Determination of F Region Height and Peak Electron Density at Night Using Airglow Emissions From Atomic Oxygen

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Measurements of the vertical column emission rates of atomic oxygen emissions arising from radiative recombination, ion-ion recombination, and dissociative recombination in the nighttime F region are sufficient to remotely sense the F layer height and peak plasma density. For example, measurements can be made of O I 1356 Å and [O I] 6300 Å, with vertical column emission rates J_{1356} and J_{6300}. To a very good approximation the peak electron density is proportional to $(J_{1356})^{1/2}$, and second-order dependence on height and exospheric temperature is very small. To a good approximation the ratio $(J_{1356})^{1/2}/J_{6300}$ is a single-valued function of the layer height.

Introduction

Measurements made of atomic oxygen emissions arising from radiative recombination, ion-ion recombination, and dissociative recombination in the nighttime F region can be used to remotely sense the F region layer height and peak electron density. For example, measurements can be made of O I 1356 Å and [O I]6300 Å, with vertical column emission rates J_{1356} and J_{6300}. To a very good approximation the peak electron density is proportional to $(J_{1356})^{1/2}$, and second-order dependence on height and exospheric temperature is very small. To a good approximation the ratio $(J_{1356})^{1/2}/J_{6300}$ is a single-valued function of height.

Second-order effects need be taken into account in deriving h_{max} from the airglow data, the most important of which is the dependence on exospheric temperature, as it affects the O_2 concentration. There is a very small dependence on n_{max}. When observations made in low-latitude regions are being interpreted, the difference in height of the layer at the northern and southern conjugate point regions can be determined and is insensitive to many neutral atmosphere parameters and second-order effects. The height differences thus obtained can be directly related to meridional winds. Also, when wave phenomena are present in the F region, the perturbations on F region plasma parameters can be accurately determined, in spite of uncertainty concerning neutral atmosphere parameters.

The ratio $(J_{1356})^{1/2}/J_{6300}$ is one of a number of ratios that could be employed. In general, the numerator should contain the column emission rate of an atomic oxygen radiative recombination emission such as the O I 905- to 910-Å continuum, O I 1356, O I 7774, or O I 4368. (The O I 1304 and O I 1027 lines and others for which the F region is optically thick are unsuitable. For details on radiative recombination and ion-ion recombination emissions see *Tinsley et al.* [1973] and *Van Zandt and Tinsley* [1974].)

The denominator should contain the column emission rate of an atomic oxygen emission from dissociative recombination, such as [O I] 6300, [O I] 6364, [O I] 2972, or [O I] 5577, if the F region component of the latter can be separated from the E region component. The ratio $(J_{7774})^{1/2}/J_{6300}$ is useful for ground-based measurements. The ratio $(J_{905-910})^{1/2}/J_{6300}$ does not involve ion-ion recombination, and a model is not needed for $n(O)$, although the uncertainties due to this are small. Emission rate $J_{905-910}$ could conceivably be measured in the daytime, giving reliable daytime values for n_{max}. We will confine our discussion to O I 1356 and [O I] 6300.

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Theory

The column emission rate $J_{1356}{}^r$, due to radiative recombination, is given by

$$J_{1356}{}^r = \int \alpha_{1356} n(O^+) n(e)\, dz \tag{1}$$

and the column emission rate due to ion-ion recombination is given by

$$J_{1356}{}^i = \int \frac{\beta_{1356} K_1 K_2 n(O) n(O^+) n(e)\, dz}{K_2 n(O^+) + K_3 n(O)} \tag{2}$$

The formalism and notation follow that of *Tinsley et al.* [1973] (see also Table 1).

The column emission rate J_{6300} due to dissociative recombination is given by

$$J_{6300}{}^d = \int \frac{K A_{6300} \gamma_1 n(O_2) n(O^+)\, dz}{A(1 + d(z)/A)} \tag{3}$$

where the formalism follows that of *Peterson and Van Zandt* [1969] (see also Table 1).

Now

$$\begin{aligned} n(e) &= n(O^+) + n(O_2{}^+) + n(NO^+) \\ &= n(O^+)[1 + B(z)] \end{aligned} \tag{4}$$

and $B(z)$ is significant only below 200 km under normal conditions and is given by

$$B(z) = \frac{\gamma_1 n(O_2)}{\alpha_1 n(e)} + \frac{\gamma_2 n(N_2)}{\alpha_2 n(e)} \tag{5}$$

and in the nighttime tropical regions with strong downward motions due to winds with $\mathbf{E} \times \mathbf{B}$ drifts it may become significant.

The term $d(z)$ is the quenching frequency and is given by

$$d(z) = S_{N_2} n(N_2) + S_e n(e) \tag{6}$$

where S_{N_2} and S_e are the quenching coefficients for quenching on N_2 and electrons, respectively. The electron quenching is nonnegligible in its effects on J_{6300} when the electron concentration is high at high altitude, as it may be with upward motion due to winds and drifts in the tropical regions. There is

TABLE 1. Reaction Rate Data

Reaction	Rate Coefficient	Reference
$O^+ + e \rightarrow O + h\nu$ (1356 Å)	$\alpha_{1356} = 8.1 \times 10^{-13} (1000/T)^{1/2}$	*Tinsley et al.* [1973]
$O + e \rightarrow O^- + h\nu$	$K_1 = 1.3 \times 10^{-15}$ cm^3 s^{-1}	*Massey* [1969]
$O^- + O^+ \rightarrow O^* + O$	$K_2 = 1.0 \times 10^{-7}$ cm^3 s^{-1}	*Olsen et al.* [1971]
	$\beta_{1356} = 0.54$	*Olsen et al.* [1971]
	$\beta_{6300} = 0.12$	*Olsen et al.* [1971]
~~$O^- + O \rightarrow O_2 + e$~~	~~$K_3 = 1.4 \times 10^{-10}$ cm^3 s^{-1}~~	~~*Fehsenfeld et al.* [1969]~~
$O^+ + O_2 \rightarrow O_2^+ + O$	$\gamma_1 = 2.0 \times 10^{-11} (300/T)$ cm^3 s$^-$	*Donahue* [1968]
$O^+ + N_2 \rightarrow NO^+ + N$	$\gamma_2 = 1.0 \times 10^{-12} (300/T)$ cm^3 s$^-$	*Donahue* [1968]
~~$O_2^+ + e \rightarrow O + O$~~	~~$\alpha_1 = 1.0 \times 10^{-7} (700/T)$ cm^3 s^{-1}~~	~~*Biondi* [1969]~~
$NO^+ + e \rightarrow N + O$	$\alpha_2 = 2.0 \times 10^{-7} (700/T)$ cm^3 s^{-1}	*Biondi* [1969]
$O(^1D) + N_2 \rightarrow O(^3P) + N_2$	$S_{N_2} = 7.0 \times 10^{-11}$ cm^3 s^{-1}	*Forbes* [1970]
$O(^1D) + e \rightarrow O + e$	$S_e = 1.7 \times 10^{-9}$ cm^3 s^{-1}	*Seaton* [1955]
	$A_{6300} = 0.0069$ s^{-1}	
	$A = 0.0091$ s^{-1}	
	$K = 1.0$	

Model for neutral atmosphere: *Walker* [1965] analytic form of *Jacchia* [1965] model with $n(O_2)_{120\ km} = 7.5 \times 10^{10}$ cm^{-3}, $n(O)_{120\ km} = 7.6 \times 10^{10}$ cm^{-3}, $n(N_2)_{120\ km} = 4.0 \times 10^{11}$ cm^{-3}, and $T_{120\ km} = 355$ K.

a very small amount of 6300 emission, due to ion-ion recombination, given by

$$J_{6300}{}^{i} = \int \frac{\beta_{6300} K_1 K_2 n(O) n(O^+) n(e)\, dz}{[K_2 n(O^+) + K_3 n(O)][1 + d(z)/A]} \tag{7}$$

This increases in importance relative to the dissociative recombination where $n(O)$ is larger relative to $n(O_2)$, i.e., at high altitudes. Under these circumstances $K_2 n(O^+) \gg K_3 n(O)$, and $n(O^+) \sim n(e)$, and it can be seen that the ratio of the volume emission rates is given approximately by

$$\frac{A\beta_{6300}K_1}{A_{6300}K\gamma_1} \cdot \frac{n(O)}{n(O_2)}$$

which with the rate coefficients given in Table 1 is negligible for normal thermospheric conditions. Thus we neglect $J_{6300}{}^{i}$ in what follows.

We can write

$$n(e) = n_m(e) S(z) \tag{8}$$

where $n_m(e)$ is the concentration at some reference height, say h_m, the height of the peak of the layer, and $S(z)$ is a shape function for the F region electron concentration.

Thus (3) becomes

$$J_{6300} = \frac{K A_{6300} n_m(e)}{A} \int \frac{\gamma_1 n(O_2) S(z)\, dz}{[1 + d(z)/A][1 + B(z)]} \tag{9}$$

Now

$$J_{1356} = J_{1356}{}^{r} + J_{1356}{}^{i} \tag{10}$$

and it is a good approximation in the height range where the 1356 emission is produced to take $n(O^+) = n(e)$, so that we can write

$$J_{1356} = n_m{}^2(e) \int \alpha_{1356} S^2(z)\, dz + n_m{}^2(e) \cdot \int \frac{\beta_{1356} K_1 K_2 n(O) S^2(z)\, dz}{K_2 n_m(e) S(z) + K_3 n(O)} \tag{11}$$

With the F layer at low altitudes the ratio of the volume emission rates of ion-ion recombination and radiative recombination is a maximum [*Hanson*, 1970] and for 1356 emission, using currently accepted rate coefficients, is about 60%. This can be seen by putting $K_2 n(e) \ll K_3 n(O)$ and the numerical values for the rate coefficients in (11). When the F layer is at high altitude or has high electron density, then $K_2 n(e) \gg K_3 n(O)$ over the height range of interest, and the second integral of (11) is negligible in comparison with the first. In either case, $(J_{1356})^{1/2}$ is proportional to n_m and nearly independent of h_m. For lower altitude layers the second-order effects on n_m are somewhat more important.

The relationship between $(J_{1356})^{1/2}/J_{6300}$ and h_m is affected by neutral atmosphere concentration variations and in particular by $n(O_2)$, which is an exponential function of exospheric temperature.

The dependence of $(J_{1356})^{1/2}$ on $n_m(e)$ for several h_m, and the dependence of the ratio $(J_{1356})^{1/2}/J_{6300}$ on h_m for several $n_m(e)$ have been calculated numerically using the rate coefficients and neutral atmosphere parameters given in Table 1. The nighttime F_2 region was represented by a modified Chapman function

$$S(z) = \exp\left\{\frac{1}{2}\left[1 - \frac{(z - h_m)}{H'(z)} - \exp\left(-\frac{(z - h_m)}{H'(z)}\right)\right]\right\} \tag{12}$$

The scale height $H'(z)$ is nearly the scale height of atomic oxygen. Since both the thermospheric temperature T and the gravitational acceleration g vary with height, the value of $H'(z)$ used in the calculations was given by

$$H'(z) = \frac{1}{2}[H(h_m) + H(z)] = \frac{k}{2m_0}\left[\frac{T(h_m)}{g(h_m)} + \frac{T(z)}{g(z)}\right] \tag{13}$$

Calculations were made for three exospheric temperatures, 800 K, 1000 K, and 1200 K, and temperature variations with height as in the *Walker* [1965] modification of the *Jacchia* [1965] model. For each exospheric temperature several values of $n_m(e)$ were used.

The integrals were evaluated over the range 150–800 km. The results are shown in Figures 1 and 2. It can be seen that the second-order variations of $(J_{1356})^{1/2}$ with h_m and T_m may for practical purposes be neglected. It can also be seen that for a given exospheric temperature the second-order variations of $(J_{1356})^{1/2}/J_{6300}$ with $n_m(e)$ are small (the order of 10 km in h_m), but variations with exospheric temperature are more important, amounting to a 30 km variation for 50 K.

For practical use of measurements of J_{1356} and J_{6300} to determine h_m one should use an iteration technique to solve (9) and (11) for these parameters. Using (11) a height of, say, $z_m = 350$ km can be taken to specify $H'(z)$ in $S(z)$ and with which ion-ion recombination can be ignored and $n_m(e)$ determined.

Then a first-order value of h_m is obtained by comparison of $(J_{1356})^{1/2}/J_{6300}$ with a curve such as shown in Figure 2 for the appropriate exospheric temperature and $n_m(e)$. Alternatively, a search is made in a subroutine for the value of h_m which with the given n_m and neutral parameters satisfies

$$\frac{(J_{1356})^{1/2}}{J_{6300}} = \left[\int \alpha_{1356} S^2(z)\,dz + \int \frac{\beta_{1356} K_1 K_2 n(\mathrm{O}) S^2(z)\,dz}{K_2 n_m(e) S(z) + K_3 n(\mathrm{O})}\right]^{1/2} \left[\frac{K A_{6300}}{A} \cdot \int \frac{\gamma_1 n(\mathrm{O}_2) S(z)\,dz}{[1 + d(z)/A][1 + B(z)]}\right]^{-1} \qquad (14)$$

Then an iteration for n_m and h_m is made once more, which is all that should be necessary.

COMPARISON WITH F REGION DYNAMIC MODELS

Significant effects might be thought to arise with the departure of the layer shape from the modified Chapman function when winds or electric fields are acting on the layer or when radiative recombination, with its square law loss rate, is relatively more important at high electron densities. A comparison of the results from the formulas as given above has been made with the results of a numerical model of the tropical *F* region, which solves the time-dependent coupled nonlinear system of equations for the O^+, NO^+, and O_2^+ number densities in the *F* region, including the effects of diffusion, $\mathbf{E} \times \mathbf{B}$ drifts and neutral wind. Examples of the use of this model have been presented by *Bittencourt et al.* [1974]. Samples for the present purposes were chosen with exospheric temperature corresponding to a value used with the formulas, and the ratio $(J_{1356})^{1/2}/J_{6300}$ was evaluated from the formulas and from the numerical model for corresponding height and electron concentrations. A plot of $(J_{1356})^{1/2}/J_{6300}$ from the formula against the same quantity from the numerical models should correspond to a ratio of the two quantities of unity and should fall on a straight line of 45° slope. Departures from the line would be due to numerical inaccuracies on account of the fairly coarse latitude and height (10 km) grid spacing in the numerical model and to departures from the Chapman layer shape if they are significant. The results shown in Figure 3 demonstrate that the departures from a ratio of unity are less

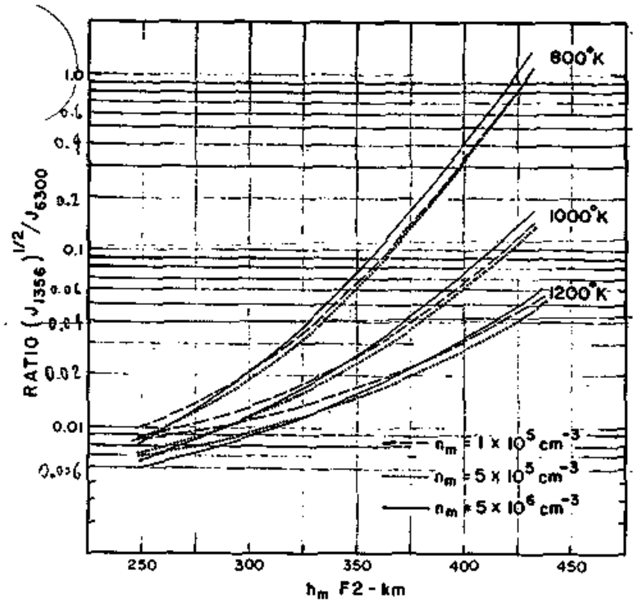

Fig. 2. Variation of $(J_{1356})^{1/2}/J_{6300}$ with h_mF_2 for exospheric temperatures 800 K, 1000 K, and 1200 K for peak electron density ($n_m(e)$) values 10^5, 5×10^5, and 5×10^6 cm^{-3}.

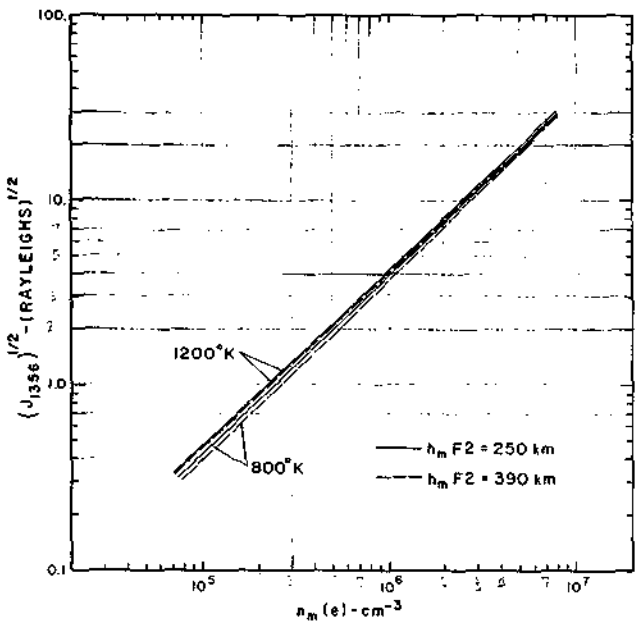

Fig. 1. Variation of $(J_{1356})^{1/2}$ with $n_m(e)$ for exospheric temperatures of 800 K and 1200 K and heights of 250 and 390 km.

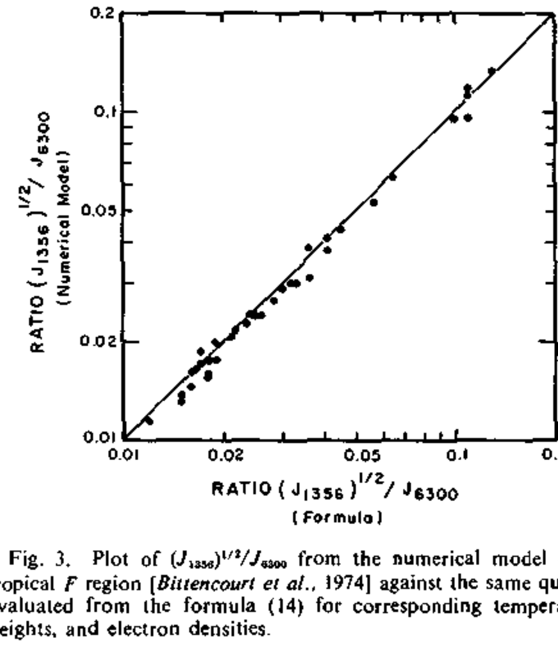

Fig. 3. Plot of $(J_{1356})^{1/2}/J_{6300}$ from the numerical model of the tropical *F* region [*Bittencourt et al.*, 1974] against the same quantity evaluated from the formula (14) for corresponding temperatures, heights, and electron densities.

than about 20%, or about 10 km in h_{max}, which can be ascribed to the numerical model. On examination of individual data points, no systematic departures from unity ratio were seen with wind velocities up to 110 m s^{-1} and electric field drift velocities up to 20 m s^{-1} or with n_{max} values up to 6 × 10^{6} cm^{-3}.

A small systematic departure of vertical profiles from the Chapman profile has been seen by direct comparison of electron concentration profiles, which is due to latitude gradients in n_{max} at small dip angles. Then the plasma concentration at altitudes other than the peak is coupled along the field line by diffusive equilibrium to a peak of different n_{max} at different latitude.

Correction to the data can always be made retrospectively if departures from Chapman layer shape become significant with, say, extreme values of latitude gradients, wind, or drift velocity. Such extreme values could be inferred, if present, from a suitable data set in latitude and/or local time.

Measurements Made Within the Layer

If measurements are made from a spacecraft within the region where the volume emission rate is significant, a correction for the column emission above the spacecraft (for nadir measurements) or below the spacecraft (for zenith measurements) must be made. Provided the nadir measurements are not made at or below the F region peak, or zenith measurements at or above the 6300-Å emission peak, the integrals (8) and (10) can be evaluated with the satellite height as one of the limits, and n_{max} and h_{max} obtained, although the iteration routine will not converge quite as rapidly as otherwise.

Determination of F Region Winds

As noted earlier, systematic errors such as in the value of $n(O_2)$ have small effects when height differences are being derived, so that the approach to remote sensing of F region heights described above is particularly suitable for obtaining height differences at conjugate points at low latitudes and using the height differences to obtain F region winds.

A study of Ogo 4 measurements of J_{1356} and J_{6300} [*Hicks and Chubb*, 1970; *Chandra et al.*, 1973] to determine winds in this way was proposed in 1972, and using the results of the numerical models as the basic reference, has led to values for the meridional and zonal F region winds in the vicinity of the Appleton anomaly [*Bittencourt et al.*, 1974; *Bittencourt*, 1975; *Tinsley et al.*, 1974].

Experimental Verification

Experimental verification of the relationship between J_{1356} and J_{6300} and h_m and n_m is equivalent to verifying (9) and (11). Equation (11) has been verified for J_{7774} by *Tinsley et al.* [1973] and for J_{1356} neglecting the smaller ion-ion recombination contribution by *Meier and Opal* [1973]. Equation (9) has been verified in a number of publications, one good example being that of *Wickwar et al.* [1974]. It has been felt desirable, however, to verify the deduction of h_m with measurements of J_{1356} and J_{6300} made simultaneous with ionosonde records. *Chandra et al.* [1975] have discussed determination of h_m and n_m along lines similar to that of this paper and have in fact essentially made the desired verification.

Conclusion

It has been shown theoretically that it is possible to sense the height and peak electron density of the nighttime F region by simply measuring the nadir intensity of two selected recombination airglow emissions. This has been done using data from Ogo 4, and with a new instrument designed for this purpose it could be done with much greater precision. It would be possible to calibrate it against an incoherent scatter radar, or the true height profile from an ionosonde, to remove systematic errors due to uncertainties in the instrumental calibration and in the rate coefficients in the equations.

It is necessary to obtain $n(O_2)$ near the 6300 emission peak from models. An error by a factor of 3 in $n(O_2)$ amounts to about 30-km error in h_m, but the error is unimportant when height differences at low-latitude conjugate points are used to determine F region winds.

When measurements are being made from a spinning satellite or h_m is otherwise determined from zenith angle scans of the emission, more independent parameters are obtained, and the analysis procedure can be modified to yield the value of $n(O_2)$ and height profiles of selected constituents.

This type of analysis has been made with limb scanning in O I 5577 alone from Ogo 6 by *Thomas and Donahue* [1972], and in this case they assumed an O_2 model and deduced horizontal and vertical electron concentration variations below the F region peak.

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References

Biondi, M. A., Atmospheric electron-ion and ion-ion recombination processes, *Can. J. Chem.*, *47*, 1711–1719, 1969.

Bittencourt, J. A., Determination of tropical F region winds from atomic oxygen airglow emissions, Ph.D. thesis, Univ. of Tex. at Dallas, Richardson, 1975.

Bittencourt, J. A., G. T. Hicks, and B. A. Tinsley, F region wind components in the magnetic meridian from Ogo 4 tropical airglow observations, Proceedings of the International Symposium on Solar Terrestrial Physics, vol. 3, pp. 328–337, São Paulo, Brazil, 1974.

Chandra, S., E. I. Reed, B. E. Troy, Jr., and J. E. Blamont, Equatorial airglow and the ionospheric geomagnetic anomaly, *J. Geophys. Res.*, *78*, 4630–4640, 1973.

Chandra, S., E. I. Reed, R. R. Meier, C. B. Opal, and G. T. Hicks, Remote sensing of the ionospheric F layer using airglow techniques, *J. Geophys. Res.*, in press, 1975.

Donahue, T. M., Ionospheric composition and reactions, *Science*, *159*, 489–498, 1968.

Fehsenfeld, F. A., A. C. Schmeltekopf, D. B. Dunkin, and E. E. Ferguson, Compilation of reaction rate constants measured in the ESSA flowing afterglow system to August, 1969, *Tech. Rep. ERL 135-AL3*, ESSA, Boulder, Colo., 1969.

Forbes, J. M., Yield of O(^1D) by dissociative recombination of O_2^+ from night airglow observations, *J. Atmos. Terr. Phys.*, *32*, 1901–1908, 1970.

Hanson, W. B., A comparison of the oxygen ion-ion neutralization and radiative recombination mechanisms for producing the ultraviolet nightglow, *J. Geophys. Res.*, *75*, 4343–4346, 1970.

Hicks, G. T., and T. A. Chubb, Equatorial aurora/airglow in the far ultraviolet, *J. Geophys. Res.*, *75*, 6233–6248, 1970.

Jacchia, L. G., Static diffusion models of the upper atmosphere with empirical temperature profiles, *Smithson. Contrib. Astrophys.*, *8*, 215, 1965.

Massey, H. S. W., Electronic and ionic impact phenomena, vol. 2, p. 1265, Oxford at the Clarendon Press, London, 1969.

Meier, R. R., and C. B. Opal, Tropical UV arcs: Comparison of brightness with f_oF_2, *J. Geophys. Res.*, *78*, 3189–3193, 1973.

Olsen, R. E., J. R. Peterson, and J. Moseley, Oxygen ion-ion neutralization reaction as related to tropical ultraviolet nightglow, *J. Geophys. Res.*, *76*, 2516–2519, 1971.

Peterson, V. L., and T. E. Van Zandt, O(^1D) quenching in the ionospheric F-region, *Planet Space Sci.*, *17*, 1725, 1969.

Seaton, M. J., The calculation of cross-sections for excitations of forbidden atomic lines by electron impact, *J. Atmos. Terr. Phys.*, *5*, 289, 1955.

Thomas, R. J., and T. M. Donahue, Analysis of Ogo 6 observations of the O I 5577-Å tropical nightglow, *J. Geophys. Res.*, *77*, 3557–3565, 1972.

Tinsley, B. A., A. B. Christensen, J. Bittencourt, H. Gouveia, P. D. Angreji, and H. Takahashi, Excitation of oxygen permitted line emissions in the tropical nightglow, *J. Geophys. Res.*, *78*, 1174–1186, 1973.

Tinsley, B. A., J. A. Bittencourt, J. E. Blamont, G. T. Hicks, and E. Reed, Tropical *F* region winds from Ogo 4 airglow data (abstract), *Eos Trans. AGU*, *55*, 1159, 1974.

Van Zandt, T. E., and B. A. Tinsley, Theory of *F* region recombination processes, *Ann. Geophys.*, *30*, 21–30, 1974.

Walker, J. C. G., Analytic representation of upper atmosphere densities based on Jacchia's static diffusion models, *J. Atmos. Sci.*, *22*, 462–463, 1965.

Wickwar, V. B., L. L. Cogger, and H. C. Carlson, The 6300-Å O(^1D) airglow and dissociative recombination, *Planet. Space Sci.*, *22*, 709–724, 1974.

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