Conjugate Photoelectron Excitation of O I 4368 Airglow Emission

Andrew B. Christensen

University of Texas at Dallas, Dallas, Texas 75230

Nelson R. Teixeira and Pramod D. Angreji

Instituto de Pesquisas Espaciaias, São José dos Campos, Brazil

Conjugate photoelectron fluxes are shown to be mainly responsible for the excitation of O I 4368 radiation observed with a grille spectrometer located at Langmuir Laboratory, New Mexico ($L = 1.7$). On the basis of observations of O I 7774 and 4368 tropical emissions at Agulhas, Negras, Brazil ($L = 1.1$), the contribution of radiative recombination to the New Mexico intensity is shown to be small. Conjugate photoelectron excitation at the Brazilian site has not been observed.

Following the suggestion by *Hanson* [1963] that photoelectrons could escape the local ionosphere, possible excitation of airglow emissions by the escape flux at the magnetically conjugate region has been explored. It was suggested by *Broadfoot and Hunten* [1966] that the strong winter maximum in N_2^+ emission observed at Kitt Peak was due to the enhanced ionization produced by conjugate photoelectrons. *Cole* [1965] suggested that the predawn enhancement of [O I] 6300 emission observed by *Barbier* [1959] was excited by fast thermal electrons heated by the conjugate flux. *Duboin et al.* [1968] confirmed the simultaneity of the predawn enhancement and the increase in electron temperature at the time of magnetic conjugate sunrise but ascribed the excitation mechanism for the [O I] 6300 to direct conjugate photoelectron impact. More recently, *Noxon and Johanson* [1970] pointed out that the increase observed at Boston ($L = 3.1$) was primarily due to an increase in dissociative recombination and excitation by direct impact usually played a minor role.

Since ionospheric reactions mainly determine both the [O I] 6300 and the N_2^+ emission rates, a knowledge of the ionospheric chemistry is required to relate the airglow observations to conjugate fluxes. The problem is not as complex with regard to the permitted lines of atomic oxygen. Because of the large (>9 ev) excitation energy, excitation by dissociative recombination is precluded and the principal excitation mechanism is particle impact.

Meier [1971] reported conjugate excitation of the resonance lines of atomic oxygen, using Ogo 4 ultraviolet photometer data. These observations extended the high-latitude boundary of conjugate excitation to L values in excess of 5, the upper limit placed on [O I] 6300 predawn enhancements by *Deehr* [1969].

Buckley and Moos [1971] reported sounding rocket data from White Sands on 1304 and 1356 emissions, which indicated conjugate photoelectron excitation. Although radiative recombination [*Hanson*, 1969] and ion-ion recombination [*Knudsen*, 1970] of O^+ can excite these lines, these mechanisms are important only in regions of very high ion densities, such as the Appleton anomalies.

In this paper, data on the 4368 and 7774 emissions obtained with a 1-meter grille spectrometer [*Tinsley*, 1966] located at Agulhas Negras, Brazil (altitude 2.4 km, latitude −22.38°, longitude 44.68°W, $L = 1.1$), are analyzed to confirm the theoretical radiative recombination coefficient given by *Tinsley et al.* [1973]. This coefficient is used in the analysis of O I 4368 observations obtained with the same spectrometer at Langmuir Laboratory, Socorro, New Mexico (altitude 3.24 km, latitude 33.98°, longitude 107.18°, $L = 1.7$), and the excitation by conjugate photoelectrons is shown to occur. Observations in Brazil when conjugate excita-

Copyright © 1973 by the American Geophysical Union.

tion would have been possible are scarce and not yet sufficient to exclude it.

Observations and Discussion

The emission from the atomic oxygen transitions at 4368 A ($3s^3S$–$4p^3P$) and 7774 ($3s^5S$–$3p^5P$) has been monitored in twilight and at night. In the normal operation of the grille spectrometer an observation consists of a 10-step scan of the spectrum repeated 8 or 16 times at a fixed azimuth and elevation. The photomultiplier output pulses are generally accumulated for 1 sec at each grating position and recorded on magnetic tape for subsequent computer data reduction.

Table 1 lists the dates of successful observations of 4368 and 7774 emissions in New Mexico and Brazil. The maximum intensities re-

TABLE 1. O I 4368 and 7774 Observations

			Peak Intensity, rayleighs	ZD,† deg	f_oF_2, MHz	Station
			1970 Data			
Jan. 28	O I 4368	New Mexico	0.8			
March 6–7	O I 4368	New Mexico	0.5	45	7.45	White Sands
Nov. 24–25	O I 4368	Brazil	0.9		D15.0S	Tucumán
Nov. 25–26	O I 4368	Brazil	1.4		D14.0S	Tucumán
Nov. 26–27	O I 4368	Brazil	0.7	0	D14.0S	Tucumán
			1971 Data			
March 21	O I 4368	Brazil	~1.0			
March 30–31	O I 4368	Brazil	0.7		J12.2S	Tucumán
March 29–30	O I 7774	Brazil	110		D10.6S	
March 31–April 1	O I 7774	Brazil	80		13.5	Tucumán
April 1–2	O I 7774	Brazil	200		D14.4S	
June 23	O I 4368	Brazil	~0.1*			
June 24–25	O I 4368	Brazil	0.1*			
June 25–26	O I 4368	Brazil	~0.1*			
June 26–27	O I 4368	Brazil	0.1*			
July 19–20	O I 4368	Brazil	0.15*			
July 20–21	O I 4368	Brazil	0.15*			
July 21–22	O I 4368	Brazil	0.2			
July 24–25	O I 4368	Brazil	0.3*			
Oct. 19–20	O I 4368	Brazil	0.4*			
Oct. 20–21	O I 4368	Brazil	0.5			
Oct. 21	O I 4368	Brazil	0.6			
Oct. 22–23	O I 4368	Brazil	0.4*			
Oct. 23–24	O I 4368	Brazil	0.5*			
Oct. 24–25	O I 4368	Brazil	0.4*			
Nov. 14–15	O I 4368	Brazil	0.55			
Nov. 15–16	O I 4368	Brazil	0.55			
Nov. 17–18	O I 4368	Brazil	0.4			
Nov. 18–19	O I 4368	Brazil	0.3			
Dec. 6	O I 7774	Brazil	50	45	12.3	INPE
Dec. 7	O I 7774	Brazil	80	45		
Dec. 12	O I 7774	Brazil	55	25	13.3	INPE
Dec. 19–20	O I 7774	Brazil	70	25		
			1972 Data			
March 15–16	O I 7774	Brazil	190	25	16.0	INPE
March 16–17	O I 7774	Brazil	135	25	17.5	INPE
March 17–18	O I 7774	Brazil	210	25		
March 19–20	O I 7774	Brazil	130*	25		
March 19–20	O I 4368	Brazil	2.5	25		
July 5	O I 4368	Brazil	<0.1		<8.3	INPE
July 6	O I 4368	Brazil	<0.1		<7.6	INPE

* No observations prior to 2100 LT.
† $ZD = 60°$ except where noted.

corded after 15° local solar depression angle at a zenith distance (*ZD*) 60° and any azimuth are listed and exceptions noted. Neither extinction nor Van Rhijn corrections have been applied to the data. Also included are the presently available f_oF_2 values obtained from Tucumán and São José dos Campos. The Tucumán ionosonde is located within the Appleton anomaly but about 2100 km west and south of Agulhas Negras. In December 1971 an ionosonde was put into operation by the Instituto de Pesquisas Espaciaias (INPE) at São José dos Campos, Brazil, 140 km southwest of the airglow site.

In a detailed analysis of the simultaneous airglow and ionospheric data, *Tinsley et al.* [1973] have shown that the tropical permitted oxygen line emissions are primarily excited by radiative recombination, i.e., $O^+ + e \rightarrow O + h\nu$. In the same paper the theoretical partial radiative recombination coefficients α_i for 4368 and 7774 emissions are discussed, and the values are listed in Table 2 of this paper. The theoretical coefficient for the 7774 emission was verified to within experimental uncertainties; however, the theoretical coefficient for 4368 is less accurate because of cascading, and simultaneous ionosonde and spectrometer observations in the Appleton anomaly were obtained only when the 4368 emission intensity was near the threshold of sensitivity, i.e., <0.1 rayleigh (see Table 1). Although this intensity was in agreement with the calculated intensity on the basis of the observed f_oF_2 values and the theoretical recombination coefficient listed in Table 2, further confirmation of the magnitude of the coefficient can be obtained by comparison of 7774 and 4368 intensities shown in Figures 1 and 2.

TABLE 2. Partial Radiative Recombination Coefficients Including Cascading in Cubic Centimeters per Second

	700°K	1000°K	2000°K
α_{7774}	7.6×10^{-13}	5.8×10^{-13}	3.4×10^{-13}
α_{4368}	0.11×10^{-13}	0.08×10^{-13}	0.05×10^{-13}
Ratio	0.014	0.014	0.015

Accuracy for 7774 estimated at 10% and for 4368 at 50% [*Tinsley et al.*, 1973].

Figure 1, in which the peak intensities of 4368 and 7774 emission and also the f_oF_2 values from Tucumán and INPE are plotted, shows the long-term trends in the Brazilian data. Actually, the intensity should vary as $(f_oF_2)^4$ for radiative recombination excitation, but, since the Tucumán f_oF_2 values were usually lower limits to the actual critical frequency, the values are shown in the first power. The low emission rates in June and July are consistent with the trend toward low f_oF_2 values shown by the Tucumán data.

The average peak zenith intensities shown in Figure 1 for five nights in the period March–April 1971 were 70 and 0.5 rayleighs for 7774 and 4368, respectively, which yield an intensity ratio of 0.007, half of the theoretical value.

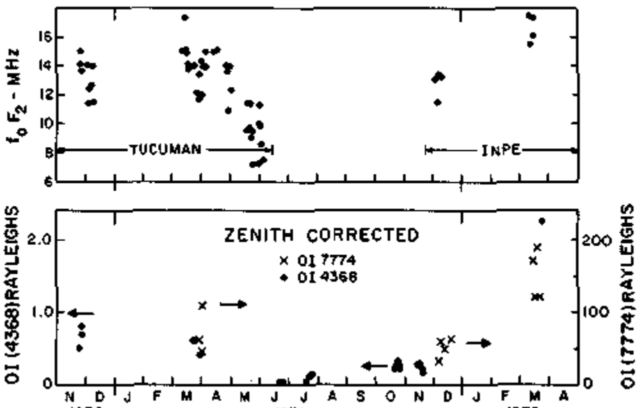

Fig. 1. Peak intensities corrected to zenith of O I 7774 and O I 4368 measured at Agulhas Negras, Brazil, and f_oF_2 measured at Tucumán, Argentina, and INPE São José dos Campos, Brazil.

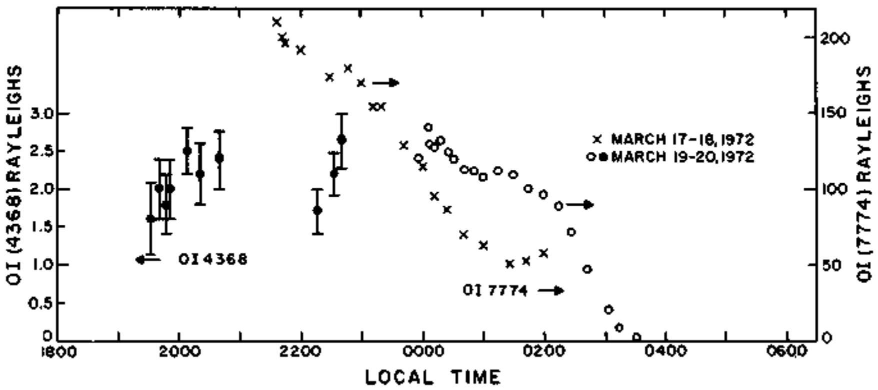

Fig. 2. Data for O I 4368 and O I 7774 obtained at Agulhas Negras (azimuth 235°, elevation 65°). On March 19–20, 4368 was observed before midnight and 7774 after midnight; 7774 data for March 17–18 are shown for comparison.

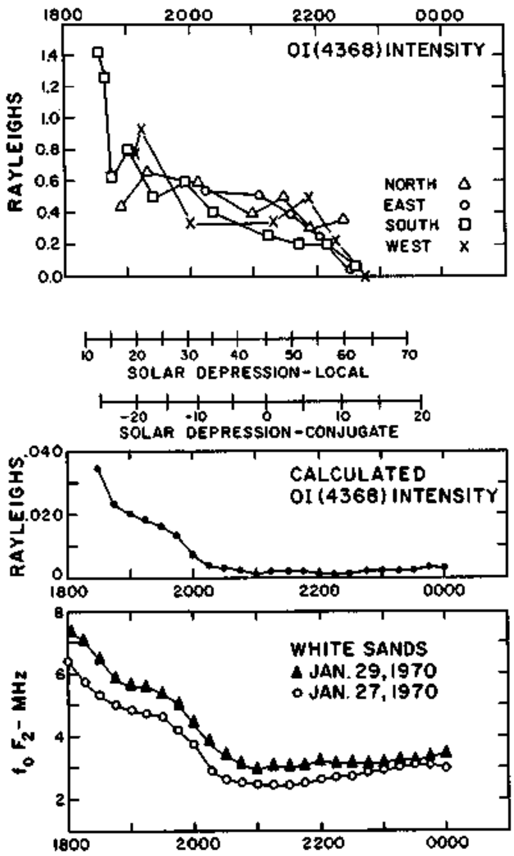

Fig. 3. The O I 4368 intensity observed on January 28, 1970, at Langmuir Laboratory, New Mexico ($ZD = 60°$) [*Tinsley*, 1970]. The calculated zenith intensity, if a radiative recombination source is assumed, is based on the f_oF_2 data for January 29, which are shown with the f_oF_2 values for January 27, 1970.

Figure 2 shows 4368 and 7774 data obtained on two nights in March 1971 in Brazil. On the evening of March 19 the spectrometer was aligned on 4368 and operated until 2245; some data gaps occurred because of clouds. The intensity was very high on that evening, i.e., 2.6 ± 0.5 rayleighs; however, the data were reduced by hand and include a systematic error estimated at <0.5 rayleigh. At midnight the instrument was aligned on 7774, and the intensity diminished from 140 rayleighs to near 0 at 0300 LT. At the time of changeover the ratio of 4368 to 7774 intensities was 0.018. However, on the basis of the 7774 data for March 17–18, also shown in the figure, it is expected that the 7774 intensity was greater earlier in the evening and the actual intensity ratio was probably somewhat smaller. Nevertheless, it is clear that the ratio inferred from these sets of measurements is consistent with the theoretical ratio of 0.014 given in Table 2, and therefore some confidence can be placed in the theoretical partial rate coefficient, $\alpha_{4368} = 0.08 \times 10^{-13}$ cm^{-3} sec^{-1}.

Observations of 4368 emission were carried out at Langmuir Laboratory [*Tinsley*, 1970], and the data are shown in Figures 3 and 4. On January 28, 1970 (Figure 3), the peak intensity was about 0.8 rayleigh. The random errors associated with the data are about ±0.1 rayleigh. The White Sands ionosonde was not in operation on this evening, so that f_oF_2 values for the preceding and following evenings are shown. The behavior of the F region on these days was quite similar.

Figure 4 shows measured intensities looking through the intersection of the White Sands ionosonde beam with the F region on March 6, 1970. The peak intensity was about 0.5 rayleigh ($ZD = 45°$). There is large scatter in the data in early twilight and during the passage of bright stars through the field of view, which does not show up on the other figures because the individual observations have been averaged together and noisy records excluded.

From α_{4368} and the measured f_oF_2 values the contribution of radiative recombination to the 4368 intensities observed in New Mexico was calculated by assuming a Chapman profile for the F region ionization density. The results are shown in Figures 3 and 4. If it is assumed that the ionosphere behaved on January 28 in a manner comparable to that on the preceding and following evenings, the contribution of radiative recombination to the total observed 4368 emission was about 1/10 when it is augmented by a Van Rhijn factor of 1.8. Thus, not only is this mechanism incapable of providing sufficient intensity, it fails to give the observed time dependence. (There is no contribution from ion-ion recombination, since the $4p^3P$ state cannot be excited.)

The cessation of emission on January 28 occurred shortly after conjugate sunset. The intensity dropped to the detection threshold at about a conjugate depression angle $\alpha_c = 10°$. This is in excellent agreement with the Ogo 4 results reported by *Meier* [1971] for conjugate electron excitation of O I 1304. Although the Ogo 4 observations were for higher L values, they indicate that the onset is not sensitive to the L value.

For the March 7, 1970, data (Figure 4), simultaneous 4368 and ionosonde data were available. In this case the radiative recombination source accounted for about one fourth of the total emission. There is a rather close temporal similarity between the two curves, and it could be argued that recombination is responsible. However, the calculated intensities (proportional to $(f_oF_2)^4$) on January 29 (Figure 3) and March 7 are comparable at

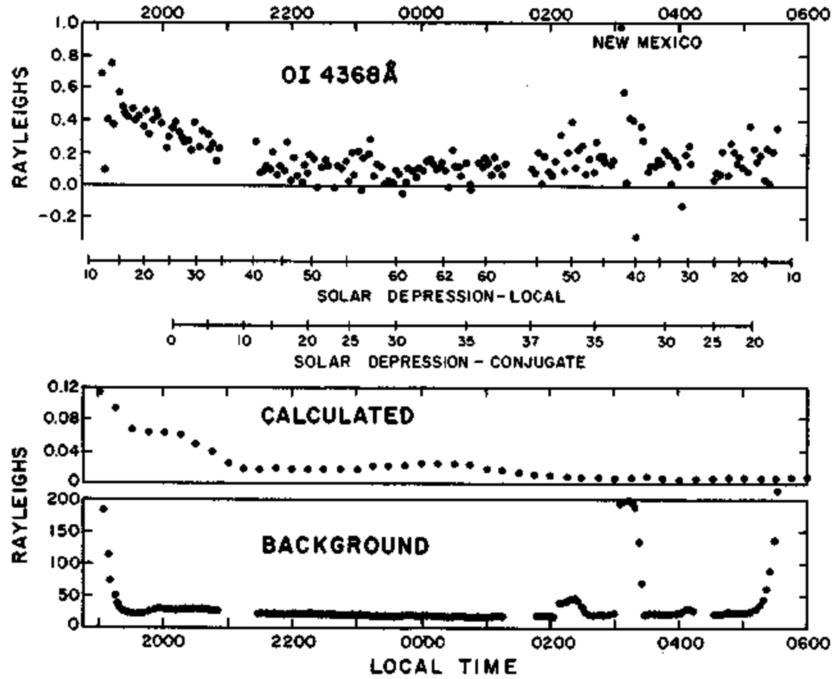

Fig. 4. The O I 4368 intensity observed at Langmuir Laboratory ($ZD = 45°$) on March 6–7, 1970, viewed through the White Sands ionosonde beam. The calculated zenith intensity of radiative recombination emission is based on f_oF_2 values of White Sands. The background curve is the intensity of the night sky passed by the spectrometer prefilter.

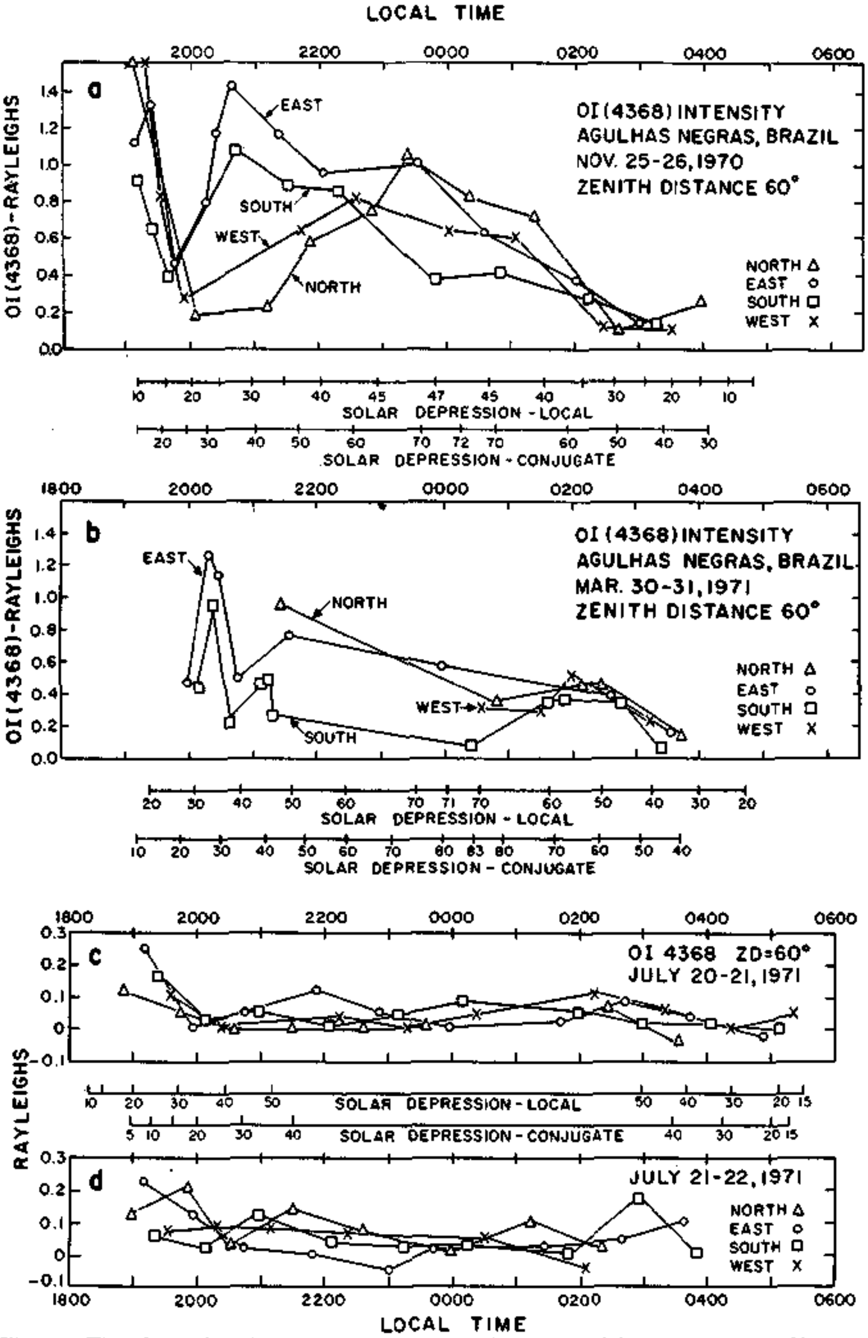

Fig. 5. The O I 4368 intensity on selected observing nights at Agulhas Negras.

equal local solar depression angles, but the observed values are similar when they are compared at equal conjugate solar depression angles. Hence the simultaneous decrease in the $(f_oF_2)^4$ and the observed intensity on March 7 does not imply a radiative recombination source of the 4368 emission.

It is instructive to compare our measurements with the Ogo 4 observations of conjugate O I 1304 emission reported by *Meier* [1971].

At conjugate sunset the 1304 ($2p^3P$–$3s^3S$) intensity ranged from 55 to 85 rayleighs for three days in 1967 at L values of 2–3.7. Meier states that there is an apparent increase of emission rate with increasing L value, but the dependence is weak. In addition, the measured 1304 intensity should be divided by 2 to take approximate account of the enhancement from photons emitted downward and resonance scattered upward to the satellite detector.

The zenith-corrected 4368 intensity measured at New Mexico at conjugate sunset was ~0.2 rayleigh. Therefore the ratio of 4368 to 1304 excitation is of the order of ½–1%.

This value is in fair agreement with what is expected on the basis of laboratory measurements of the excitation cross sections. Electron impact excitation cross sections for atomic oxygen have been measured by *Zipf and Stone* [1971]. They report that at 15 ev the excitation directly into the $3s^3S$ level accounts for 10% of the 1304 photons, whereas cascading through the 8446 and 4368 channels gives 84 and 6%, respectively. At 30 ev the 4368 channel does not provide a significant fraction of the total 1304 excitation. Since both the cross section and the conjugate photoelectron spectrum decline at energies above the threshold [cf. *Rao and Maier*, 1970], most of the excitation will be due to low-energy electrons, and we might reasonably expect the 6% contribution at 15 ev to be representative of the total excitation ratio, which is 5–10 times larger than that given by the observations. However, the

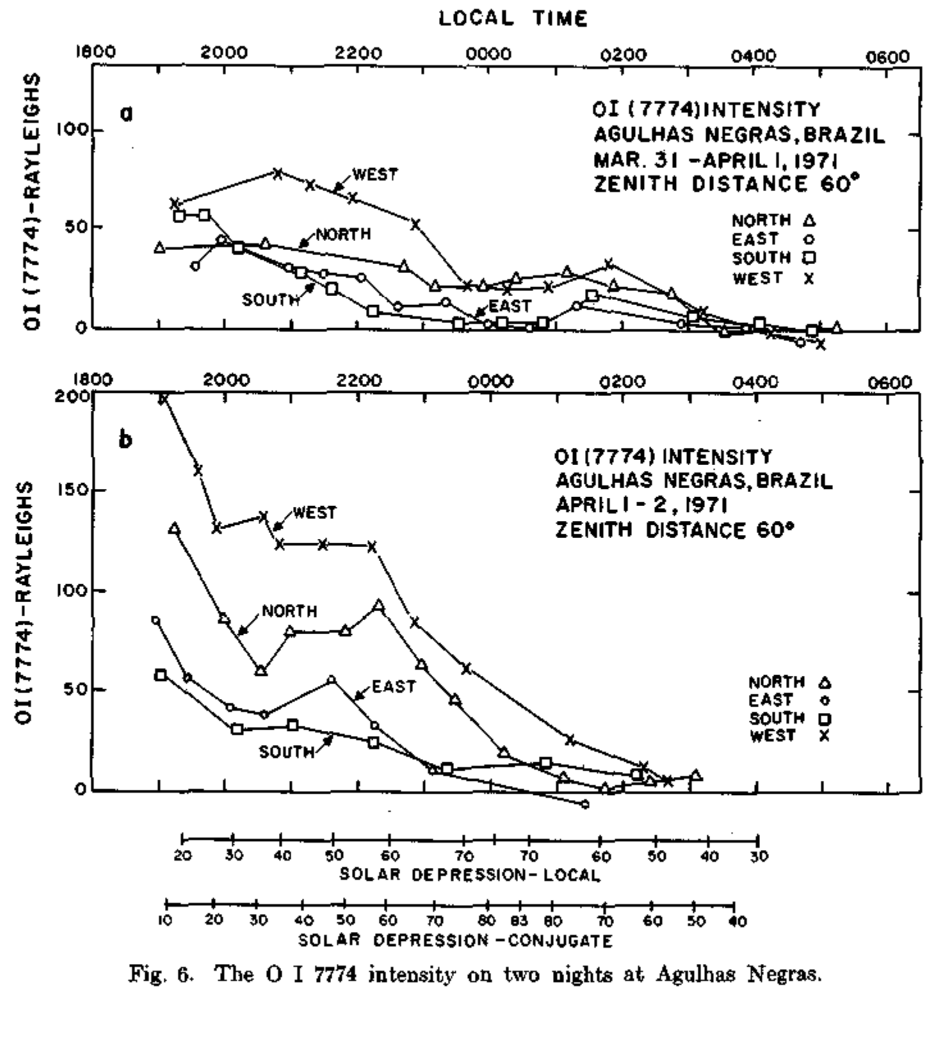

Fig. 6. The O I 7774 intensity on two nights at Agulhas Negras.

laboratory measurements have been repeated with improved techniques. These new measurements of the ^5S cross section do not show the strong cascade peak near the threshold (E. J. Stone and E. C. Zipf, private communication, 1972); thus it is implied that substantially less than 6% of the ^5S excitations are preceded by 4368 photons.

Recently, *Sawada and Ganas* [1973] carried out distorted wave calculations for electron impact on atomic oxygen. Their cross section for the excitation of the ^5S level does not show a large cascade peak and has a shape very similar to that of the most recent laboratory cross section. Their results indicate that, for the energy range 15–20 ev, about 13% of the ^5S excitations arise from cascade through the $4p^3P$ level. According to *Dick* [1970], the $4p^3P$ level has two channels of decay with transition probabilities, A (2.9 μ)/A (4368) $\sim$ 5. Therefore the cascading through the 4368 channel should account for $\sim$2% of the ^3S excitations, which is the same magnitude as that derived from the field observations of 1304 and 4368.

Bennett [1969] reported a lower limit of L = 1.1 for the occurrence of [O I] 6300 predawn enhancement and suggested that the occurrence was due to large collisional losses along the path between the conjugate points. Our Brazilian site lies close to this limit at L = 1.13, and we find no evidence for conjugate excitation in our data, which are shown in Figures 5 and 6. The intensity in early evening on November 25–26, 1970 (Figure 5*a*), shows a sharp decline, which is tempting to attribute to local photoelectron excitation, but, since sunset occurred first at the conjugate region, conjugate photoelectrons, if they are present, would be masked by locally produced fluxes.

Figure 6*b* shows a strong early evening maximum in 7774 emission, but Figure 6*a* does not. If either local or conjugate photoelectrons were responsible, a more reproducible time dependence would be expected.

The Brazilian observation of 4368 in local winter (Figures 5*c* and 5*d*) show maximum intensities of $\sim$0.25 rayleigh at α_c < 10°, which are comparable to intensities measured in New Mexico. However, our most recent 4368 measurements were obtained in the same season a year later with the ionosonde operating and exhibit intensities expected from a radiative recombination source. Actually, judging from the rapid decline in the photoelectron intensity after α_c reaches about 5°, observations of conjugate excitation would not be expected, since the observations generally began too late in the evening. The small time interval between local and conjugate sunset combined with local weather conditions at the Brazilian site makes observations of conjugate effects difficult.

Acknowledgments. We wish to acknowledge the assistance of Dr. Brian A. Tinsley in both the observational and the interpretive portions of this work. Also we wish to thank Dr. Jose R. Manzano for kindly supplying Tucumán ionosonde records.

This work was supported in part by NSF grants GA-18767 and GA-33262X and NASA institutional grant NGL-44-004-001 at UTD and INPE research funds.

* * *

The Editor thanks E. Zipf and another referee for their assistance in evaluating this report.

REFERENCES

Barbier, D., Recherches sur la raie 6300 de la luminescence atmosphérique nocturne, *Ann. Geophys.*, *15*, 179–217, 1959.

Bennett, R. T., Latitude dependence of 6300-A (O I) twilight airglow enhancement, *J. Geophys. Res.*, *74*, 381–383, 1969.

Broadfoot, A. L., and D. M. Hunten, N_2^+ emission in the twilight, *Planet. Space Sci.*, *14*, 1303–1319, 1966.

Buckley, J. L., and H. W. Moos, Vacuum ultraviolet spectra of the late twilight airglow, *J. Geophys. Res.*, *76*, 8378–8383, 1971.

Cole, K. D., The predawn enhancement of 6300-A airglow, *Ann. Geophys.*, *21*, 156–158, 1965.

Deehr, C. S., The predawn enhancement of 6300 A(O I) airglow: Morphology and variation with solar activity, *Ann. Geophys.*, *25*, 867–879, 1969.

Dick, K. A., Some spectrometric results from the NASA 1968 airborne auroral expedition, *J. Geophys. Res.*, *75*, 5605–5608, 1970.

Duboin, M.-L., G. Lejeune, M. Petit, and G. Weill, Excitation of the oxygen lines and ionospheric heating by conjugate photoelectrons, *J. Atmos. Terr. Phys.*, *30*, 299–304, 1968.

Hanson, W. B., Electron temperatures in the upper atmosphere, *Space Res.*, *3*, 282–302, 1963.

Hanson, W. B., Radiative recombination of atomic oxygen ions in the nighttime *F* region, *J. Geophys. Res.*, *74*, 3720–3722, 1969.

Knudsen, W. C., Tropical ultraviolet nightglow from oxygen ion-ion neutralization, *J. Geophys. Res.*, *75*, 3862–3866, 1970.

Meier, R. R., Observations of conjugate excitation of the O I 1304-A airglow, *J. Geophys. Res.*, *76*, 242–247, 1971.

Noxon, J. F., and A. E. Johanson, Effect of magnetically conjugate photoelectrons on O I(6300 A), *Planet. Space Sci.*, *18*, 1367–1379, 1970.

Rao, B. C. N., and E. J. R. Maier, Photoelectron flux and protonospheric heating during the conjugate point sunrise, *J. Geophys. Res.*, *75*, 816-822, 1970.

Sawada, T., and P. S. Ganas, Distorted wave calculations of electron impact excitation of atomic oxygen, *Phys. Rev. A*, *7*, 617–626, 1973.

Tinsley, B. A., The circularly symmetric grille spectrometer, *Appl. Opt.*, *5*, 1139-1145, 1966.

Tinsley, B. A., O I 4368 A emission following twilight, *J. Geophys. Res.*, *75*, 3932–3934, 1970.

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

Zipf, E. C., and E. J. Stone, Photoelectron excitation of atomic oxygen resonance radiation in the terrestrial airglow, *J. Geophys. Res.*, *76*, 6865–6874, 1971.

(Received August 31, 1972;
accepted December 19, 1972.)