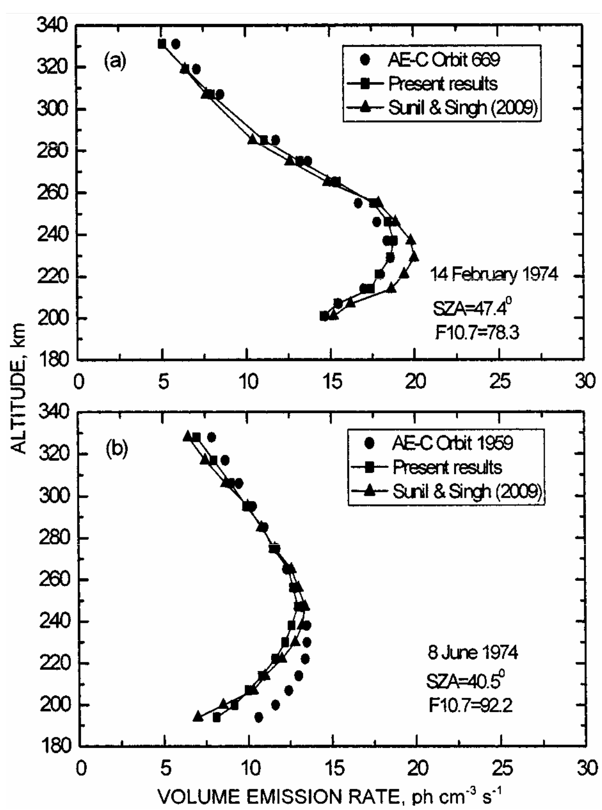

Fig. 2 — Comparison of present modeled volume emission rates with the AE-C orbit data for: (a) AE-C orbit 669 and (b) AE-C orbit 1959 [earlier model results of Sunil & Singh[21] also shown]

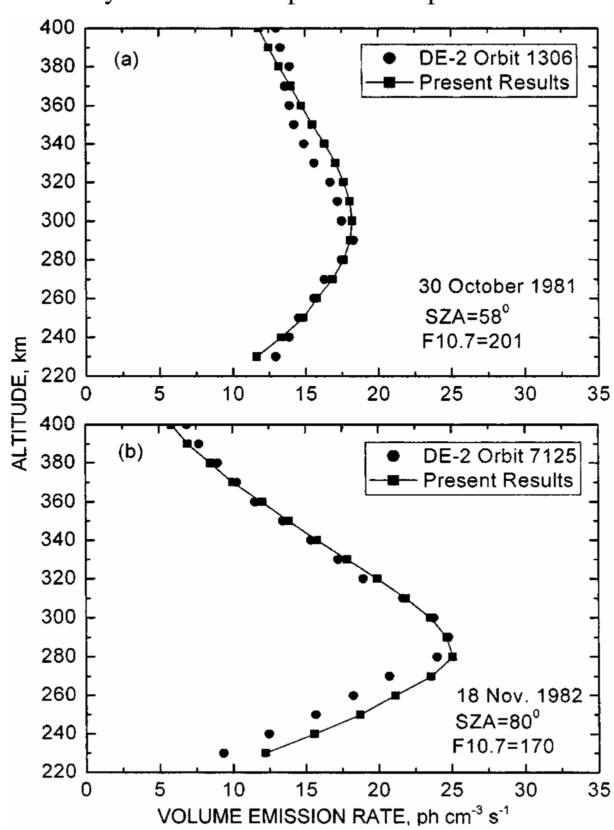

Fig. 3 — Comparison of present modeled volume emission rates with the DE-2 orbit data for: (a) DE-2 orbit 1306 and (b) DE-2 orbit 7125

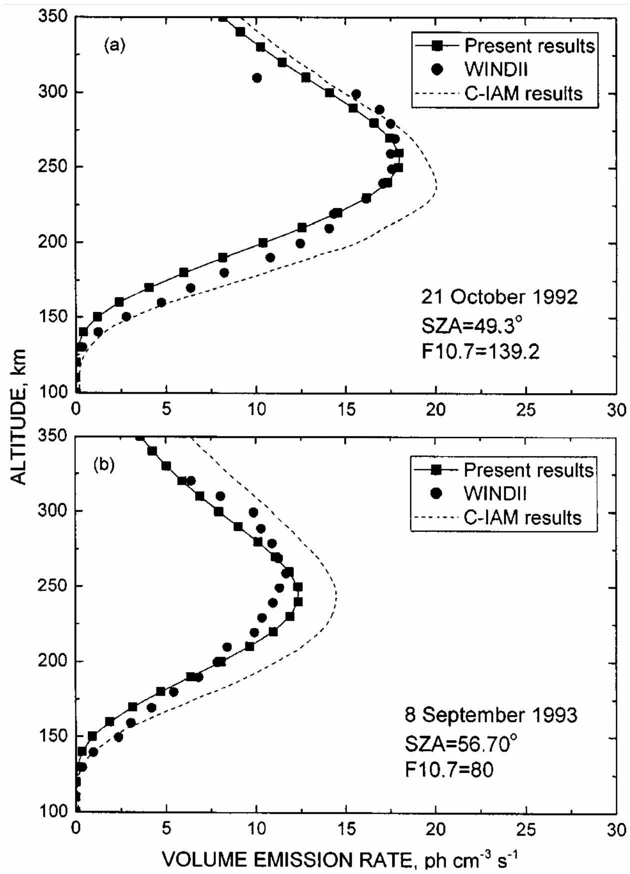

Fig. 4 — Zonally averaged volume emission rates of 7320 Å dayglow emission for the equatorial latitude band 20°S to 20°N for: (a) 21 October 1992; and (b) 8 September 1993 [comparison is made amongst present results, WINDII measurements and C-IAM results]

rate coefficient, k_{11}, in the present model results in better agreement with the experimental observations as compared to the earlier models. Further, it would be worthwhile to mention that in the absence of simultaneous measurement of the ambient electron number density, this number density has been used from IRI-07 model. However, the good agreement between the present modeled results and the experimental observations shows that the ambient electron number density used from the IRI-07 model appears to be quite consistent. In some cases, at lower altitudes (below PER altitude), the agreement between the modeled results and experimental observations is not as good as that at higher altitudes (above PER altitude) for two cases (8 June 1974 and 18 November 1982). One of the reasons for this disagreement may be the inconsistency in neutral number density which is used from the NRLMSISE-00 model. There is large attenuation of the solar EUV flux within a span of few kilometers below the peak emission rate region. The attenuation depends on the neutral number density. A little variation in the neutral number density may significantly affect the production rate of $O^+(^2P)$ state. The NRLMSISE-00 model is a semi-empirical model and it is quite likely that the neutral number densities provided by this model may not be consistent for these two cases. This fact is also discussed by Shepherd *et al.*[23] in their paper. It is clear from above discussion that the present model is in good agreement with the measurements, and would be quite appropriate to study the 7320 Å dayglow emission.

4 Conclusion

A comprehensive model is developed by incorporating the updated transition probabilities and reaction rate coefficients to study the 7320 Å dayglow emission. The present model is validated with the help of observations as provided by instruments onboard Atmosphere Explorer-C satellite, Dynamics Explorer-2 spacecraft and Upper Atmosphere Research Satellite. It has been found that the present model results are in good agreement with the measurements. The agreement between the present modeled results and the measurements is as good as possible in the light of all relevant possible errors in the measurements, the model neutral atmosphere, the model ionosphere, reaction rate coefficients and transition probabilities. The good agreement between the present model results and the measurements shows that the updated input parameters are quite consistent with each other. The present model may be used to study the $O^+(^2P)$ 7320 Å dayglow emission.

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