

The 630 nm Dayglow

STANLEY C. SOLOMON

High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado

VINCENT J. ABREU

Space Physics Research Laboratory, University of Michigan, Ann Arbor

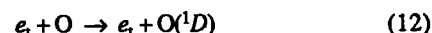
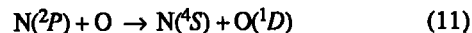
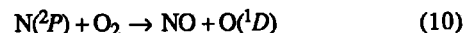
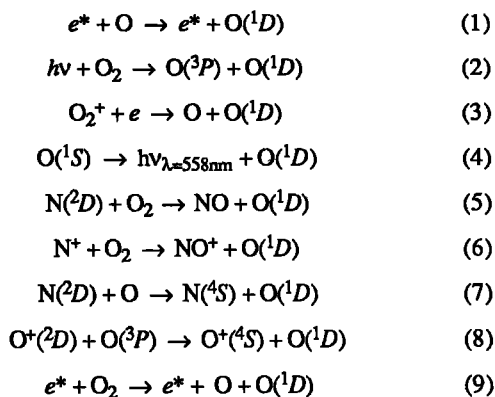
The daytime thermospheric emission at 630 nm from the ($^3P-^1D$) transition of atomic oxygen is examined using data from the Atmosphere Explorer C and E spacecraft. Observed altitude distributions of the emission rate measured using the Visible Airglow Experiment are compared with those calculated from in situ measurements of ion and neutral densities and temperatures, and from a model of the photon and photoelectron flux. Good agreement is obtained for most orbits with photoelectron impact on O, photodissociation of O₂, and dissociative recombination of O₂⁺ providing most of the production. Implications for some of the controversial points of O(1D) chemistry, such as the solar EUV and Schumann-Runge continuum flux, the yield of O(1D) from the reaction of N(2D) with O₂, the value of spontaneous transition coefficients, and the rate of quenching by O(3P) are discussed.

INTRODUCTION

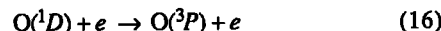
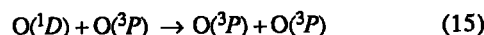
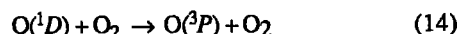
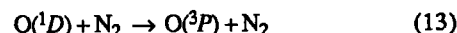
In a recent paper [Solomon *et al.*, 1988] the mechanisms thought to result in production and loss of O(1D) in the nighttime thermosphere under auroral conditions were examined. In the dayglow, the chemistry is similar excepting that energetic electrons are produced by photoionization rather than by auroral electron precipitation, and there is an important additional source due to photodissociation of molecular oxygen. Since there is still a great deal of question as to whether the auroral O($^3P-^1D$) emission at 630 nm is adequately characterized by the available laboratory, satellite, and ground based data, it may be asked whether the chemical scheme used for auroral calculations produces reasonable comparison with dayglow measurements. The 630 nm dayglow has been examined before using data from the Atmosphere Explorer (AE) spacecraft [Hays *et al.*, 1978; D. G. Torr *et al.*, 1980; 1981]. In view of subsequent laboratory measurements and theoretical calculations, an updated study is indicated.

Production and loss reactions of O(1D) are summarized below, and those peculiar to the dayglow discussed. Rate coefficients given by Solomon *et al.* [1988] are not repeated here; additions and revisions are listed in Table 1.

Production



Loss



Photoionization and Photoelectrons

Determination of the solar EUV flux is the crucial element of the photoionization calculation, which in turn drives the production of photoelectrons. Comparisons between calculated and measured photoelectron fluxes using AE data have been partially successful [e.g., Nagy *et al.*, 1977] but there is a lack of agreement on whether the most comprehensive measurements available, from the EUV spectrometer on AE [Hinteregger *et al.*, 1981], are accurate in the 5–25 nm region. Richards and Torr [1984; 1988] have presented photoelectron calculations suggesting that the Hinteregger fluxes for low solar activity are a factor of ~2 low in this spectral region. Support for this assertion is found in the rocket measurements of Ogawa and Judge [1986]; see also the discussion by Link *et al.* [1988]. There has also been controversy about the magnitude of flux variations over a solar cycle [Lean, 1987], particularly concerning H Lyman α but implicitly extending throughout the EUV and FUV as the H Lyman α and H Lyman β fluxes are often used to scale other chromospheric fluxes [e.g., Hinteregger *et al.*, 1981; Tobiska, 1988].

In addition, uncertainties in electron impact excitation cross sections affect the calculation of photoelectron fluxes, as discussed by Richards and Torr [1984; 1988]. They conclude that the smallest possible electron impact excitation cross sections, in conjunction with an increase in the 5–25 nm solar flux, result in good agreement with measurements by the AE

photoelectron spectrometer (PES) [Doering *et al.*, 1973]. Excitation cross sections for O are open to debate, but it is difficult to reconcile the cross sections adopted by Richards and Torr for N₂ and O₂ in the 30–70 eV range with some of the laboratory measurements [e.g., Zipf and McLaughlin, 1978; Wakiya, 1978]. As for the O(¹D) excitation cross section, although the measurements by Shyn and Sharp [1986] are in good agreement with earlier theoretical work [Henry *et al.*, 1969; Vo Ky Lan *et al.*, 1972; Thomas and Nesbet, 1976], Doering and Gulcicek [1988] have measured a cross section about 1.5 times the theoretical value at its peak of 5 eV, decreasing to be less than the theoretical value at 20–30 eV. This is a possible source of uncertainty in the rate of production of O(¹D) by electron impact on O(³P).

Photodissociation

Photodissociation of O₂ in the Schumann-Runge continuum (SRC) is a significant source of O(¹D), particularly in the 150–200 km region. Consequently, the evaluation of solar fluxes in the 135–175 nm region is important. Again, there is some question as to whether the Hinteregger fluxes [M. R. Torr *et al.*, 1980] are correct. Rocket experiments conducted during the same solar minimum (cycles 20–21) [Rottman, 1981] found systematically higher fluxes. Data from the Solar-Mesosphere Explorer (SME) satellite [Rottman *et al.*, 1982; Rottman, 1983] support the rocket results, although the deduced variation with solar activity is smaller. Rocket measurements during the declining phase of cycle 21 are in accord with the SME data [Mount and Rottman, 1983; 1985].

Recent Developments

Reaction (5) of N(²D) with O₂ remains the most controversial of the O(¹D) sources; see Solomon *et al.* [1988] for further discussion. Recent laboratory work [Piper *et al.*, 1987] suggests a 20% lower total rate coefficient than previously used [Lin and Kaufman, 1971]. As for the yield of O(¹D), measurement of the vibrational distribution of NO resulting from (5) [Fraser *et al.*, 1988] essentially confirms the findings of Kennealy *et al.* [1978] that the O(¹D) channel is favored (Fraser *et al.* estimate a yield of 0.76). However, as in the earlier experiment, this conclusion rests on the assumption that O(¹D) is created whenever energetically possible. It remains in conflict with the estimate of 0.1 or less by Link *et al.* [1983], supported by the laboratory measurements of Langford *et al.* [1986]. Meier *et al.* [1989] also argue against a large yield of O(¹D) from this reaction, based on ground-based auroral spectroscopy, on the lack of enhanced O₂ atmospheric band emission observed in the atmosphere and laboratory, and on a re-analysis of the Sharp *et al.* [1979] rocket data.

The overall rate of reaction (7) is of indirect importance to O(¹D) production as it pertains to the N(²D) density. There has been a long-standing discrepancy between the aeronomically derived rates of $4\text{--}7 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ [Frederick and Rusch, 1977; Richards *et al.*, 1981] and laboratory rate of $\sim 1.8 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ [Davenport *et al.*, 1976; Iannuzzi and Kaufman, 1980] for this reaction. Jusinski and Slanger [1987] measured an even higher rate, greater than $2 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ at thermospheric temperatures. However, new measurements by Miller *et al.* [1988] find a rate coefficient of $\sim 1 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$, and work in progress (W. T. Rawlins, personal communication, 1988) also yields a preliminary estimate of $\sim 1 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$. Information on the products of this reaction, or of reaction (11), is not yet available.

Theoretical work by Guberman [1988] on the dissociative recombination of O₂⁺ (reaction (3)) indicates that the yield of O(¹D) decreases slowly with increasing vibrational excitation. Yee *et al.* [1989] show that this can be a source of variation in production which can be accounted for by use of the electron/atomic oxygen number density ratio, although they do not observe this effect in the nightglow.

Loss rates have been discussed by Link and Cogger [1988]. In a note added in proof, they cite Baluja and Zeppen [1988] who calculated a value for the total O(³P-¹D) transition probability $A_{1D} = 7.7 \times 10^{-3} \text{ s}^{-1}$. This value is lower than the Froese-Fischer and Saha [1983] value of $9.3 \times 10^{-3} \text{ s}^{-1}$ but higher than the Kernahan and Pang [1975] value of $(6.8 \pm 1.3) \times 10^{-3} \text{ s}^{-1}$, although it is within their estimated error. They conclude that O(¹D) quenching by O(³P) [Abreu *et al.*, 1986] is not required to explain 630 nm nightglow data.

AIRGLOW MEASUREMENT TECHNIQUE

The AE satellites carried two filter wheel photometers known as the Visible Airglow Experiment (VAE) [Hays *et al.*, 1973]. The narrow field of view channel (0.75° half cone) is employed in this study; it pointed backward along the orbital track, perpendicular to the vertical, when the satellite was despun, and turned in the orbital plane when the satellite was spinning. Despun elliptical orbits are employed here because they avoid the potential problem that if the instrument points too far below the horizontal, sunlight scattered by the middle atmosphere penetrates the baffles. Also, the signal to noise ratio is increased since the photometer is always oriented in the proper direction for limb measurements rather than less than 10% of the time when the satellite is spinning. The altitude change of the satellite is used to scan the limb, and the near-spherical distribution of the dayglow is exploited by use of the Abel inversion method [Roble and Hays, 1972] to recover volume emission rate profiles. The photometer signal is integrated over 4 s intervals, and the Abel integral is evaluated by finding the linear derivative between successive points and solving the resulting expression analytically for each altitude interval.

This technique results in extremely accurate altitude profile measurement provided that the extraterrestrial background and vehicle glow is negligible and that the departure from spherical symmetry is sufficiently small that the inversion algorithm is unaffected. Vehicle glow is avoided by use of the backward looking direction and the extraterrestrial background emission is less than 10% of the 630 nm dayglow at the altitudes of interest so long as the Sun and Moon are avoided. Departure from spherical symmetry is a potentially larger problem. Figure 1 shows a sequence of 630 nm volume emission rate profiles produced using a comprehensive thermosphere/ionosphere airglow model [Solomon and Roble, 1988] in conjunction with the Mass Spectrometer Incoherent Scatter (MSIS-86) model atmosphere [Hedin, 1987] and the International Reference Ionosphere (IRI) [Belitza, 1986] for solar zenith angles (SZA) of 30°, 50°, and 70°. For this range of SZA, the profile change is small. An example of the effect on the inversion algorithm is demonstrated by simulating the brightness the instrument would measure, including noise and field of view effects, as the satellite moves through this model emission from a location where SZA=60° at 160 km to one where SZA=30° at 400 km (similar to AE-C orbit 610). In Figure 2, the recovered volume emission rate as a function of altitude is compared to that which the satellite traversed. The

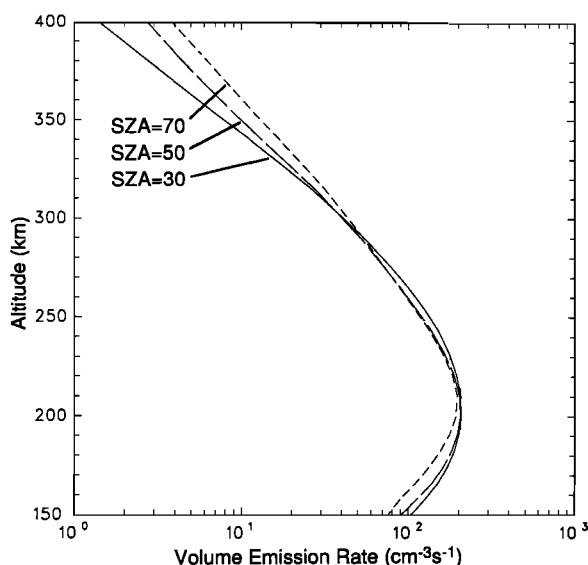


Fig. 1. Modeled 630 nm emission in the dayglow, using MSIS-86 and IRI. Three volume emission rate profiles are shown, for solar zenith angles of 30°, 50°, and 70°.

estimated error is less than 10% and is particularly small near the peak of the emission layer. The assumption of spherical symmetry is a valid approximation for $z > 150$ km and $SZA < 70^\circ$, provided that the SZA changes by less than $\sim 30^\circ$ during the course of a measurement sequence.

COMPARISON WITH MODEL

An additional advantage of the use of elliptical orbits for airglow measurement is that the in-situ measurements made by the satellite may be employed to reduce some of the uncertainties inherent in modeling and focus on rate coefficients rather than compositional variations. The open source spectrometer (OSS) [Nier *et al.*, 1973] provided measurements of neutral O and N₂ density; the retarding potential analyzer (RPA) [Hanson *et al.*, 1973] specified the electron density/total ion density and is used to normalize ion composition data from the Bennett ion mass spectrometer (BIMS) [Brinton *et al.*, 1973]. Neutral, electron, and ion temperatures were measured by the neutral atmosphere temperature experiment (NATE) [Spencer *et al.*, 1973], the cylindrical electrostatic probe (CEP) [Brace *et al.*, 1973], and RPA, respectively.

The approach used is to employ these measurements whenever possible and to use models only when necessary, for instance, for the O₂ density, which is taken from MSIS-86, and for the solar EUV flux. The photoelectron flux presents an additional problem in that shielding effects on AE-C rendered those data difficult to interpret. In addition, the coarse spectral resolution available through the AE Unified Abstract (UA) files is insufficient for low-energy excitation calculations. Therefore, photoelectron fluxes are calculated from modeled solar EUV fluxes using the two-stream electron transport method [Nagy and Banks, 1970]. The downward electron flux at the top of the model is calculated by assuming that conditions at the magnetically conjugate point were similar, and that attenuation through the plasmasphere is negligible. The Hinteregger solar EUV reference spectrum (SC#21REFW), binned using the scheme of Torr and Torr [1985] and scaled for solar activity using the $F_{10.7}$ association model of Hinteregger *et al.* [1981], is used to compute photoionization rates. This

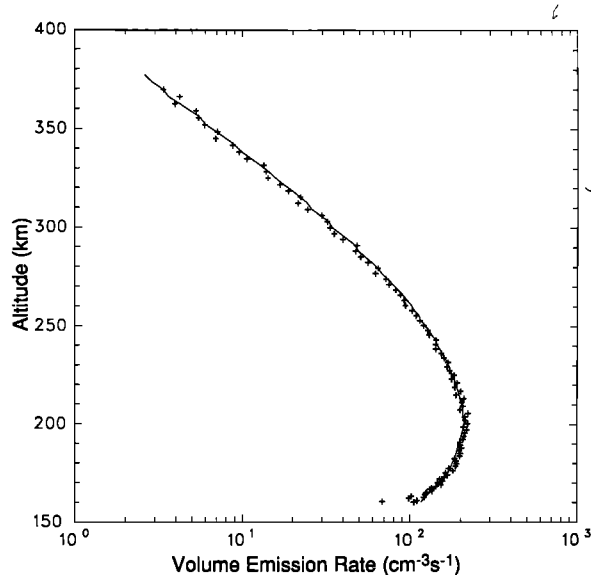


Fig. 2. Simulation of the Abel inversion method for a despun elliptical orbit. The emission rate which a satellite would traverse as it moved through the model shown in Figure 1 is represented by the solid line. The inverted measurements it would make are represented by pluses.

scaling, based on long-term correlations, can only approximate the flux on a particular day, but is a small adjustment here since all but one of the orbits used were near low solar activity. The flux is increased in the interval 5–57 nm in accordance with the measurements of Ogawa and Judge [1986]; the normalization factor employed decreases linearly from 2.1 at $F_{10.7}=68$ to 1.0 at $F_{10.7}=300$. This factor is similar to that proposed by Richards and Torr [1984] but is applied to a wider spectral region and hence has a considerably larger effect on photoelectron production. Richards and Torr used the F74113 reference spectrum as a base value, however, which is higher

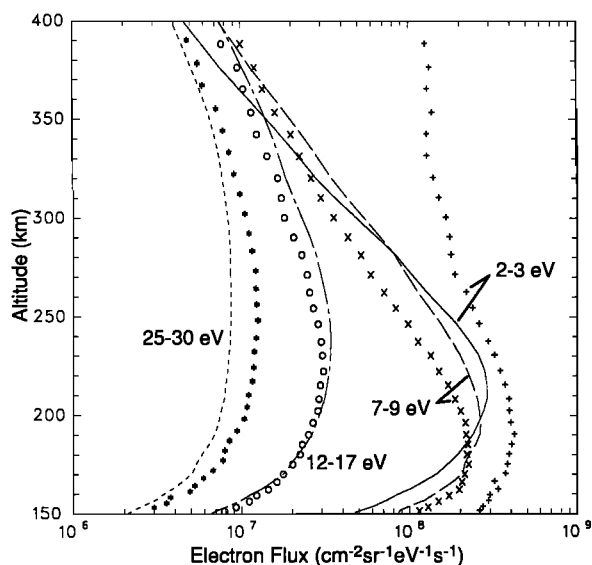


Fig. 3. Comparison of modeled photoelectron flux to measurements by the photoelectron spectrometer for AE-E orbit 468. Model shown with lines: dotted, 25–30 eV; dash-dot, 12–17 eV; dashed, 7–9 eV; solid, 2–3 eV. Measurements shown with symbols: asterisks, 25–30 eV; open circles, 12–17 eV; crosses, 7–9 eV; pluses, 2–3 eV.

TABLE 1. Rate Coefficients and Branching Ratios

Reaction	Rate Coefficient (cm ³ s ⁻¹) or Yield	Reference
O ₂ ⁺ +e → O+O	1.6×10 ⁻⁷ (T _e /300) ^{-0.55} , T _e >1200	Walls and Dunn [1974]; Torr et al. [1976]
	1.95×10 ⁻⁷ (T _e /300) ^{-0.7} , T _e <1200	Mehr and Biondi [1969]; Alge et al. [1983]
N(² P)+O → N+O	1.2×10 ⁻¹¹	Zipf et al. [1980]
N(² P)+O ₂ → NO+O	2.0×10 ⁻¹²	Zipf et al. [1980]
N(² P)+NO → N+NO	1.8×10 ⁻¹⁰	Rees and Jones [1973]
O ₂ ⁺ +N → NO ⁺ +O	1.2×10 ⁻¹⁰	Fehsenfeld [1977]
O ⁺ +N(² D) → N ⁺ +O	1.3×10 ⁻¹⁰	Constantinides et al. [1979]
O(¹ S)+O ₂ → O+O ₂	4.0×10 ⁻¹² exp(-865/T _n)	Slanger et al. [1972]
O(¹ D) from O ₂ ⁺ +e	1.2	Abreu et al. [1983]
O(¹ D) from O ₂ ⁺ +e, alternate	-0.2log ₁₀ [(T _e /300) ^{-0.7} e/O]	approx. to Yee et al. [1989]
O(¹ S) from O ₂ ⁺ +e	0.12+0.02log ₁₀ [(T _e /300) ^{-0.7} e/O]	approx. to Yee et al. [1989]
O(¹ S) from N ₂ (A ² Σ _u ⁺)+O	0.75 (v=0 only)	Piper [1982]
N ₂ (A)(v=0)/N ₂ (A)(all v)	0.25	Cartwright [1978]
O(¹ D) from N(² D)+O	0.03	Olson and Smith [1974]
O(¹ D) from N(² P)+O ₂	0.0	assumed
O(¹ D) from N(² P)+O	0.0	assumed

in the 5–40 nm region than SC#21REFW by 1.1 to 1.9. Photoionization cross sections are taken from Samson and Pareek [1985] and Kirby et al. [1979]. Electron impact cross sections are those used by Solomon et al. [1988], including the Henry et al. [1969] value for O(¹D). The resulting photoelectron fluxes are compared to PES measurements for AE–E orbit 468 in Figure 3. The model reproduces the altitude dependence of the measured fluxes reasonably well with the exception of the lowest energy channel, 2–3 eV. At high altitude the discrepancy is extreme. The measurement made by this channel is more suggestive of the thermal population than a photoelectron flux. The discrepancy in the 7–9 eV channel from 200 to 300 km is also troubling as it indicates a possible overestimation of photoelectron production by the model near the peak of the O(¹D) electron impact cross section. Agreement below 200 km is fairly good, however.

As O(¹S) and N(²D) are precursor excited species to O(¹D), and N₂(A) in turn a precursor to O(¹S), these must be calculated in photochemical equilibrium using the measured densities and temperatures and modeled photon and photoelectron fluxes. The chemical scheme employed is as in Solomon et al. [1988] and Solomon and Roble [1988]; reaction rates revised from or not included in Solomon et al. [1988] are listed here in Table 1. N(²P) chemistry has been added, and several other reactions involving odd nitrogen are included. Reactions (10) and (11) are assumed to have zero yield of O(¹D) in the absence of information to the contrary. Photodissociation of N₂ is included as a source of N(²D) [Richards et al., 1981]. The rate of photodissociation of O₂ in the SRC is calculated using the solar flux parameterization and cross sections presented by M. R. Torr et al., [1980] but normalized to reflect the measurements of Rottman [1981] and Mount and Rottman [1983; 1985]. In some cases minor ion densities at low concentrations are not given by the abstract files, in particular, N⁺ and

N₂⁺ below about 220 km. In these instances the ion densities in question are calculated by the model, which only affects minor sources such as (6) but can cause inflections in the altitude profile. Quenching of O(¹D) by (13)–(16) is included, and 630 nm emission calculated using the Froese-Fischer and Saha [1983] coefficients.

Orbits are selected for analysis which were despun and elliptical, passed through the dayglow at SZA<60°, had the 630 nm filter on channel one, and for which all necessary density and temperature measurements are available from the UA data base. These criteria reduce the number of available orbits to half a dozen; they are listed in Table 2. The measured and modeled volume emission rates for each orbit are plotted against altitude in Figures 4a–4f. The modeled rates are further broken down into each contributing production reaction. Reactions (8), (9), and (12) are not shown due to their small contributions. An error bar is included for each measurement plot, representative of the estimated uncertainty due to the type of SZA variation encountered on that orbit. As can be seen from the scatter in the data points, the uncertainty is smallest near the peak of the layer. AE–C orbit 2076 is an example of an orbit which does not quite meet the selection criteria, as the SZA was 65° at 200 km and greater at lower altitude; consequently, it has a larger uncertainty than the others. It is included anyway because it gives some idea of the low altitude behavior of the emission near twilight.

Comparison is quite good for most of the orbits studied, the principal exception being AE–C orbit 3246, which occurred during higher solar activity than the others. The poor fit at high altitudes for this orbit suggests that the contribution from reaction (1) is overestimated, probably due to an overestimation of the solar EUV flux. The model calculation of electron density in the F₁ region is 40–60% higher than the RPA measurement for this orbit. Since the model is within

TABLE 2. Information About Orbits

AE–	Orbit	Date	F _{10.7}	A _p	~SZA	~Latitude
C	608	74040	83	4	47°	N.H. mid-latitude
C	610	74040	83	4	47°	N.H. mid-latitude
C	2076	74169	82	10	65°	N.H. high latitude
C	3246	74261	124	19	31°	near equator
E	468	75361	75	31	29°	near equator
E	1961	76110	79	5	20°	near equator

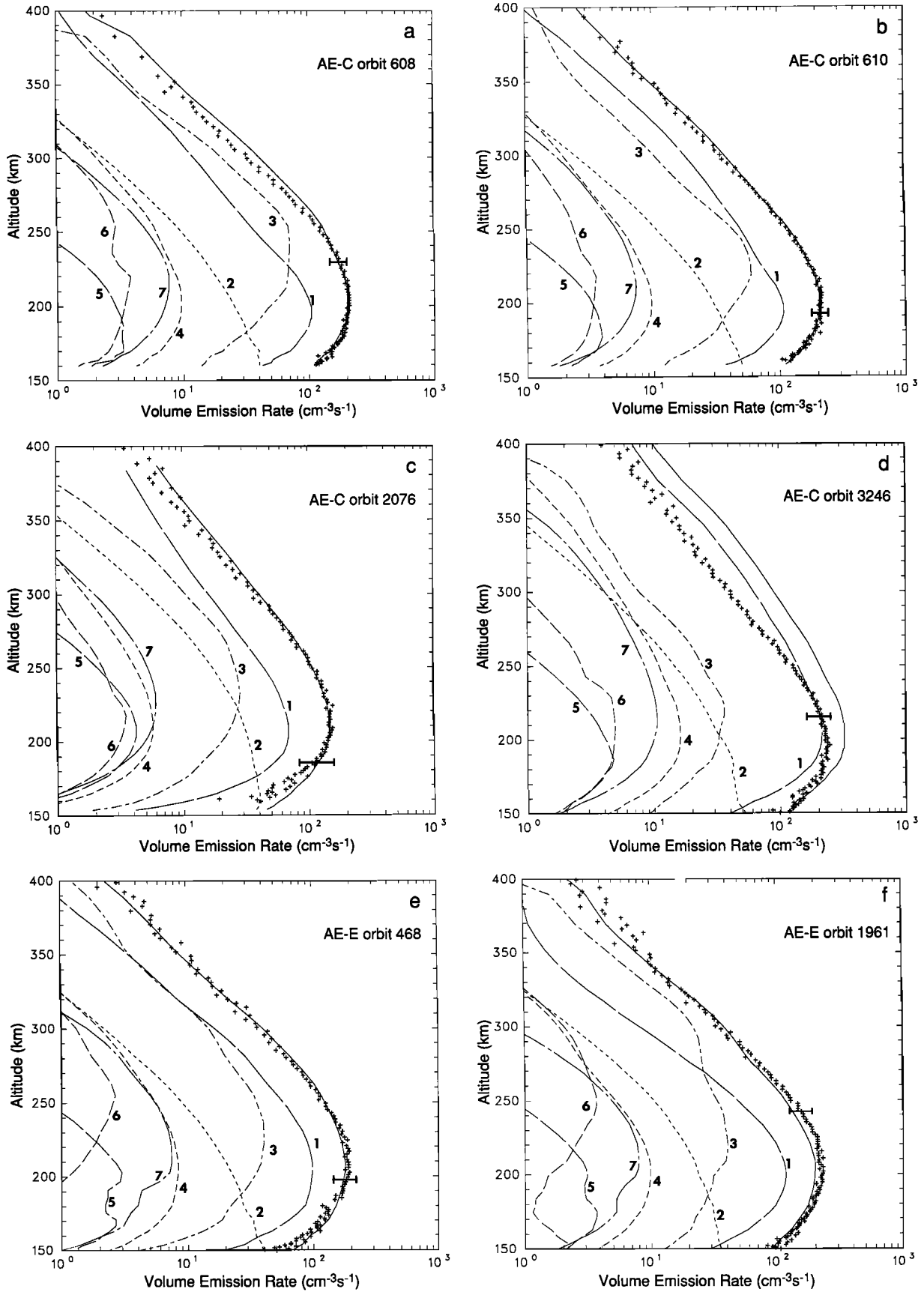


Fig. 4. Measured and modeled 630 nm volume emission rate profiles. Inverted measurements from the Visible Airglow Experiment are represented with pluses. Total modeled emission is shown with a solid line. Contributing sources: (1) e^*+O ; (2) $h\nu+O_2$; (3) O_2^++e ; (4) $O(^1S)$; (5) $N(^2D)+O_2$; (6) N^++O_2 ; (7) $N(^2D)+O$. Not shown: $O^+(^2D)+O_2$, e^*+O_2 , e^+O . (a) AE-C orbit 608. (b) AE-C orbit 610. (c) AE-C orbit 2076. (d) AE-C orbit 3246. (e) AE-E orbit 468. (f) AE-E orbit 1961.

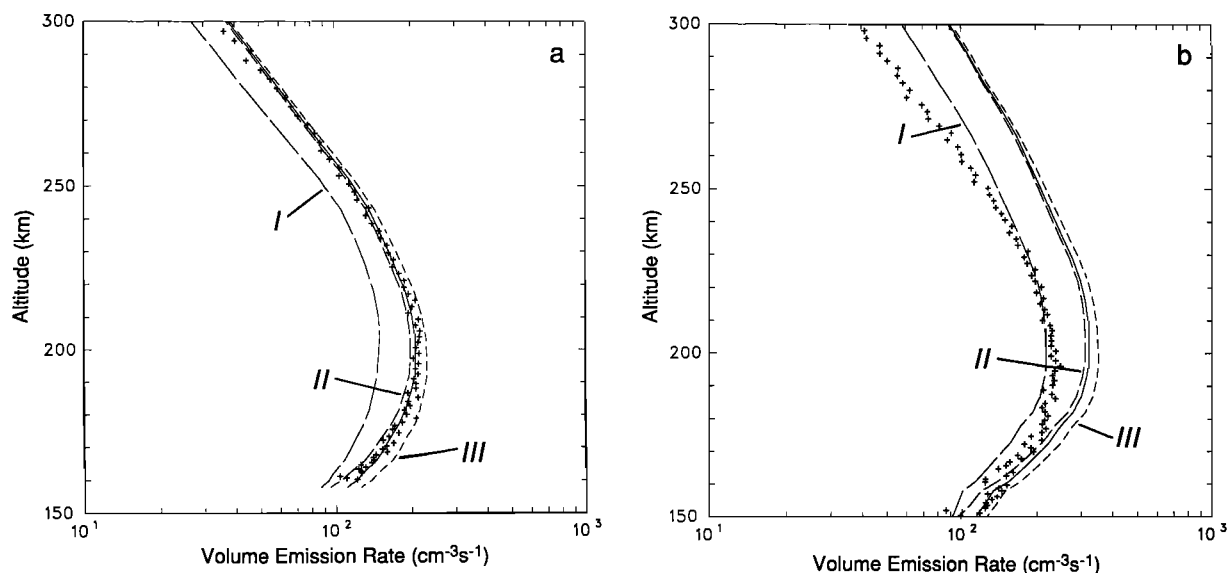


Fig. 5. Sensitivity to variations in production rates for (a) AE-C orbit 610 and (b) AE-C orbit 3246. The scales are expanded so that the differences at low altitude may be more easily seen. Pluses, measurement. Solid line, standard model. Dashed lines, adjusted model: (I) lower EUV flux; (II) lower UV flux in the SRC; (III) high yield from $N(^2D)+O_2$. See text.

20% of measured F_1 electron densities on the other orbits, and since diffusion is negligible in this region (below 200 km) this further suggests a problem with the solar flux scaling.

SENSITIVITY STUDIES

Because of uncertainties associated with the magnitude of several of the production mechanisms and loss rates, it is difficult to discern whether or not there is more observed 630 nm emission in the dayglow than can be explained by the adopted photochemistry. To better understand how some of these uncertainties affect the modeled volume emission rate, we have conducted a series of sensitivity tests, varying in turn the solar EUV and SRC fluxes, the yield from (3) and from (5), and the loss rates due to (15) and (17).

AE-C orbits 610 and 3246 are used to investigate production rate changes as they have the best and worst overall fit, respectively. Figures 5a and 5b show the effects of (I) restoring the solar flux in the 5–57 nm region to the *Hinteregger et al.* [1981] spectrum, (II) restoring the SRC flux to the *M. R. Torr et al.* [1980] values, and (III) employing an $O(^1D)$ yield of 0.8 from reaction (5). A fourth model, which employs a yield of $O(^1D)$ from (3) that decreases with increasing vibrational excitation from ~ 1.3 at $e/O=10^{-4}$ to ~ 0.7 at $e/O=10^{-2}$, is not plotted, as it is almost indistinguishable from the standard model. Although it is possible to obtain better agreement for orbit 3246 by reducing the solar EUV flux, it is at the cost of disrupting the correspondence for orbit 610. The $O(^1D)$ yield from reaction (5) has a smaller effect on total production than

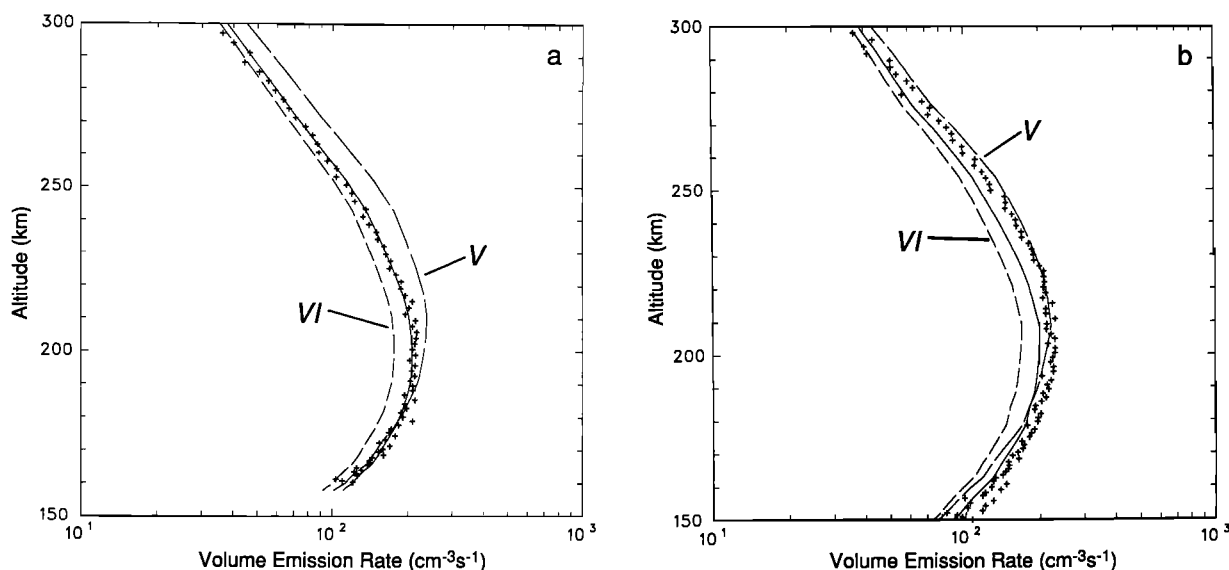


Fig. 6. Sensitivity to variations in loss rates for (a) AE-C orbit 610 and (b) AE-E orbit 1961. Crosses, measurement. Solid line, standard model. Dashed lines, adjusted model: (V) no O quenching and lower transition probabilities; (VI) including O quenching and intermediate transition probabilities. See text.

in the work by *D. G. Torr et al.* [1980; 1981] because the higher *Davenport et al.* [1976] rate for reaction (7) is used. It is notable that adopting both model II and model III would retain good agreement for orbit 610.

In Figures 6a and 6b loss rates are varied by (V) eliminating quenching by O and using the lower *Kernahan and Pang* [1975] transition probabilities and (VI) including quenching by O but using the intermediate *Baluja and Zeippen* [1988] transition coefficients. AE-C orbit 610 and AE-E orbit 1961 are examined, the latter because of the small discrepancy from 200 to 250 km. Better agreement is obtained in this region using model V, but the standard model does better at lower altitude. Model VI would obtain good agreement only if production were increased, or quenching by O included but at a reduced rate.

CONCLUSION

The fundamental question in aeronomic modeling of excited atomic oxygen is whether the available laboratory and solar measurements and theoretical calculations are adequate to explain the observed airglow. Although discrepancies persist, reasonable agreement has been obtained for O(¹D) in the dayglow during low solar activity, as well as in the aurora [*Solomon et al.*, 1988] and nightglow [*Abreu et al.*, 1983; 1986; *Link and Cogger*, 1988]. Progress made in laboratory and theoretical work has reduced the uncertainties involved and improved the agreement between model and measurement. However, it must be emphasized that a unique set of model parameters cannot be obtained from this type of analysis alone.

To increase our understanding of the dayglow, especially with respect to its solar cycle variation, the most important need is for new measurements of the solar UV and EUV flux.

Acknowledgments. The authors thank R. G. Roble and J. H. Yee for their comments. This work was supported by the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program, by NASA grant NAGW-496 to the University of Michigan, and by NASA Solar-Terrestrial Theory Program grant W-16320 to the National Center for Atmospheric Research. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

The Editor thanks G. G. Sivjee and another referee for their assistance in evaluating this paper.

REFERENCES

- Abreu, V. J., S. C. Solomon, W. E. Sharp, and P. B. Hays, The dissociative recombination of O₂⁺: The quantum yield of O(¹S) and O(¹D), *J. Geophys. Res.*, **88**, 4140, 1983.
- Abreu, V. J., J. H. Yee, S. C. Solomon, and A. Dalgarno, The quenching rate of O(¹D) by O(³P), *Planet. Space Sci.*, **11**, 1143, 1986.
- Alge, E., N. G. Adams, and D. Smith, Measurements of the dissociative recombination coefficients of O₂⁺, NO⁺, and NH₄⁺ in the temperature range 200–600 K, *J. Phys. B*, **16**, 1433, 1983.
- Baluja, K. L., and C. J. Zeippen, M1 and E2 transition probabilities for states within the 2p⁴ configuration of the O I isoelectronic sequence, *J. Phys. B*, **21**, 1455, 1988.
- Belitza, D., International reference ionosphere: Recent developments, *Radio Sci.*, **21**, 343, 1986.
- Brace, L. H., R. G. Theis, and A. Dalgarno, The cylindrical electrostatic probes for Atmosphere Explorer-C, -D, and -E, *Radio Sci.*, **8**, 341, 1973.
- Brinton, H. C., L. R. Scott, M. W. Pharo, and J. T. Coulson, The Bennett ion mass spectrometer on Atmosphere Explorer-C, -D, and -E, *Radio Sci.*, **8**, 323, 1973.
- Cartwright, D. C., Vibrational populations of the excited states of N₂ under auroral conditions, *J. Geophys. Res.*, **83**, 517, 1978.
- Constantinides, E. R., J. H. Black, and A. Dalgarno, The photochemistry of N⁺ ions, *Geophys. Res. Lett.*, **6**, 569, 1979.
- Davenport, J. E., T. G. Slanger, and G. Stewart, The quenching of N(²D) by O(³P), *J. Geophys. Res.*, **81**, 12, 1976.
- Doering, J. P., and E. E. Gulcicek, Direct electron excitation cross sections for forbidden transitions in atomic oxygen at low energies, *Eos Trans. AGU*, **69**, 417, 1988.
- Doering, J. P., C. O. Bostrom, and J. C. Armstrong, The photoelectron spectrometer experiment on Atmosphere Explorer, *Radio Sci.*, **8**, 387, 1973.
- Fehsenfeld, F. C., The reaction of O₂⁺ with atomic nitrogen, *Planet. Space Sci.*, **25**, 195, 1977.
- Fraser, M. E., W. T. Rawlins, and S. M. Miller, Auroral chemiexcitation and infrared branching ratios for the fundamental and first overtone vibrational transitions of NO(X²Π, v≤12), *Eos Trans. AGU*, **69**, 419, 1988.
- Frederick, J. E., and D. W. Rusch, On the chemistry of metastable atomic nitrogen in the F region deduced from simultaneous satellite measurements of the 5200 Å airglow and atmospheric composition, *J. Geophys. Res.*, **82**, 3509, 1977.
- Froese-Fischer, C., and H. P. Saha, Multiconfiguration Hartree-Fock results with Briet-Pauli corrections for forbidden transitions in the 2p⁴ configuration, *Phys. Rev. A*, **28**, 3169, 1983.
- Guberman, S. L., The production of O(¹D) from dissociative recombination of O₂⁺, *Planet. Space Sci.*, **36**, 47, 1988.
- Hanson, W. B., D. R. Zuccaro, C. R. Lippincott, and S. Sanatani, The retarding potential analyzer on Atmosphere Explorer, *Radio Sci.*, **8**, 309, 1973.
- Hays, P. B., G. Carignan, B. C. Kennedy, G. G. Shepherd, and J. C. G. Walker, The visible airglow experiment on Atmosphere Explorer, *Radio Sci.*, **8**, 369, 1973.
- Hays, P. B., D. W. Rusch, R. G. Roble, and J. C. G. Walker, The O I (6300 Å) airglow, *Rev. Geophys.*, **16**, 225, 1978.
- Hedin, A. E., MSIS-86 thermospheric model, *J. Geophys. Res.*, **92**, 4649, 1987.
- Henry, R. J. W., P. G. Burke, and A. L. Sinfailam, Scattering of electrons by C, N, O, N⁺, O⁺, and O⁺⁺, *Phys. Rev.*, **178**, 218, 1969.
- Hinteregger, H. E., K. Fukui, and B. R. Gilson, Observational, reference, and model data on solar EUV, from measurements on AE-E, *Geophys. Res. Lett.*, **8**, 1147, 1981.
- Iannuzzi, M. P., and F. Kaufman, Rates of some reactions of N(²D and ²P) near 300 K, *J. Chem. Phys.*, **73**, 4701, 1980.
- Jusinski, L. E., and T. G. Slanger, Determination of rate coefficient for quenching of N(²D) by O(³P), *Eos Trans. AGU*, **68**, 1388, 1987.
- Kennealy, J. P., F. P. delGreco, G. E. Caledonia, and B. D. Green, Nitric oxide chemiexcitation occurring in the reaction between metastable nitrogen atoms and oxygen molecules, *J. Chem. Phys.*, **69**, 1574, 1978.
- Kernahan, J. H., and H. L. Pang, Experimental determination of absolute A coefficients for 'forbidden' atomic oxygen lines, *Can. J. Phys.*, **53**, 455, 1975.
- Kirby, K., E. R. Constantinides, S. Babeu, M. Oppenheimer, and G. A. Victor, Photoionization and photoabsorption cross sections of He, O, N₂, and O₂ for aeronomic calculations, *At. Data and Nucl. Data Tables*, **23**, 63, 1979.
- Langford, A. O., V. M. Bierbaum, and S. R. Leone, Branching ratios for electronically excited oxygen atoms formed in the reactions of N⁺ with O₂ at 300 K, *J. Chem. Phys.*, **84**, 2158, 1986.
- Lean, J., Solar ultraviolet irradiance variations: A review, *J. Geophys. Res.*, **92**, 839, 1987.
- Lin, C. L., and F. Kaufman, Reactions of metastable nitrogen atoms, *J. Chem. Phys.*, **66**, 435, 1971.
- Link, R., and L. L. Cogger, A reexamination of the O I 6300-Å nightglow, *J. Geophys. Res.*, **93**, 9883, 1988.
- Link, R., G. R. Gladstone, S. Chakrabarti, and J. C. McConnell, A reanalysis of rocket measurements of the ultraviolet dayglow, *J. Geophys. Res.*, **93**, 14,631, 1988.
- Link, R., J. C. McConnell, and G. G. Shepherd, An analysis of the spatial distribution of dayside cleft optical emissions, *J. Geophys. Res.*, **88**, 10,145, 1983.
- Mehr, F. J., and M. A. Biondi, Electron temperature dependence of recombination of O₂⁺ and N₂⁺ ions with electrons, *Phys. Rev.*, **181**, 264, 1969.
- Meier, R. R., D. J. Strickland, J. H. Hecht, and A. B. Christensen, Deducing composition and incident electron spectra from ground-based auroral optical measurements: A study of auroral red line processes, *J. Geophys. Res.*, in press, 1989.

- Miller, S. M., C. P. Fell, and J. I. Steinfeld, Rate constants for the quenching of N^* by $O(^3P)$, *Eos Trans. AGU*, **69**, 1347, 1988.
- Mount, G. H., and G. J. Rottman, The solar absolute spectral irradiance 1150–3173 Å: May 17, 1982, *J. Geophys. Res.*, **88**, 5403, 1983.
- Mount, G. H., and G. J. Rottman, Solar absolute spectral irradiance 118–300 nm: July 25, 1983, *J. Geophys. Res.*, **90**, 13,031, 1985.
- Nagy, A. F., and P. M. Banks, Photoelectron fluxes in the ionosphere, *J. Geophys. Res.*, **75**, 6260, 1970.
- Nagy, A. F., J. P. Doering, W. K. Peterson, M. R. Torr, and P. M. Banks, Comparison between calculated and measured photoelectron fluxes from Atmosphere Explorer C and E, *J. Geophys. Res.*, **82**, 5099, 1977.
- Nier, A. O., W. E. Potter, D. R. Hickman, and K. Mauersberger, The open-source neutral-mass spectrometer on Atmosphere Explorer-C, *Radio Sci.*, **8**, 271, 1973.
- Ogawa, H. S., and D. L. Judge, Absolute solar flux measurement shortward of 575 Å, *J. Geophys. Res.*, **91**, 7089, 1986.
- Olson, R. E., and F. T. Smith, Collision spectroscopy in diatomic systems, report PYU-1848, SRI Int., Menlo Park, Calif., 1974.
- Piper, L. G., The excitation of $O(^1S)$ in the reaction between $N_2(A^3\Sigma_u^+)$ and $O(^3P)$, *J. Chem. Phys.*, **77**, 2373, 1982.
- Piper, L. G., M. E. Donahue, and W. T. Rawlins, Rate coefficients for $N(^2D)$ reactions, *J. Chem. Phys.*, **91**, 3883, 1987.
- Rees, M. H., and R. A. Jones, Time dependent studies of the aurora, II, Spectroscopic morphology, *Planet. Space Sci.*, **21**, 1213, 1973.
- Richards, P. G., and D. G. Torr, An investigation of the consistency of the ionospheric measurements of the photoelectron flux and solar EUV flux, *J. Geophys. Res.*, **89**, 5625, 1984.
- Richards, P. G., and D. G. Torr, Ratios of photoelectron to EUV ionization rates for aeronomic studies, *J. Geophys. Res.*, **93**, 4060, 1988.
- Richards, P. G., D. G. Torr, and M. R. Torr, Photodissociation of N_2 : A significant source of thermospheric atomic nitrogen, *J. Geophys. Res.*, **86**, 1495, 1981.
- Roble, R. G., and P. B. Hays, A technique for recovering the vertical number density profile of atmospheric gases from planetary occultation data, *Planet. Space Sci.*, **20**, 1727, 1972.
- Rottman, G. J., Rocket measurements of the solar spectral irradiance during solar minimum, *J. Geophys. Res.*, **86**, 6697, 1981.
- Rottman, G. J., 27-day variations observed in solar U.V. (120–300 nm) irradiance, *Planet. Space Sci.*, **31**, 1001, 1983.
- Rottman, G. J., C. A. Barth, R. J. Thomas, G. H. Mount, G. M. Lawrence, D. W. Rusch, R. W. Sanders, G. E. Thomas, and J. London, Solar spectral irradiance, 120 to 190 nm, October 13, 1981 – January 3, 1982, *Geophys. Res. Lett.*, **9**, 587, 1982.
- Samson, J. A. R., and P. N. Pareek, Absolute photoionization cross sections of atomic oxygen, *Phys. Rev. A*, **31**, 1470, 1985.
- Sharp, W. E., M. H. Rees, and A. E. Stewart, Coordinated rocket and satellite measurements of an auroral event, 2, The rocket observations and analysis, *J. Geophys. Res.*, **84**, 1977, 1979.
- Shyn, T. W., and W. E. Sharp, Differential excitation cross-section of atomic oxygen by electron impact: ($^3P-^1D$ transition), *J. Geophys. Res.*, **91**, 1691, 1986.
- Slinger, T. G., B. J. Wood, and G. Black, *Chem. Phys. Lett.*, **17**, 401, 1972.
- Solomon, S. C., and R. G. Roble, Simulation of the global thermospheric airglow, paper presented at Fall Meeting, AGU, San Francisco, Calif., 1988.
- Solomon, S. C., P. B. Hays, and V. J. Abreu, The auroral 6300 Å emission: Observations and modeling, *J. Geophys. Res.*, **93**, 9867, 1988.
- Spencer, N. W., H. B. Niemann, and G. R. Carignan, The neutral atmosphere temperature instrument, *Radio Sci.*, **8**, 284, 1973.
- Thomas, L. D., and R. K. Nesbet, Low energy electron scattering by atomic oxygen, *Phys. Rev. A*, **11**, 170, 1976.
- Tobiska, W. K., A solar extreme ultraviolet flux model, Ph.D. thesis, Univ. of Colo., Boulder, 1988.
- Torr, D. G., M. R. Torr, J. C. G. Walker, A. O. Nier, L. H. Brace, and H. C. Brinton, Recombination of O_2^+ in the ionosphere, *J. Geophys. Res.*, **81**, 5578, 1976.
- Torr, D. G., P. G. Richards, and M. R. Torr, Destruction of $N(^2D)$ by O_2 : A major source of 6300 Å dayglow emission, *Geophys. Res. Lett.*, **7**, 410, 1980.
- Torr, D. G., P. G. Richards, M. R. Torr, and V. J. Abreu, Further quantification of the sources and sinks of thermospheric $O(^1D)$ atoms, *Planet. Space Sci.*, **29**, 595, 1981.
- Torr, M. R., and D. G. Torr, Ionization frequencies for solar cycle 21: Revised, *J. Geophys. Res.*, **90**, 6675, 1985.
- Torr, M. R., D. G. Torr, and H. E. Hinteregger, Solar flux variability in the Schumann-Runge continuum as a function of solar cycle 21, *J. Geophys. Res.*, **85**, 6063, 1980.
- Vo Ky Lan, N. Feautrier, M. Le Dourneuf, and H. Van Regemorter, Cross-section calculations for electron-oxygen scattering using the polarized orbital close coupling theory, *J. Phys. B*, **5**, 1506, 1972.
- Wakiya, K., Differential and integral cross sections for the electron impact excitation of O_2 , I, Optically allowed transitions from the ground state, *J. Phys. B*, **11**, 3913, 1978.
- Walls, F. G., and G. H. Dunn, Measurement of total cross sections for electron recombination with NO^+ and O_2^+ using storage techniques, *J. Geophys. Res.*, **79**, 1911, 1974.
- Yee, J. H., V. J. Abreu, and W. B. Colwell, Aeronomic determinations of the quantum yields of $O(^1S)$ and $O(^1D)$ from dissociative recombination of O_2^+ , in *Dissociative Recombination: Theory, Experiments, and Applications*, edited by J. B. A. Mitchell and S. L. Guberman, World Scientific, Singapore, 1989.
- Zipf, E. C., and R. W. McLaughlin, On the dissociation of nitrogen by electron impact and by E.U.V. photo-absorption, *Planet. Space Sci.*, **26**, 449, 1978.
- Zipf, E. C., P. S. Espy, and C. F. Boyle, The excitation and collisional deactivation of metastable $N(^2P)$ atoms in auroras, *J. Geophys. Res.*, **85**, 687, 1980.

V. J. Abreu, Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109.

S. C. Solomon, High Altitude Observatory, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307.

Received January 13, 1989;

revised February 28, 1989;

accepted March 2, 1989.