Excitation of Oxygen Permitted Line Emissions in the Tropical Nightglow

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The ultraviolet oxygen emissions at 1304 and 1356 A in the tropical nightglow seen from Ogo 4 by Hicks and Chubb and Barth and Schaffner are accompanied by emissions at 7774 and 4368 A, which have been studied from the ground by looking through the beam of an ionosonde operated under the Appleton anomaly ionization peaks. Simultaneous [O I] 6300-A measurements were also made. A theoretical value for the partial rate coefficient for 7774 emission by radiative recombination has been obtained, and from the ionospheric data and a model atmosphere the expected rates of radiative recombination and ion-ion recombination were calculated. The time variations and absolute intensity of the calculated and observed intensities agree reasonably well, when the uncertainties involved are considered. It is concluded that radiative recombination is the major source of the tropical oxygen permitted line emissions, accompanied by a small contribution from ion-ion recombination.

The permitted oxygen emissions in the tropical nightglow were brought to the attention of aeronomers when they were seen in the O I 1304 and O I 1356 lines of atomic oxygen from Ogo 4. Measurements were made by *Hicks and Chubb* [1970] with filter photometers and by *Barth and Schaffner* [1970] with a scanning spectrometer. An earlier measurement of O I 4368 was made by *Ingham* [1962], O I 7774 emission has been observed by *Weill and Joseph* [1970], and 4368 and 7774 emissions have been observed by *Tinsley* [1972].

Three excitation mechanisms have been suggested: (1) radiative recombination due to *Hanson* [1969], (2) ion-ion recombination due to *Knudsen* [1970], and (3) particle precipitation discussed by *Hicks and Chubb* [1970].

The problem with particle excitation is that any exciting electrons would have to have an energy of $\sim$10 ev to produce the right ratios of spectral line intensities and to fail to excite lower-altitude constituents such as molecular nitrogen. Although some particles have been measured in the equatorial regions, they do not have either the right energy or sufficient flux or the right geographical position to explain the optical data [*Tinsley*, 1972].

The UV emissions were observed in bands 12°–15° on either side of the magnetic equator at all longitudes. These bands coincide closely in position with the region of high electron density known as the Appleton anomaly [*Martyn*, 1955; *Lyon and Thomas*, 1963] and with the positions of occurrence of the intertropical red arcs in [O I] 6300-A emission [*Barbier and Glaume*, 1960; *Barbier et al.*, 1961], which are known to be produced by ion-atom interchange followed by dissociative recombination. The observed spatial, diurnal, and seasonal variations of the permitted oxygen emissions correspond to those of the electron density in the anomaly very well, as is expected for a recombination mechanism.

Using estimates of the partial coefficient for radiative recombination and an electron density measured near the site and time of one of their strongest emissions, Barth and Schaffner concluded that the observed intensities were higher by an order of magnitude than those predicted for radiative recombination. This conclusion will be considered in more detail later.

Hanson [1970] has discussed the ratios of predicted intensities for radiative recombination and ion-ion recombination and concluded that, with reasonable rate coefficients, ion-ion recombination should always be less than radiative

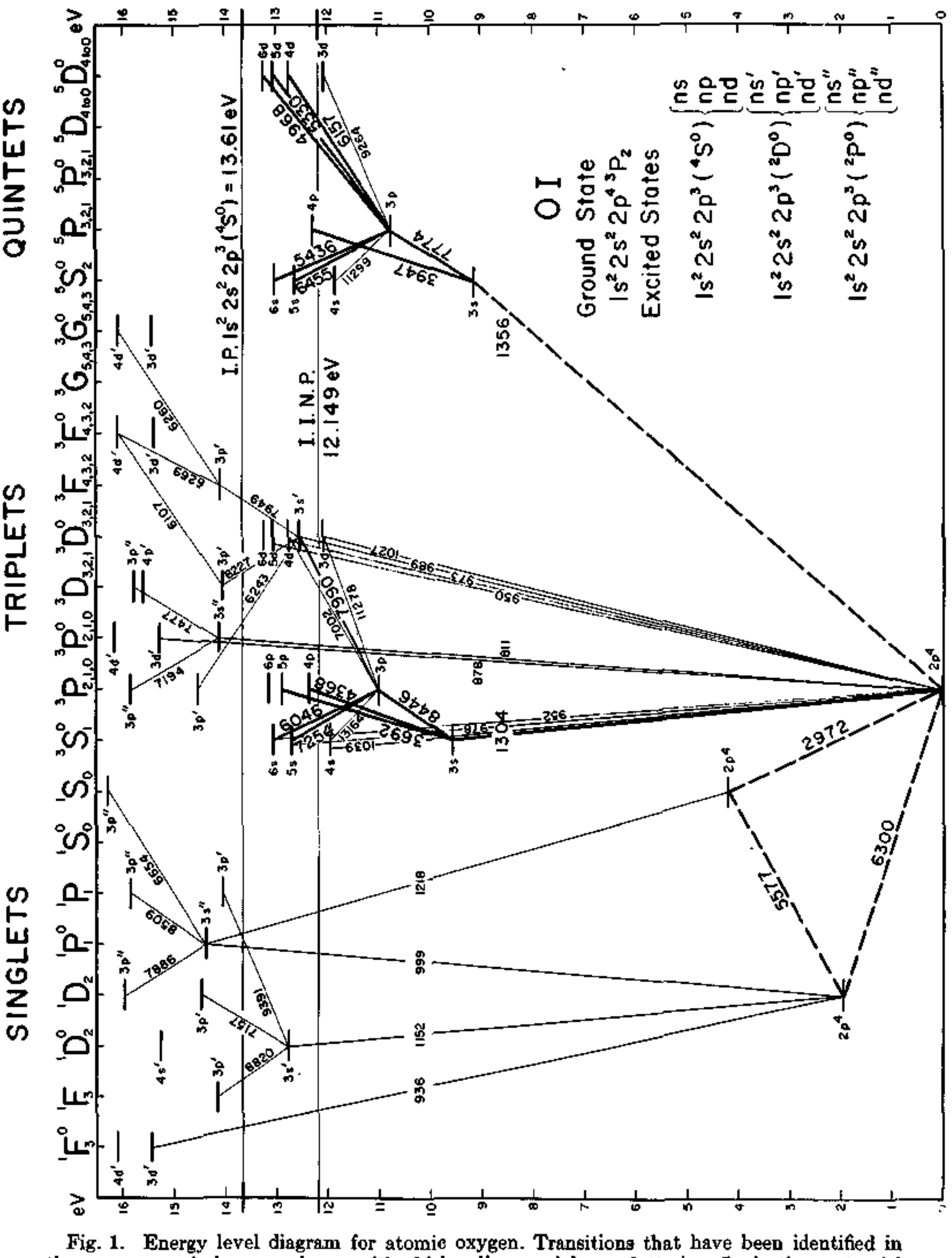

Fig. 1. Energy level diagram for atomic oxygen. Transitions that have been identified in the aurora or airglow are shown with thicker lines and larger lettering. Ionization potential IP = 13.61 ev, and ion-ion neutralization potential IINP = 12.149 ev.

recombination, particularly so when the F region maximum is high.

Figure 1 is a term diagram for atomic oxygen. The 4368-A ($3s^3S$–$4p^3P$) and 7774-A ($3s^5S$–$3p^5P$) emissions might be expected to be measurable from the ground when 1304-A ($2p^4\ ^3P$–$3s^3S$) and 1356-A ($2p^4\ ^3P$–$3s^5S$) emissions were occurring. Both these emissions have been found under the expected circumstances [*Tinsley*, 1972]. Other lines, e.g., 8446 A ($3s^3S^0$–$3p^3P^0$) and 1027 ($2p^4\ ^3P$–$3d^3D^0$), should also be present. All these high-excitation potential lines are regarded here as permitted lines to distinguish them from the well-known forbidden airglow lines [O I] 5577 and [O I] 6300. Although the 1356 transition is forbidden, the lifetime of the $3s^5S$ level is very short, i.e., 190 μsec [*Wells and Zipf*, 1972]. Therefore deactivation is negligible, and it is included in what are here called tropical oxygen permitted line emissions.

Weill and Joseph [1970] made measurements of 6300 and 7774 emissions in the direction of the intertropical arcs from a station in Israel. The ratio I 7774/I 6300 was variable and reached as high as 35%. Weill and Joseph calculated that this ratio would be attained with radiative recombination and dissociative recombination taking place at an altitude near 300 km. This paper reports further 7774 and 6300 observations made simultaneously with the operation of an ionosonde, so that the absolute intensities of the calculated and observed emissions could be compared. The optical observations were made at the Agulhas Negras site in Brazil (altitude 2.4 km, latitude −22.38°, longitude 44.68°W) chosen to be approximately under the Appleton anomaly at night. A number of sky scans and meridian scans have been made.

The ionosonde data were taken at São José dos Campos, 140 km southwest of the spectrometer site. The optical observations were therefore made at 25° zenith distance to view through the intersection of the ionosonde beam at the 300-km level. Calculations have been made of the partial rate coefficient for radiative recombination for the 7774 emission and other emissions. Further calculations then yield the expected 7774 emission rates for radiative recombination and ion-ion recombination for comparison with the data.

RADIATIVE RECOMBINATION RATE COEFFICIENTS

The reaction

$$O^+(^4S) + e^- \rightarrow O^x + h\nu \qquad (1)$$

represents the direct recombination into an excited state or ground state, yielding a photon of continuum radiation $h\nu'$. The excited oxygen atom cascading to the ground state is represented by $O^x \rightarrow O(^3P) + \sum h\nu$, where $\sum h\nu$ is the photons emitted in one or more transitions in the cascade. The column emission rate in the transition designated by i is then

$$J_i = \int \alpha_i n(O^+) n(e^-)\, dh \qquad (2)$$

where α_i is the partial rate coefficient for this transition.

A calculation has been made by R. C. Kirkpatrick (unpublished work, 1971) of the rates of direct recombination for singly ionized oxygen

TABLE 1. Partial Rate Coefficients for O^+ ($^4S^0$) Radiative Recombination into n, l Configurations at 700 °K

	STF Calculation					Hydrogenic Approximation					
n, l	0	1	2	3	4	5	6	7	8	9	Sum over l
2		4.532									4.532
3	0.795	0.654	1.311								2.760
4	0.251	0.385	0.781	0.478							1.895
5	0.119	0.233	0.464	0.416	0.206						1.438
6	0.068	0.150	0.293	0.308	0.234	0.105					1.158
7	0.043	0.102	0.195	0.224	0.206	0.130	0.040				0.940
8	0.029	0.073	0.137	0.165	0.168	0.129	0.067	0.017			0.785
9	0.020	0.054	0.100	0.125	0.135	0.119	0.078	0.034	0.008		0.673
10	0.015	0.041	0.075	0.098	0.105	0.107	0.076	0.043	0.017	0.005	0.582
11–∞											6.735
Total											21.498

Units are 10^{-13} cm^3 sec^{-1}.

TABLE 2. Partial Rate Coefficients for O^+ ($^4S^0$) Radiative Recombination into n, l Configurations at 1000 °K

	STF Calculation					Hydrogenic Approximation					
n, l	0	1	2	3	4	5	6	7	8	9	Sum over l
2		3.816									3.816
3	0.662	0.537	1.076								2.275
4	0.204	0.316	0.644	0.384							1.548
5	0.098	0.190	0.382	0.333	0.161						1.164
6	0.056	0.122	0.241	0.246	0.183	0.068					0.916
7	0.036	0.082	0.161	0.179	0.160	0.098	0.029				0.745
8	0.024	0.059	0.112	0.132	0.131	0.098	0.049	0.012			0.617
9	0.017	0.043	0.082	0.100	0.105	0.090	0.057	0.024	0.005		0.523
10	0.012	0.033	0.062	0.077	0.084	0.080	0.056	0.031	0.012	0.003	0.450
11–∞											4.797
Total											16.851

Units are 10^{-13} cm^3 sec^{-1}.

(in the lowest state $^4S^0$) into n, l configurations of neutral oxygen of the same parentage for $n \leq 10$. He used scaled Thomas Fermi cross sections without configuration interaction taken into account for the range $l < 5$ and the hydrogenic approximation for $l > 5$. Kirkpatrick obtained results for temperatures ranging from 10^2 ° to 10^6 °K. The values for temperatures of 700°, 1000°, and 2000°K are given in Tables 1–3.

Calculations of the hydrogenic approximation for n values greater than 10 have been made following *Seaton* [1959], and the totals for n from 11 to ∞ are also given in the tables.

Since the partial rate coefficients for the transitions of interest are determined much more by cascading from higher levels than by the direct recombinations, it is necessary to evaluate the cascading. Accurate cascading calculations have not been made, but useful results may be obtained by using certain approximations.

The cascading proceeds independently in the triplet and quintet states, the direct recombination rates into the triplet and quintet states being in the ratio 3:5. The population rates by cascading would also be in the ratio 3:5 but for the branching to the ground state at the $3d^3D^0$ state. The branching ratio for this transition, O I 1207 A ($2p^4\ ^3P$–$3d^3D^0$), is 0.62 according to *Green and Barth* [1967]. There is no corresponding branching for the quintet transitions, since the transition to the ground state is forbidden and competes with a permitted transition.

We approximate the population rate for the $3d^3D^0$ state by assuming one quarter of the cascade from the triplet states above it goes into $3d^3D^0$. The partial recombination coefficient for 1027-A emission α_{1027} is then given by

$$\alpha_{1027} = 0.62 \times \tfrac{3}{8}[\tfrac{1}{4}(\alpha_T - \alpha_{GS} - \alpha_{3s} - \alpha_{3p} - \alpha_{4s}) + \tfrac{3}{4}\alpha_{3d}] \qquad (3)$$

where α_T is the total coefficient, α_{GS} is the ground state coefficient, and α_{3s} and the like are coefficients for direct recombination into the specified states. Then

$$\alpha_{1304} = \tfrac{3}{8}[\alpha_T - \alpha_{GS}] - \alpha_{1027} \qquad (4)$$

Also

$$\alpha_{1356} = \tfrac{5}{8}[\alpha_T - \alpha_{GS}] \qquad (5)$$

We approximate the population rate for the $3p^5P$ state by assuming that three quarters of the cascading to the $3s^5S$ state is via the $3p^5P$ state. Then

$$\alpha_{7774} = \tfrac{3}{4} \times \tfrac{5}{8}[\alpha_T - \alpha_{GS} - \alpha_{3s}] \qquad (6)$$

The 8446-A ($3s^3S^0$–$3p^3P$) partial coefficient α_{8446} is obtained in a similar way as α_{7774} but with allowance for branching in α_{1027}; i.e.,

$$\alpha_{8446} = \tfrac{3}{4} \times \tfrac{3}{8}[\alpha_T - \alpha_{GS} - \alpha_{3s}] - \alpha_{1027} \qquad (7)$$

The approximation taken to determine α_{4368} is that one tenth of the cascade from the triplet states above it goes into the $4p^3P$ state. Thus

$$\alpha_{4368} = \frac{1}{6} \times \frac{3}{8}\left[\frac{1}{10}(\alpha_T - \alpha_{GS} - \alpha_{3s} - \alpha_{4s} - \alpha_{3p} - \alpha_{3d}) + \frac{9}{10}\alpha_{4p}\right] \qquad (8)$$

We approximate the population rate for the

TABLE 3. Partial Rate Coefficients for O^+ ($^4S^0$) Radiative Recombination into n, l Configurations at 2000 °K

	STF Calculation					Hydrogenic Approximation					
n, l	0	1	2	3	4	5	6	7	8	9	Sum over l
2		2.757									2.757
3	0.459	0.357	0.720								1.536
4	0.143	0.208	0.429	0.239							1.019
5	0.067	0.124	0.255	0.208	0.093						0.747
6	0.038	0.080	0.161	0.154	0.106	0.044					0.583
7	0.023	0.053	0.108	0.112	0.093	0.061	0.018				0.468
8	0.016	0.037	0.075	0.082	0.076	0.062	0.030	0.007			0.385
9	0.011	0.027	0.054	0.062	0.061	0.057	0.036	0.015	0.003		0.326
10	0.008	0.021	0.041	0.047	0.049	0.051	0.035	0.018	0.007	0.002	0.279
11–∞											2.391
Total											10.464

Units are 10^{-13} cm^3 sec^{-1}.

where the factor ⅙ takes account of the 5:1 branching from the $4p^3P$ to the $4s^3S^0$ state [*Dick*, 1970]. Recombination into the ground state produces a 905- to 910-A continuum, and the partial rate coefficient for this is designated $\alpha_{905\text{-}10}$. Table 4 lists the results for 700°, 1000°, and 2000°K. The coefficients for 905–10, 1356, and 1304 should be accurate to within about 10%, the 7774 and 8446 and 1027 coefficients to perhaps 30%, and the 4368 coefficient to perhaps 50%.

Calculated Expected Emission Rates

The expected emission rates due to radiative recombination and ion-ion recombination were calculated by using the f_oF_2 and h_{max} data from the ionosonde, the *Jacchia* [1971] model atmosphere for the exospheric temperature, and the *Jacchia* [1971] model for atomic oxygen height profiles for ion-ion recombination calculations. The calculations were made on a Burrows 3500 computer at INPE.

Electron density profiles. The ionograms could give only bottomside true height profiles, and the topside is equally important for radiative recombination. Consequently, it was necessary to fit a model electron density profile to the data and convenient to use it for the whole profile. *Chandra* [1963] found that a modified Chapman function with a variable scale height gradient is in good agreement with the electron density distribution obtained experimentally within the height range of 100 km below the F_2 peak to an altitude of about 700 km. After sunset, Chandra found that the departure from a Chapman function became small, as was expected from purely theoretical considerations [*Dungey*, 1956]. It is not clear whether a Chapman function would also be a good representation of nighttime profiles, especially the topside portions, in the Appleton anomaly region, where electric fields causing vertical drifts are important.

From the ionograms obtained simultaneously with the optical data, values for f_oF_2 and h_{max} were extracted. From the relation

$$N_{max} = 1.24 \times 10^4 (f_oF_2)^2 \qquad (9)$$

where f_oF_2 is in megahertz, the values for N_m, the electron density at the F_2 region peak, were obtained. The heights h_{max} of the peak were obtained by the '10-point method of reduction of ionograms' [*Schmerling*, 1967]. The Chapman function used was

TABLE 4. Partial Rate Coefficients for O^+($^4S^0$) Radiative Recombination Yielding Emission in Transition Listed

Transition	700°K	1000°K	2000°K
α_{905-10}	4.5	3.8	2.8
α_{1027}	1.1	0.9	0.5
α_{1304}	5.2	4.0	2.4
α_{1356}	10.6	8.1	4.8
α_{7774}	7.6	5.8	3.4
α_{8446}	3.4	2.6	1.5
α_{4368}	0.11	0.08	0.05

Units are 10^{-13} cm^3 sec^{-1}.

$$n(e^-) = n_{max} \exp \frac{1}{2}\left[1 - \frac{h - h_{max}}{H} - \exp\left(-\frac{h - h_{max}}{H}\right)\right] \quad (10)$$

where $n(e^-)$ was calculated for each height h by using a mean scale height,

$$H = [H_0\,(\max) + H_0(h)]/2 \quad (11)$$

where $H_0(\max)$ is the scale height of atomic oxygen at the F_2 peak and $H_0(h)$ is the scale height of atomic oxygen at the height considered by using the *Jacchia* [1971] temperature profile for the time of observation.

Calculations of 5 points below the peak were made for some ionograms by using the 10-point method, and the results were in reasonably good agreement with the values calculated by means of the above Chapman function.

Radiative recombination calculation. For F region heights it is a very good approximation to take $n(O^+) = n(e^-)$. Then

$$J_i = \int \alpha_i [n(e^-)]^2 \, dh \quad (12)$$

The integral given in (12) was computed for 7774-A emission by using the electron density distribution with height obtained for each ionogram as was described previously. The values of α_{7774} used were as given in Table 4 and interpolated for the exospheric temperature at the time of observation as a function of height.

Ion-ion recombination calculation. The production of O^- ions by the radiative attachment reaction

$$O + e^- \rightarrow O^- + h\nu' \quad (13)$$

is followed by mutual neutralization with O^+

$$O^- + O^+ \rightarrow O^x + O^x + KE \quad (14)$$

leaving one or both oxygen atoms in an excited state, which can then decay or cascade to the ground state in one or more transitions. Because only 12.149 ev is available for producing excited atoms (ionization potential 13.614 volts minus electron affinity for oxygen 1.465 volts), the possible transitions are fewer than those with radiative recombination, and in particular the 4368-A emission is not produced. A list of the states excited and their fraction of the total recombinations as a function of temperature has been given by *Olsen et al.* [1971].

The loss process

$$O^- + O \rightarrow O_2 + e^- \quad (15)$$

is important in reducing the O^- density, and the product of equations 5 and 7 of *Hanson* [1970] give the volume emission rate when this process is taken into account. The resulting column emission rate is

$$J_i = \int \frac{\beta_i K_2 K_1 n(O)[n(e^-)]^2}{K_2 n(e^-) + K_3 n(O)} \, dh \quad (16)$$

where β_i is the fraction of the total recombinations yielding the transition i and K_1, K_2, and K_3 are the reaction rate coefficients for (13), (14), and (15). Equation 16 was integrated from 90 to 900 km by using $n(e^-)$ and $n(O)$ obtained as described earlier. The rate coefficients used were: $K_1 = 1.3 \times 10^{-15}$ cm^3 sec^{-1} [*Massey*, 1969], $K_2 = 1.5 \times 10^{-7}$ cm^3 sec^{-1} [*Magee*, 1952; *Olsen et al.*, 1971], $K_3 = 1.4 \times 10^{-10}$ cm^3 sec^{-1} [*Fehsenfeld et al.*, 1969], and $\beta_{7774} = 0.42$ [*Olsen et al.*, 1971], and changes in the rate coefficients with temperature were neglected.

RESULTS AND DISCUSSION

The 7774 observations were made with a grille spectrometer [*Tinsley*, 1966]. Near 7774 A the reduction of the observed spectra is complicated by the presence of the O H(9, 4) band. Figure 2 shows two spectra of the region 7860 to 7660 A and illustrates the position of the O I quintet relative to the O H lines. Each emission line is recorded as a negative excursion by the grille spectrometer. The contribution of the Q_2 line to the quintet lines is estimated by using the observed Q_1 intensity. The ratio of the Q_1 to Q_2 line is assumed to be constant and is measured when the oxygen emission is very weak. This procedure is satisfactory when the intensity is greater than approximately 10 rayleighs, but for lower intensities there is substantial uncertainty. This uncertainty may be as high as ±5 rayleighs. The absolute calibration is estimated as ±20%.

Figure 3 shows a comparison of observed and calculated 7774 intensities for December 19–20, 1971, when $F_{10.7}$ was 139. The observed intensities have been corrected to the zenith. The cal-

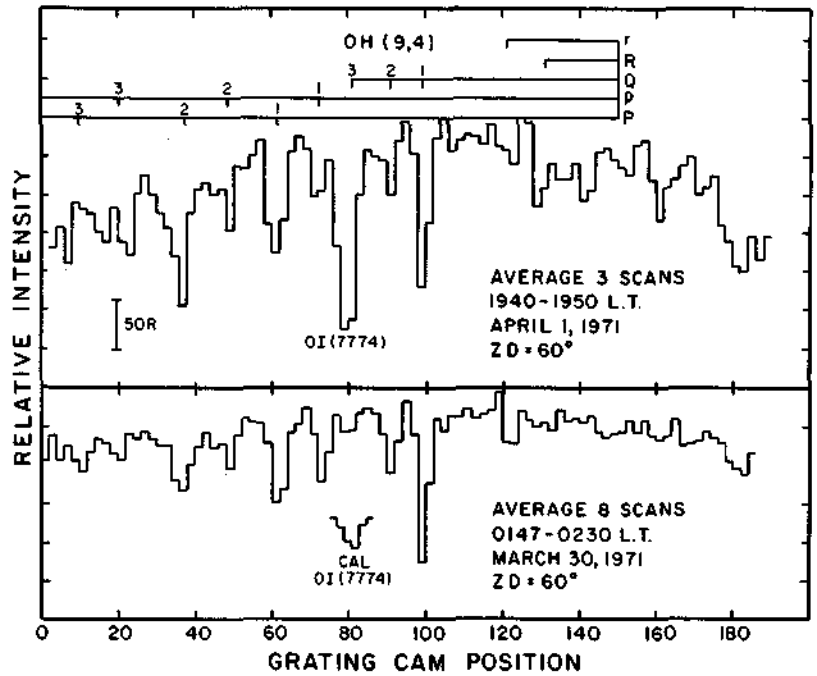

Fig. 2. Spectra obtained with grille spectrometer scanning every step in the region 7860 A to 7660 A for strong O I 7774 emission and weak O I 7774 emission. The grille spectrometer operates by nulling out each spectral element in turn; hence emission lines appear as negative excursions. The calibration profile was obtained from an oxygen discharge tube.

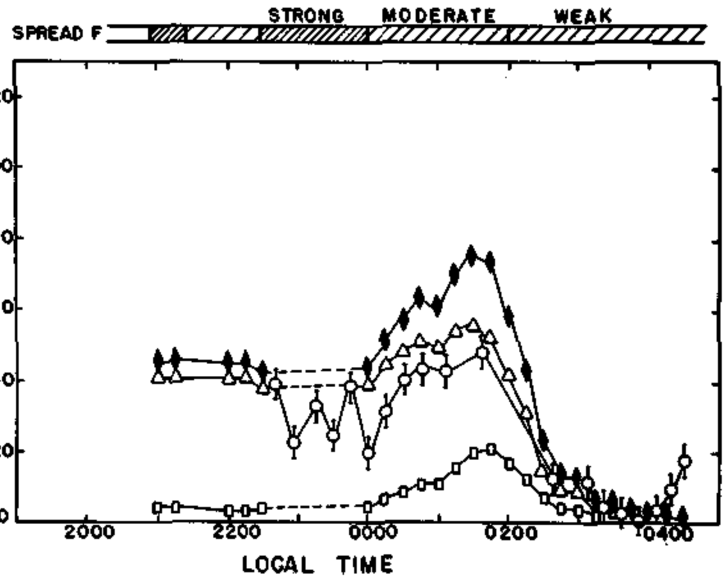

Fig. 3. Comparison of observed and calculated O I(7774 A) intensities for December 19–20, 1971, in Agulhas Negras, Brazil. The degree of severity of spread F is indicated at the top of the figure. Error bars represent only dispersion between several adjacent observations, which have been averaged. Observed intensities (circles), intensities calculated by ion-ion recombination (squares), intensities calculated by radiative recombination (triangles), and total calculated intensities (diamonds).

culated radiative recombination and ion-ion recombination contributions are each shown; their sum is also shown. The increase in ion-ion recombination between 0100 and 0200 hours resulted from a decrease in h_{max} from about 350 to 220 km. There are uncertainties in the calculated radiative recombination values, since the layer thickness is determined by the assumed topside profile. The presence of spread *F* caused errors in reading the ionograms. Also the observing conditions were not good with clouds up to 2230 and mist present at times. Note that the highest intensities did not come with the strongest spread *F*. As can be seen, the observed intensity is about 50% lower than the theoretical, rather than being higher, but the time variations agree.

Ion-ion recombination is only a small part of the total with the rate coefficients used. Increasing the ion-ion rate coefficient relative to the radiative coefficient would make the time variations agree less well. In view of the uncertainties the overall agreement between theory and observation is considered reasonable. Figure 4 shows the ionospheric data for December 19–20, 1971.

Figure 5 shows data from December 6, 1971, with generally lower intensities, but again observed values are lower than theoretical and there is reasonably good agreement in the time variations. On December 6 $F_{10.7}$ was 115.

Data were obtained on March 15–16, 1972. The observed 7774 intensity was almost 200 rayleighs in the zenith at 2030 hours. Owing to a malfunction of the ionosonde the critical frequencies on the ionograms were not recorded, and only lower limits for 7774 emission could be calculated. These amounted to about half the observed values.

A 6300-A photometer was also operating, looking in the same direction. The time variations do not agree, but it must be remembered that dissociative recombination depends very much on the height of the layer, whereas radiative recombination does not.

Figure 6 shows March 16–17, 1972, data with peak 7774 intensities of 135 rayleighs. At 1930 hours f_oF_2 was 16.7 MHz. The calculated 7774 intensities are in reasonable agreement with the observed 7774 intensities, when the uncertainties are considered. At 0230 hours, presumably, the layer came down and rapidly decayed by dissociative recombination. In the evening and the morning, scans were made in the magnetic meridian. The morning scan was made at a time when the 6300 emission was rapidly increasing but the 7774 emission was rapidly decreasing. Figure 7 shows the meridian scan results. The

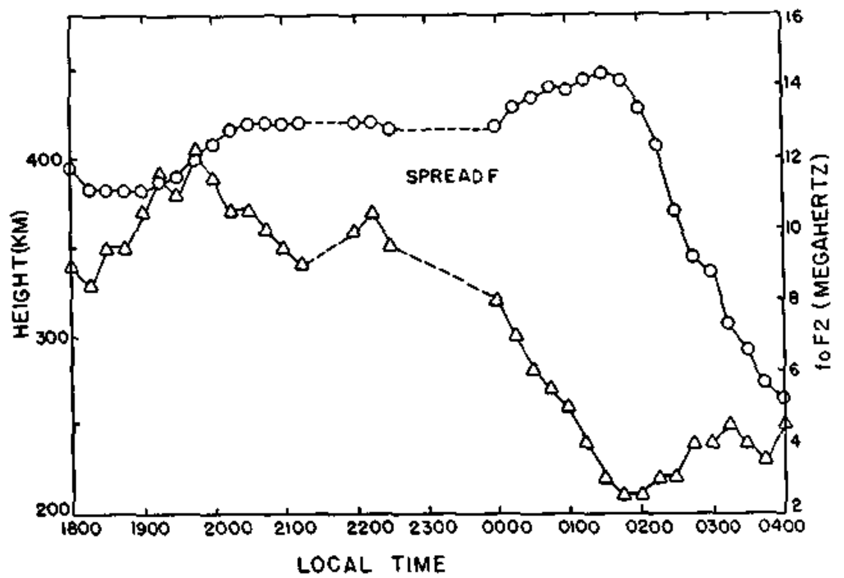

Fig. 4. Critical reflection frequency f_oF_2 (circles) and height of maximum electron density h_{max} (triangles) from ionograms at São José dos Campos, Brazil, on December 19–20, 1971.

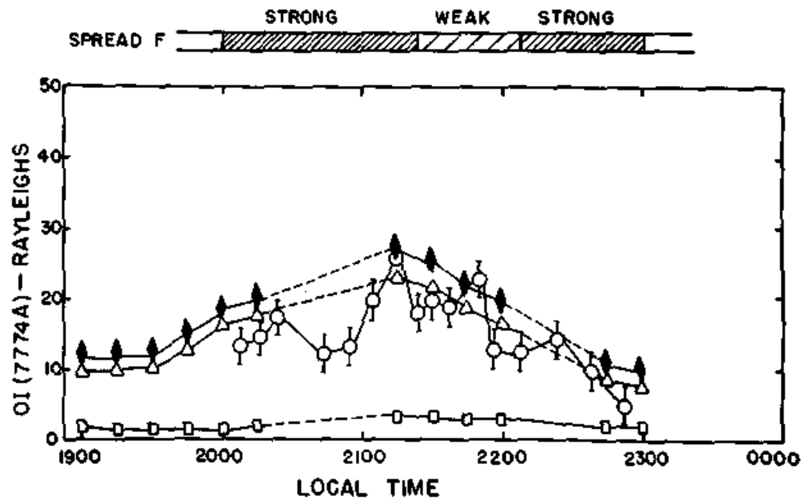

Fig. 5. Comparison of observed and calculated O I(7774 A) intensities for December 6, 1971 in Agulhas Negras. Observed intensities (circles), intensities calculated by ion-ion recombination (squares), intensities calculated by radiative recombination (triangles), and total calculated recombination intensities (diamonds).

data have been corrected for the Van Rhijn effects and show that at 1922–2000 hours the arc in 7774 was centered overhead, but in 6300 it was about 40° from the zenith toward magnetic south. This separation is to be expected where the electron density enhancement is field aligned, since here the field dips at 30° to the south. The radiative recombination would maximize at the F_2 peak, whereas the dissociative recombination would maximize farther down the field line in regions of increasing O_2 abundance.

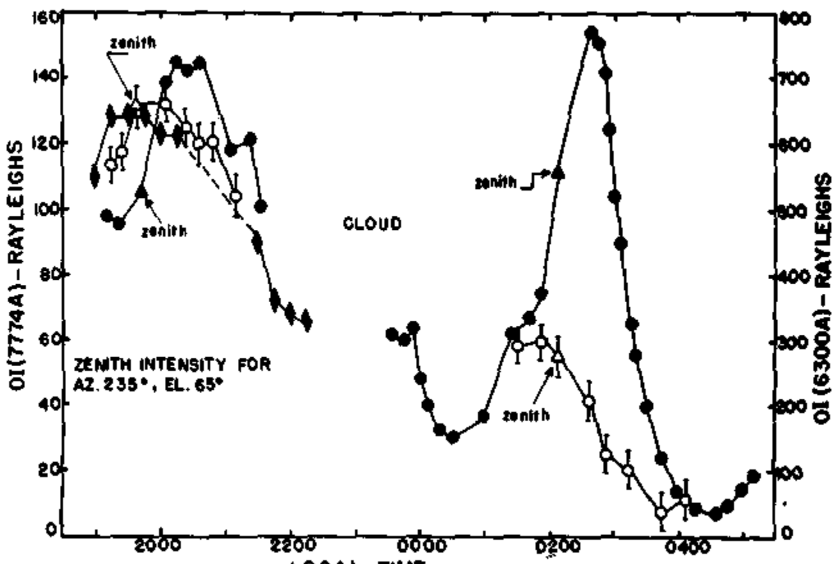

Fig. 6. Observed O I(7774 A) intensities (open circles), observed O I(6300 A) intensities (closed circles), and total calculated O I(7774 A) intensities (diamonds) for March 16–17, 1972, at Agulhas Negras.

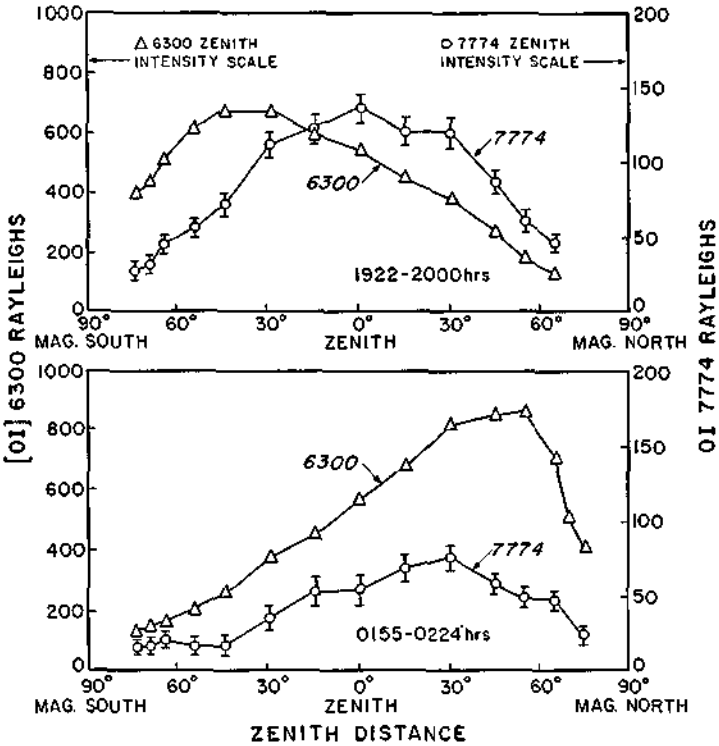

Fig. 7. Scans made in the magnetic meridian March 16–17, 1972. A correction for the time variations during the 0155–0224 scan could put the 6300 peak to the south of the 7774 peak.

The 0155- to 0224-hour observations do not show this effect of the 6300 maximum south of the 7774, perhaps because the 6300-A emission was increasing rapidly with time while the 7774-A emission was decreasing.

On March 17–18 a peak zenith intensity of 190 rayleighs was recorded when the observations began at 2136 hours.

To summarize the results, the observed intensities are approximately what one would expect from the fact that radiative recombination is the dominant recombination process, ion-ion recombination being a small contribution to the emission.

Discussion of Previous Results

The average peak intensity for the three nights of 7774 observations in March 1972 was 170 rayleighs, as compared with an average peak intensity for 1356-A emission of 240 rayleighs found by Hicks and Chubb for the period October 1 to November 15, 1967. By chance the average $F_{10.7}$ flux for the March observations was 134 as compared with an average value of 133 for the 1967 data. Since the partial recombination rate coefficient for 1356 is greater than that for 7774 (8.1×10^{-13} and 5.8×10^{-13} cm^{-3} sec^{-1}, respectively), radiative recombination seems a reasonable explanation of the Hicks and Chubb data also.

One may ask, Why did it previously seem that there were quantitative discrepancies between observed and calculated intensities? In a review paper [*Tinsley*, 1972] it was stated that the discrepancy between the observed and the calculated intensities was quite serious, but the occurrence of electron densities high enough to provide the observed intensities could not be ruled out. It is likely that the f_oF_2 values used in previously calculated intensities were an unreliable indication of peak f_oF_2 values at the anomaly. One factor not taken into account is that the UV experiments picked out the peak UV intensity at whatever latitude near the equator it happened to be located, whereas the ionogram f_oF_2 values used were averages for fixed latitudes, which would not necessarily correspond to the latitude of the peak.

Barth and Schaffner [1970] considered that there was an order of magnitude discrepancy. A number of effects may be responsible for this. The second figure of Barth and Schaffner's paper shows all the intensities found on an equatorial pass from which one spectrogram was compared with an Ahmedabad ionosonde observation. The spectrogram chosen was the one with the brightest emission, 1.7 kR of 1304 emission and 1.4 kR of 1356 emission. Fluctuations between adjacent spectrograms should be regarded as effects of noise according to Barth and Schaffner; therefore an average of several spectrograms, some of which showed less than 200 rayleighs, should be used. Also, Ahmedabad is on the high-latitude side of the anomaly, at about 17° magnetic latitude, and so its ionogram data should be compared with the weaker UV observations at that latitude, not at the peak at 13°–14° latitude. (The dip I at Ahmedabad for 1970 was 32° at the ground and 31.5° at 400 km [*Barish and Roederer*, 1969]. From the formula $\tan \theta = \frac{1}{2} \tan I$ the dip latitudes θ are 17.3° and 17.0°, respectively.) Also, Barth and Schaffner have systematically higher intensities than Chubb and Hicks and higher dayglow intensities than have been found by others. For example, Figure 1 of Barth and Schaffner's paper shows a dayglow 1304 intensity of 35 kR, whereas *Meier and Prinz* [1971] show 14 kR for the same solar zenith angle in their Figure 5. More extensive 1304 dayglow data from the Ogo 4 spectrometer given in Figure 1 of the paper by *Thomas* [1970] are about three times as intense as those from the Ogo 4 photometer as given by *Meier and Prinz* [1971]. Hence it seems that the Barth and Schaffner calibration should be revised downward considerably.

Barth and Schaffner also noted that their intensity ratio I 1304/I 1356 varied from 1 to 4, the average being 1.8. A correction for radiative transfer reduces this to 0.9. A similarly corrected ratio of 0.5 was obtained for 2 days' data by Hicks and Chubb. The partial recombination coefficients yield a ratio of 0.5. The higher value obtained by Barth and Schaffner and its large variation are not understood, but calibration and noise effects cannot be ruled out. The ratio in their brightest spectrogram, referred to above, was 1.2, which reduces to 0.6 when it is corrected for radiative transfer.

Anderson [1972] has used theoretical calculations of electron production, loss, ambipolar diffusion, vertical $\mathbf{E} \times \mathbf{B}$ drift, and neutral winds to calculate 1304 emission rates. For $F_{10.7} = 160$ units and a neutral equatorward wind, Anderson calculated total 1304 emission rates (radiative plus ion-ion recombination) of 200 rayleighs for the northern band and 112 rayleighs for the southern band with an electric field model based on Jicamarca observations.

Anderson concludes that his emission rates are lower than those observed, but the comparison with observations should be examined more closely. The average peak intensity of 1356-A emission seen by *Hicks and Chubb* [1970] for the period October 1 to November 15, 1967, when the average $F_{10.7}$ was 133 units, was 240 rayleighs from their Figure 9. From their measured I 1356/I 1304 ratio of 1.08 this is equivalent to 220 rayleighs of 1304 emission, independent of the uncertainty of the absolute calibration of the 1356 detector. When the radiative transfer effects are corrected for, the average 1304 intensity is reduced to 110 rayleighs. If allowance is made for the difference in $F_{10.7}$ values and uncertainties in the adequacy of the model, Anderson's calculations seem in reasonable agreement with the observations of Hicks and Chubb. The problem of the higher Barth and Schaffner intensities has already been discussed.

So our conclusion is that previous quantitative discrepancies between observed and calculated intensities cannot be considered reliable. We find that radiative recombination is indeed responsible for most of the tropical oxygen permitted line emissions, accompanied by a small contribution from ion-ion recombination.

NOMENCLATURE

The phenomenon of the tropical oxygen permitted line emissions discussed above should be described as airglow, and not aurora, since it shares with other emissions commonly regarded as airglow the energy source derived from the absorption of solar radiation and it is not due to particle precipitation in the auroral zone or elsewhere [see also *Barth and Schaffner*, 1970].

The acronym Troples (tropical oxygen permitted line emission) was used to describe the phenomenon in a previous publication [*Tinsley*, 1972]. It did not have the disadvantage of the acronyms EEFU [*Hicks and Chubb*, 1970] or TUVA [*Barth and Schaffner*, 1970] of excluding the visible (4368 A) and infrared (7774 A) emissions by describing the phenomenon as ultraviolet or far ultraviolet emissions. The description as permitted line emissions clearly separates the several lines emitted in this phenomenon from the well-known oxygen forbidden line emissions at 6300, 5577, and 2972 A. The 1356-A emission is regarded as permitted in this context because of the short (190 μsec) lifetime of the upper level compared with deactivation times in the F region, as was mentioned earlier.

However, several workers in the field have objected to Troples on this ground, and also to the tropical connotation, since a weaker emission should be present everywhere. The use of acronyms is to be discouraged where a direct reference to the excitation mechanism would not be clumsy. However, if an acronym is needed for the phenomenon of the tropical oxygen emissions resulting from radiative recombination and ion-ion recombination, Troples would appear to be more suitable than terms restricted to the UV.

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