Simultarieous Measurements of the OH(8,3) Band and OI 5577 Å Airglow Emissions*

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Simultaneous measurements of the night airglow OH(8,3) band and OI 5577 Å have been made at Cachoeira Paulista (22.7°S, 45,2°W) during June-August 1976. Correlations between the nocturnal variations of these emissions and also with the OH rotational temperature are presented. It is found that OH (8,3) is correlated with the rotational temperature but with a time lag of about 1 hour. The variations of 5577 Å lead the OH (8,3) by about 2 to 3 hours. The rotational temperature co-varies with 5577 Å, rather ttian OH (8,3) and there is no significant time lag. Based on the correlation study, the nocturnal variations of the two emissions can be explained by the atmospheric density perturbation caused by solar tides and internal gravity waves.

As luminescências atmosféricas da banda OH(8,3) e da linha OI 5577 Å em Cachoeira Paulista (22.7°S, 45.2°W) foram medidas simultâneamente durante os meses de junho e agosto de 1976. São apresentadas as correlações entre as variações noturnas das intensidades das duas emissões e a temperatura rotacional, deduzida através da medida de OH. Os resultados mostram uma boa correlação entre a intensidade de OH e a temperatura rotacional, porém, com aproximadamente 1 hora de atraso. As variações de 5577 Å estão adiantadas em relação a OH (8,3) em 2 a 3 horas. As variações de temperatura rotacional estão mais bem correlacionadas com 5577 Å do que som OH(8,3) e não há atraso de tempo significante. Com base neste estudo *de* correlação, as variações das e-

missões podem ser explicadas pela perturbação na densidade atmosférica causada por marés solares e ondas de gravidade internas na alta atmosfera.

1. INTRODUCTION

Hydroxyl bands (0.4 - 4.5 m) and the oxygen green line OI 5577 Å are the most intense emissions in the upper mesosphere and lower thermsphere. As both the emissions depend on the atomic oxygen density and its variations, simultaneous measurements of these two emissions will te of interest to help elucidating the photochemical and dynamical processes occurring in the emitting region.

The altitude of the 5577 Å emission peak is in the region of about 90 to 100 Km which corresponds to the altitude where the peak density of atomic oxygen is located. The 5577 Å emission layer isabout 10 Km thick. The OH emission comes from the altitude of about 80 to 90 Km in which the peak of ozone production is located, and is about 10 to 15 Km thick. Because of this difference of emission altitude, a study of the correlation between the variation of both the emissions should be useful to study time-dependent dynamical processes, such as vertical transport of atomic oxygen by turbulence and tidal and gravity wave propagation.

This kind of study, however, has been attempted by only a few groups of researchers. Rao and Kulkarni (1971)[1] have mentioned that there was no obvious relationship between the 5577 Å and OH emissions, showing scattered positive and negative correlaticn coefficients. In a previous paper (Takahashi *et al.*, 1977)[2], we found a low correlation although the emissions showed similar trends, increasing their intensities after midnight.

In this paper we examine the relationship between the emissions in more detail, including the correlation between the nocturnal variations, the time lag and the amplitudes of the variations. The rotational temperature (hereafter referred as ROT) could be deduced from the measurement of the intensity ratio of the Q $(K-K$ transitions, whe-

re K is the rotational quantum number) and R $((K+1)-K$ transitions) branches of the OH(8,3) band. This temperature, approximately equal to the ambient gas kinetic temperature, is also included in the present study.

2.OBSERVATIONS AND RESULTS

Measurements of the 5577 Å and OH(8,3) band emissions have been made at Cachoeira Paulista $(22.7^O$S, 45.2^OW) since 1973. Some results of these observations have been published elsewhere (Teixeira et al., 1975)[3]. This study is based on measurements made from June to August 1976, and is restricted to nights in which at least 6 hours of continuous observations were obtained.

In Fig.1 nocturnal variations of 5577 Å, OH(8,3) and ROT are shown for 8 nights in June and July 1976. It is difficult to see any general characteristic in the variations observed on individual nights. Assuming that the minor constituents (0, O_3, H, OH, HO_2, etc.) in the emitting layer are in photochemical equilibrium and that there is no dynamical disturbance, the atomic oxygen density above 90 Km remains constant (Shimazaki and Laird, 1971)[4]. so that the 5577 Å intensity should not change. The OH(8,3) intensity should decrease monotonically because of a loss of atomic oxygen below 85 Km (Moreels, 1977)[5].

The observed variations, however, are more complicated. It can be seen that short period (less than 6 hours) wavelike variations are superposed on the variation of the longer period. Comparing the variations of the three parameters, 5577 Å, OH(8,3) and ROT, it should be noted that:

1. In general, the variation of 5577 Å is anti-phased with OH(8,3), not only in tne case of short period, but also for long period variations (July 25 and 23, respectively).

2. ROT co-varies with 5577 Å rather than with OH(8,3). This is most clearly observaòle on June 19, July 23 and July 24.

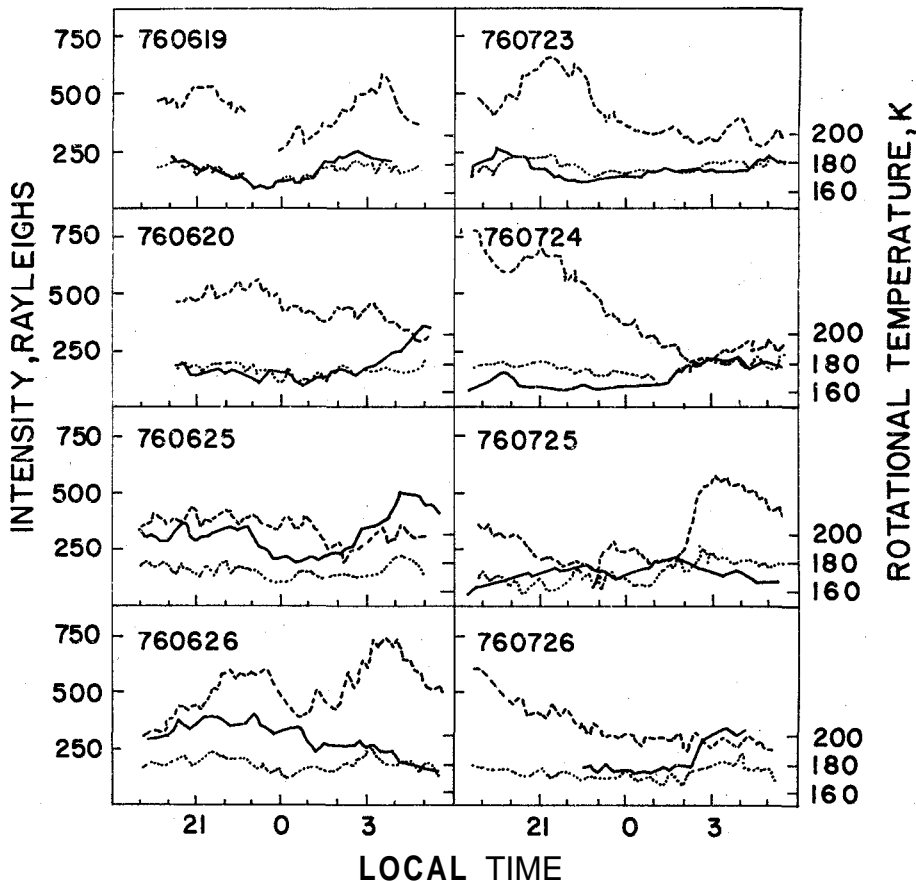In order to examine the relationship between the three para-

Fig.1 - Nocturnal variation of 5577 Å (full line), OH(8,3) (broken line) and OH rotational temperature (dotted line) on some selected nights.

meters in more detail, we have calculated cross-correlation coeffi-cients for various time shifts. In Fig.2 we show the correlation, for time shifts up to about 3 hours, between OH(8,3) and 5577 Å, OH (8,3) and ROT and ROT and 5577 Å. Correlation curves are shown for 3 indivi-dual nights and for all 18 niyhts taken conjointly. For each of the 3 nights shown, the OH(8,3) lags ROT and 5577 Å. On June 19, the three correlation coefficients are positive at time lag zero, but maximum values occur after 40 minutes and 80 minutes for OH/ROT and OH/5577 Å respectively. On July 25, the correlation coefficient for zero time shift is negative for OH/5577 Å, whereas after 2h 40min. the value reaches a positive maximum.
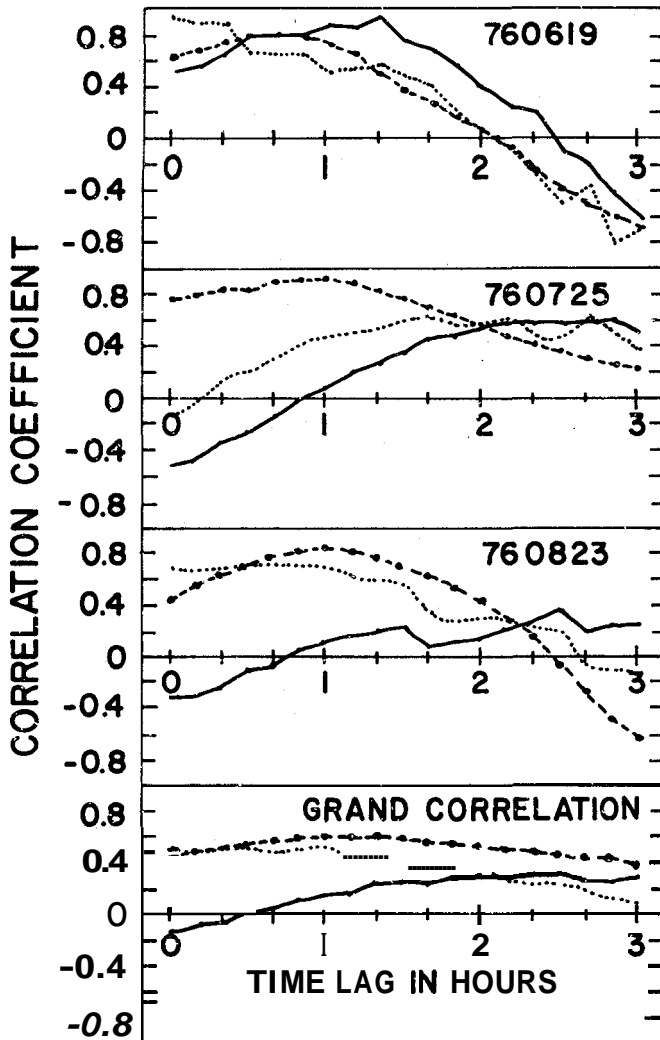
Fig.2 - Variation of the correlation coefficients between OH(8,3) and 5577 Å (full line), OH(8,3) and OH rotational temperature (broken line) and OH rotational temperature and 5577 Å (dotted line) with time shifts.

In order to show the general trend, the conjoint correlation is also shown in Fig.2. It may be seen that:

1. ROT leads OH(8,3) by about 1 hour,

2. 5577 Å leads OH(8,3) by about 2 to 3 hours,

3. There is no significant time lag between ROT and 5577 Å.

It is interesting to note that the phase lag between $OH(8,3)$ and 5577 Å results in a small negative correlation for zero time shift. It is presumably for this reason that Rao and Kulkarni (1971)[1] observed no significant correlation between these parameters.

The fact that 5577 Å leads $OH(8,3)$ might be explained by a downward transport of atomic oxygen due to an increase of turbulence. This, however, does not explain the time lag between $OH(8,3)$ and ROT. We believe that a more reasonable explanation is that both temperature and density are modulated by the downward propagation of a wavelike disturbance. A phase difference between the density and temperature fields is predicted by tidal theory (Chapman and Lindzen, 1970)[6].


3. EMISSION PROFILES OF OI 5577 Å And OH(8,3)

The generally accepted excitation mechanism of the 5577 Å emission from the lower thermosphere, suggested by Chapman (1931)[7], is the three-body recombination of atomic oxygen.

$$0 + 0 + 0 \rightarrow 0(^1S) + 0_2 \quad K_1 = 4.8 \times 10^{-33} \text{ cm}^6\text{sec}^{-1}$$

(Felder and Young, 1972)[8] (1)
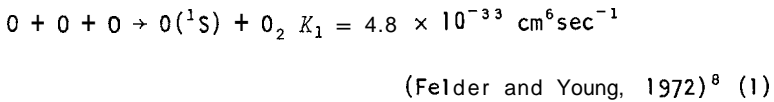
followed by the $^1S - {}^1D$ transition, with the Einstein coefficient A_{32}

$$0(^1S) \rightarrow 0(^1D) + h\nu \ (5577 \text{ Å}) \quad A_{32} = 1.28 \text{ sec}^{-1} \tag{2}$$
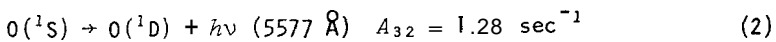
and $^1S - {}^3P$ transition, with the Einstein coefficient A_{31}

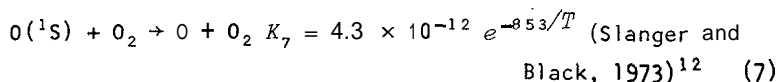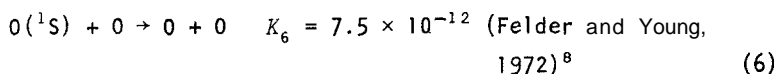$$0(^1S) \rightarrow 0(^3P) + h\nu \ (2972 \text{ Å}) \quad A_{31} = 0.078 \text{ sec}^{-1}, \tag{3}$$
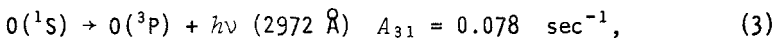
where K is the reaction rate coefficient.

Barth (1964)[9] has suggested another possible excitation by electronically excited molecular oxygen.

$$0 + 0 + M \rightarrow 0_2^* + M \tag{4}$$

$$0_2^* + 0 \rightarrow 0(^1S) + 0_2 \tag{5}$$
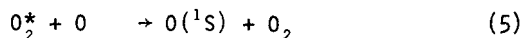
According to Donahue et $al.$ (1973)[10], there is no reason to believe that the Barth mechanism makes any significant contribution to the 5577 $\overset{o}{A}$ emission. In a recent paper, Slanger and Back (1977)[11] have tried to show that the Barth mechanism does in fact explain the observed intensity and altitude distribution of the 5577 $\overset{o}{A}$ emission, better than the Chapmari mechanism. They do this, however, on the basis of their recent redetermination of the overall rate coefficient for the $O(^1S)$ producing reaction which is a factor of 10 greater than the Felder and Young's (1972)[8] value.

Quenching of $O(^1S)$ by 0 and O_2 is important,

$$O(^1S) + 0 \rightarrow 0 + 0 \quad K_6 = 7.5 \times 10^{-12} \text{ (Felder and Young,}$$
$$\text{1972)[8]} \tag{6}$$

$$O(^1S) + O_2 \rightarrow 0 + O_2 \quad K_7 = 4.3 \times 10^{-12} \, e^{-853/T} \text{ (Slanger and}$$
$$\text{Black, 1973)[12]} \tag{7}$$

Assurring that the atornic oxygen distribution is in photochemical equilibrium, the 5577 $\overset{o}{A}$ emission rate is given by

$$j(5577, Z) = A_{32} \left[O(^1S) \right]$$

$$= \frac{A_{32} \, K_1 \, [0]^3}{A_{31} + A_{32} + K_6 \, [0] + K_7 \, [0]} \text{ Photons cm}^{-3}\text{sec}^{-1}, \tag{8}$$

where the sauare orackets represent number density in cm^{-3}. Then the zenith intensity in Rayleighs is given by

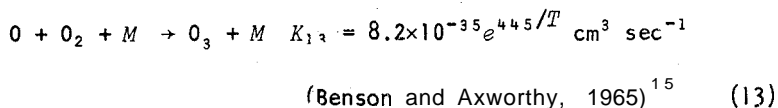$$J(5577) = 1.28 \times 10^{-6} \int_0^\infty \frac{K_1 \, [0]^3}{1.36 + K_6 \, [0] + K_7 \, [O_2]} \tag{9}$$

In the case of the excitation of OH, the hydrogen-ozone mechanism suggested by Bates and Nicolet (1950)[13] is the most probable process,

$$H + O_3 \rightarrow OH^* \, (v \leqslant 9) + O_2 \tag{10}$$

$$OH^* \, (v \leqslant 9) \rightarrow OH \, (v=0) + Ohv \tag{11}$$
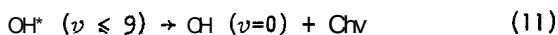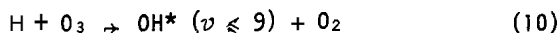
Chemical quenching by atomic oxygen is a main loss process of OH,

$$OH^* + O \rightarrow O_2 + H \quad K_{12} = 4.0\times10^{-11} \text{ cm}^3\text{sec}^{-1} \text{ (Wilson,1972)}[14]$$

(12)
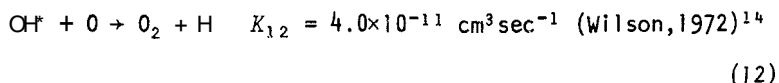
In the processes (10) to (12), hydrogen acts as a catalyst for the destruction of ozone, so that the production of OH^* is related to the density of ozone. The production of ozone depends on the atomic oxygen concentration as follows:

$$O + O_2 + M \rightarrow O_3 + M \quad K_{13} = 8.2\times10^{-35}e^{445/T} \text{ cm}^3 \text{ sec}^{-1}$$

(Benson and Axworthy, 1965)[15]   (13)

where M is a third body (N, or O_2) and T is the atmospheric temperature. If the main loss process of ozone is the reaction (10) around the altitude of 80 km, the ozone density in photochemical equilibrium is given as
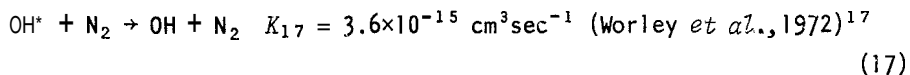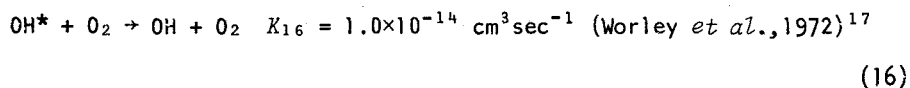
$$\left[O_3\right] = \frac{K_{13} \; \left[O\right] \; \left[O_2\right] \; \left[M\right]}{K_{10}\left[H\right]}$$

(14)

Another possible mechanism to produce the excited OH is a reaction of hydroperoxyl with atomic oxygen (Nicolet, 1970)[16],

$$HO_2 + O \rightarrow OH^* \; (v \leqslant 6) + O_2$$

(15)
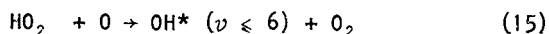
The energy released by the reaction (15) is sufficient to excite the OH only to the vibrational level equal to or less than 6.

Collisional quenching by O_2 and N_2 will be important on the lower side of the emitting layer,

$$OH^* + O_2 \rightarrow OH + O_2 \quad K_{16} = 1.0\times10^{-14} \text{ cm}^3\text{sec}^{-1} \text{ (Worley } et \; al., 1972)[17]$$

(16)

$$OH^* + N_2 \rightarrow OH + N_2 \quad K_{17} = 3.6\times10^{-15} \text{ cm}^3\text{sec}^{-1} \text{ (Worley } et \; al., 1972)[17]$$

(17)

The OH(8,3) band emission rate, then, considering the cascading transition from $v = 9$ to $v < 8$, is

$$j(OH(8,3),Z) = A_{83}[OH(v = 8, Z)]$$

$$= A_{83} \frac{K_{13}[O][O_2][M] \{\beta_8(\tau_Q^{-1} + \tau_9^{-1}) + A_{98}.\beta_9\}}{(\tau_Q^{-1} + \tau_8^{-1})(\tau_Q^{-1} + \tau_8^{-1})} \quad \text{Photons cm}^{-3} \text{ sec}^{-1}$$

$$(18)$$

Where $Av'v''$ represents the Einstein transition probability from the vibrational level v' to v'',

$$A_{83} = 0.0296 \text{ sec}^{-1}$$

$$A_{96} = 2.64 \text{ sec}^{-1}$$

$$\tau_8^{-1} = \sum_{v''=0}^{7} A_{8v''} = 13.5 \text{ sec}^{-1}$$

$$\tau_9^{-1} = \sum_{v''=0}^{8} A_{9v''} = 15.6 \text{ sec}^{-1}$$

β_v represents the rate of new excitation of the level v, $\beta_8 = 0.29$, $\beta_9 = 0.54$

and $\tau_Q^{-1} = K_{12}[O] + K_{16}[O_2] + K_{17}[N_2]$: the quenching factor.

Then the zenith intensity of $OH(8,3)$ is given in Rayleighs by

$$J(OH(8,3)) = 0.0296 \times 10^{-6} \int_0^\infty \frac{K_{13}[O][O_2][M] \{0.29(\tau_Q^{-1}+15.6)+1.43\}}{(13.5+\tau_Q^{-1})(15.6+\tau_Q^{-1})} dZ$$

$$(19)$$

The calculated 5577 $\overset{o}{A}$ and $OH(8,3)$ emission profiles are shown in Fig.3. The appropriate atomic oxigen density profile wastakenfrom Fukuyama's (1974)[18] model for $30°N$. O_2 and N_2 density profiles are from Banks and Kockarts (1973)[19]. The 5577 $\overset{o}{A}$ emission has a peak at around 92 Km, a width of about 10 Km and total zenith intensity of 170 Rayleighs. On the other hand, the $OH(8,3)$ emission has a peak at 84 Km, is about 8 Km thick and the zenith intensity is 570 Rayleighs. The e-
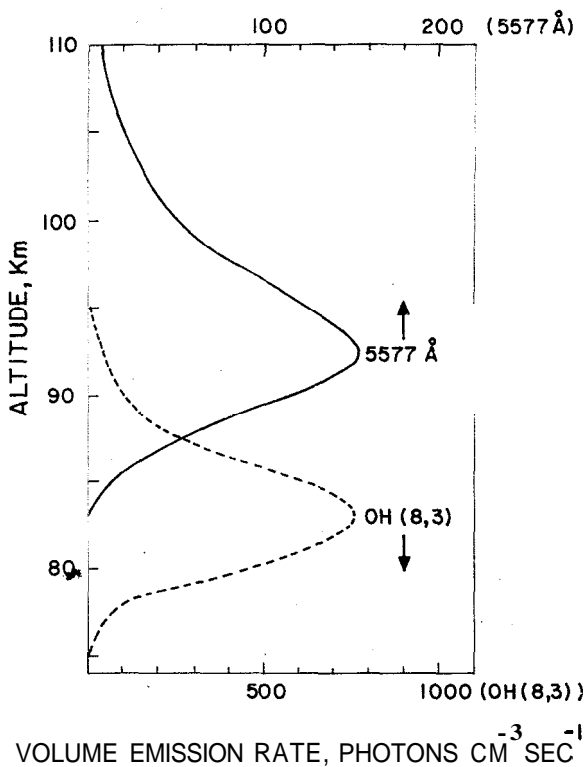
Fig.3 - Calculated profiles of the volume emission rates of 5577 Å and OH
(8,3).

mission peaks of 5577 Å and OH(8,3) correspond to the peaks of the ato-
mic oxygen density and the ozone production rate, respectively, as men-
tioned previously. Both the profiles and intensities of the 5577 Å and
OH(8,3) are consistent with the results of rocket measurements (Rogers
et al.,1973)[20] and ground based observations (Takahashi et al.,1977)[2].

4. DYNAMICAL EFFECTS IN THE EMISSION LAYERS

Only a few studies have been made on the effect of atmosphe-
ric motions on the airglow in the lower thermosphere. The effect   of
the vertical wind on the 5577 Å emission has been studitd by Tohmatsu
and Nagata (1963)[21]. Gadsden and Marovich (1969)[22] have examined the
case of pressure wave propagation. The effect of eddy diffusion onthe
OH emission has been studied by Moreels et al. (1977)[5], who showed that

an increase of the OH intensity, of the right order of magnitude to explain the post-midnight maximum frequently observed in OH, can be obtained by an increase of the eddy diffusion coefficient by a factor of 10.

In this study we have examined the intensity variation of the 5577 Å and OH(8,3) emission when a wavelike density variation propagates through the emission layers. This kind of perturbation can be expected to result from the propagation of gravity waves and tidal oscillations. The fractional perturbation in the density, at height Z and at time t, can be written, when the phase propagates downwards,

$$\delta n(Z,t) = \delta n(Z_0)_{max} \exp(\frac{Z-Z_0}{2H}) \sin\left[2\pi(\frac{t}{T} + \frac{Z}{\lambda})\right] \qquad (20)$$

where T and A represent the period and vertical wavelength of the wave respectively H is the atmospheric scale height. The exponential factor in the right hand side of the expressions represents an increase of amplitude with height. $\delta n(Z_0)$ represents the amplitude of the perturbation at height Z_0. In our calculation we have used a value of 0.04 for this parameter at 80 km, based on calculations for the theoretical solar semi-diurnal tide at our latitude (Batista, 1976)[23].

In Fig.4a., the time dependent intensity variations are shown for the case of $T = 12$ hours and $A = 60$ km, representing the solar semi-diurnal tidal oscillation. The effect of a short wavelength $(A = 20$ Km) and a short period $(T = 6$ hours) such as might be produced by a gravity wave, is shown in Fig. 4b. The interrelationship between vertical wavelength and the amplitude of the airglow variations is shown in Fig. 5. The variations of the integrated emission intensity is small when the wavelength is less than or of the order of the width of the emitting region. As a result of this, the perturbation in OH are greater than those in 5577 Å for very short wavelength, because of the narrower emitting region. For wavelengths greater than 17 Km the 5577 Å variation is greater than the OH. This is mainly a result of the exponential growth of the wave amplitude with height, together with the difference of 10 Km in the height of emission.

For longer wavelengths greater than about 100 Km, the intensity variations reach their maximum of 70% in the case of 5577 Å and
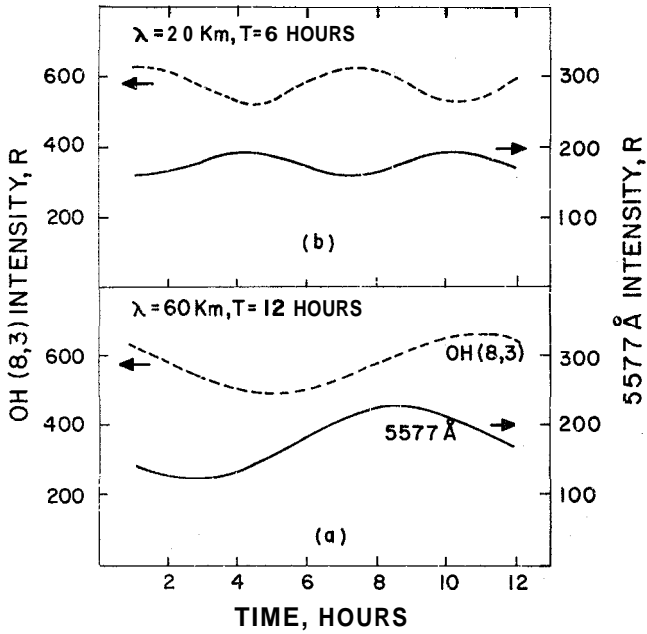
Fig.4 - Intensity variation of 5577 Å and OH(8,3) produced by a downward propagating atmospheric perturbation.
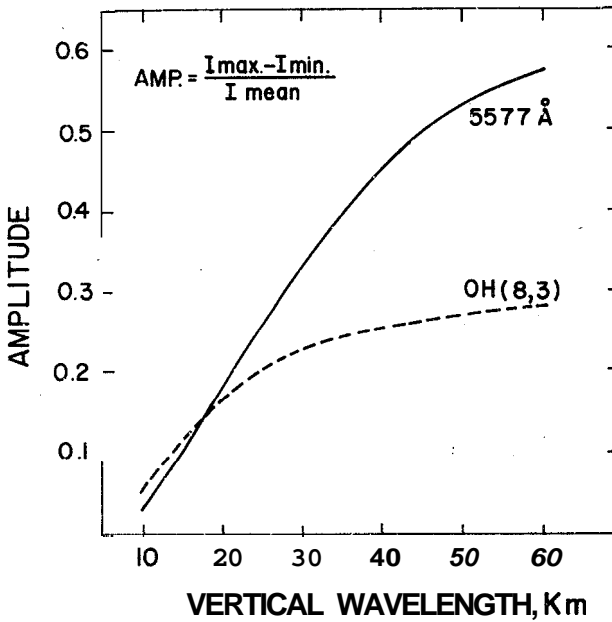

Fig.5 - Amplitude (peak to peak) of the variation of 5577 Å and OH(8,3) with different vertical wavelengths (h).

30% for the OH$(8,3)$ (assuming an 8% peak to peak variation in atmospheric density at 80 Km). These relative amplitudes are in agreement with the observed variation. When well correlated variations of short period and thus presumably of short vertical wavelength, are observed, the amplitude of the OH oscillation is equal to or greater than that of the 5577 Å. An example of this may be found in Fig. 1, for July 25, 1976. This again is in agreement with the results of the model calculations.

It would appear, then, that a major part of the nocturnal variations observed in the 5577 Å and OH emissions can be explained on the basis the downwards phase propagation of atmospheric density perturbations. The longer period (more than 6 hours) fluctuations appear to correspond tc solar tidal osciliations, and the shorter periods to internal gravity waves.

5. CONCLUSIONS

On the basis of 18 nights of observations we find that:

1. The correlation coefficient between OH$(8,3)$ and 5577 Å for zero time shift is − 0.14. A maximum positive correlation of 0.29 is observedfor the 5577 Å intensity taken 2.5 hours before the OH.

2. A maximum correlation of 0.60 is obtained between ROT and OH $(8,3)$, with ROT leading OH by 1 hour.

3. A maximum correlation of 0.50 is found between ROT and 5577 Å for zero time shift. On some occasions simultaneous sudden increases in the two parameters have been observed.

4. The time lag between the 5577 Å and OH intensity variations can be explairied by the downward propagation of a wavelike·perturbation in the atmospheric density. The relative amplitudes of the long period variations are in agreement with the perturbation being caused by the solar semi-diurnal tide. The downward phase propagationobserved in the shorter period oscillations is consistent with their being caused by internal gravity waves produced in the lower atmosphere.

In aur model calculaticn we have assumrd that photochemical equilibrium would be maintained in the presence of atmospheric density perturbations. This assumptions should be examined more closely, when the disturbances are large and rapid compared to the time constants of the chemical reaction processes.

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