A Simultaneous Observation of the Height Profiles of the Night Airglow OI 5577 Å, O₂ Herzberg and Atmospheric Bands

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(Received October 6, 1986)

Height distributions of the OI 5577 Å, O₂ Herzberg and Atmospheric bands in the night airglow were simultaneously measured with photometers on board a rocket flown from Uchinoura (31°N). The volume emission rates attained its maximum at a height of 96 km for the 5577 Å, at 97 km for the Herzberg bands and at 94 km for the Atmospheric band, being in agreement with previous observations. The ratio of the volume emission rates of the Herzberg bands to the 5577 Å exhibited a constant value with height, and that of the Atmospheric band to the 5577 Å varied with height in proportion to the atmospheric density. Some implications to the excitation mechanism are presented and discussed according to this result along with the recent data on reaction rate coefficients from laboratory experiments.

1. Introduction

Rocket observations of night airglow emissions have been attempted to investigate their height distributions and thereby to infer excitation processes of the emissions. Night airglows such as OI 5577 Å (¹S→¹D), O₂ Herzberg bands ($A^3\Sigma_u^+ \rightarrow X^3\Sigma_g^-$), O₂ Atmospheric bands ($b^1\Sigma_g^+ \rightarrow X^3\Sigma_g^-$), O₂ Infrared Atmospheric bands ($a^1\Delta_g \rightarrow X^3\Sigma_g^-$) and OH Meinel vibration-rotation bands have been extensively observed so far. These emissions are so faint that use of a filter photometer instead of a spectrometer is preferable to get frequent sampling rates with respect to height. However, there are some difficulties in measuring these airglow emissions by using a photometer aboard a rocket. We have to discriminate the relevant airglow emission from contaminations by the airglow continuum, the star background and artificial emissions due to aerodynamic effects of a rocket flight. A change in rocket attitude during a flight also is a serious problem since it may cause an apparent change in the emission intensity according to a change in the look angle of a photometer.

It is doubtful that earlier observations paid attention to these error factors and made adequate corrections to them. Many of the height profiles of night airglows published so far seem to include serious errors. Despite these drawbacks, rocket observations have provided us with useful information on physically reasonable

features of the height distributions, so that we may construct an average feature each of them.

It is true that oxygen airglows such as OI 5577 Å and O₂ Herzberg and Atmospheric bands are excited through recombination of atomic oxygen, but there is a debate on the point that the excitation occurs directly through 3-body recombination or it needs a 2-step excitation process; see e.g., BATES (1981), R. J. THOMAS (1981), LLEWELLYN *et al.* (1979), and GREER *et al.* (1981). A measurement of atomic oxygen density on board the same rocket for the airglow measurement may provide us with a solution. L. THOMAS *et al.* (1979), R. J. THOMAS and YOUNG (1981) and WITT *et al.* (1984) made simultaneous measurements of atomic oxygen and airglow, and proposed a preference to the 2-step excitation process. They employed an OI 1304 Å lamp for resonance fluorescence/absorption, one of the most promising techniques to measure atomic oxygen in the lower thermosphere on board a rocket. This technique still has difficulties with respect to uncertainties in the shape of the emission line of the lamp and the Doppler shift due to a rocket motion. Since these factors seriously affect the estimation of atomic oxygen density, accuracy of the reported density values of atomic oxygen should be carefully examined. The proposal for the 2-step excitation process does not seem to be conclusive yet.

In our present study we have made a rocket observation of the night airglow OI 5577 Å, O₂ Herzberg bands and O₂ Atmospheric band with high precision. An analysis has been made on this simultaneous data set to infer some information about the excitation processes.

2. Instrumentation

2.1 5577 Å photometer

It is essentially important to discriminate the 5577 Å emission from the background continuum in a photometric measurement of the airglow 5577 Å emission. This is commonly made possible with 2-color photometry. In order to double the sampling rate, our present 5577 Å photometer is of a dual structure having two photomultipliers Hamamatsu R1104 of multi-alkali photo-cathode and four interference filters. Two of these filters are for 5577 Å and other two are for the background continuum at 5030 Å and 5310 Å. These filters are mounted on a rotating disc, and two of them (for 5577 Å and the background) are alternatively put in each optical path to the photomultipliers for a time duration of 0.7 s. The FWHM (full width at the half maximum) bandwidths are 20 Å for the 5577 Å filter, 35 Å for the 5030 Å and 37 Å for the 5310 Å.

The field of view (FOV) of the photometer is 2.5° circular in full angle. A light source for calibration and a shutter are inserted in the optical path every three rotations of the filter disc. The photometer was calibrated with the aid of a standard lamp whose brightness was known in terms of star brightness, and it was also compared with the airglow photometer at Kiso Observatory of Tokyo Astronomical Observatory (TAO).

2.2 Herzberg band photometer

This photometer comprises of an interference filter and a Hamamatsu R166 photomultiplier of cesium telluride photo-cathode. The central wavelength of the filter pass-band is 2760 Å and the FWHM bandwidth is 160 Å; therefore, this photometer mainly senses the (6,2) and (7,2) bands of the O₂ Herzberg I system. The FOV is 6.4° circular in full angle.

The photometer does not have any device to discriminate the band emission from the background continuum, and it continuously measures the emission at a single pass-band. The background continuum of the airglow is believed to be negligibly small in the wavelengths 2500–3000 Å because the NO₂ airglow does not extend to the wavelengths below 3980 Å, the dissociation limit of NO₂. In the 2500–3000 Å region, there is no intense emission band other than the Herzberg I. The 2972 Å airglow of O(¹S→³P) may be a possible source of contamination. The 2972 Å airglow intensity may have been 10 Rayleighs (1 Rayleigh=1R=10⁶ photons s⁻¹ per cm²-column) at the time of our present observation according to an evaluation from the measured intensity of the 5577 Å airglow. On the other hand, the intensity of the Herzberg (7,2) or (6,2) band which is located at around the center of the filter pass-band has been evaluated to be about 80 R (DEGEN, 1977). Considering that the photometer sensitivity at 2972 Å decreases to 17/1000 of the maximum sensitivity at 2760 Å, the OI 2972 Å airglow makes a negligible contamination to our present photometer.

The continuum emission in the star background can be subtracted by using the data obtained above the emission layer of the airglow. The apparent emission intensity of the star background was roughly 1/4 of that of the Herzberg airglow at 2760 Å.

The photometer was absolutely calibrated with a deuterium lamp Optronic UV-40 whose irradiance was measured with the NBS 1973 irradiance scale and supplied by the manufacturer.

2.3 Atmospheric band photometer

The (0,0) band of the Atmospheric system of O₂ at 7619 Å is one of the most intense features in the near infrared airglow at night, and its intensity is as large as 6 kilo-Rayleighs (kR) (WITT *et al.*, 1979). On the other hand, the intensity of the continuum airglow is about 1 R Å⁻¹ in the spectral region around 7500 Å (NOXON, 1978). Consequently, a single-color photometry can discriminate the (0,0) 7619 Å band airglow from the continuum with a good accuracy.

This 7619 Å photometer consists of a photomultiplier Hamamatsu R636 of gallium arsenide photo-cathode and an interference filter of a FWHM bandwidth of 150 Å. The FOV is 3° circular in full angle. A shutter operates every 90 s to measure the dark current of the photomultiplier. The sensitivity change of the photometer during the flight is monitored by inserting a fluorescent plate in the optical path every 60 s.

The photometer was calibrated with a standard light source in the laboratory of the University of Tsukuba before the flight. Its sensitivity was too low to measure the

star background, so that the photometer output only showed the dark current when it was aloft above the emission layer of the airglow.

3. Observation

The photometers were flown on board the sounding rocket S310.10 from Uchinoura (31°15'N, 131°05'E) at 1200 UT (2100 LMT) on August 24, 1981. A solar flare of Importance 2 occurred on August 21, and it was magnetically disturbed on August 24 because of the recovery phase of a magnetic storm. The solar 10.7 cm radio flux was 259 in units of $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$ and the daily sum of the geomagnetic activity index Kp was 31.

The photometers began the measurement at a height of 63 km when the nose cone of the rocket was open, and continued the measurement during the ascent up to a height of 186 km and during the descent. The rocket was spin-stabilized and its attitude was determined within an error of about 1° by using a star sensor and a 2-component magnetic sensor aboard the rocket. The spin axis of the rocket changed slowly with a coning motion of 14° in half angle and of a period of 195 s. When the rocket was at a height of 95 km, the direction of its spin axis was (31°, 136°) and (8°, 117°) in the ascent and the descent, respectively represented as (zenith angle, azimuth). All the photometers were installed in such a way that their line of sight was 30° away from the spin axis of the rocket; therefore, the look direction of the photometer swept the sky at a rate of 0.975 Hz, but its zenith angle was less than 61° throughout the observation.

Sky-scanning of the photometers enabled us to examine a possibility of any contaminating emissions which might arise from aerodynamic effect around a rocket. Any contamination exceeding the noise level was not found during the ascent and the most part of the descent. However, in the heights 90–110 km during the descent, a strong emission feature was observed at a direction of the rocket wake with a width of 2°–4°. This was detected by all photometers at wavelengths of 2760 Å, 5030 Å, 5310 Å, 5577 Å and 7619 Å. The 7150 Å and 7330 Å photometers, which were also aboard the same rocket to measure the continuum and OH (8,3) band respectively, detected the emission. Its apparent emission rate was $16 \text{ R } \text{Å}^{-1}$, $3.2 \text{ R } \text{Å}^{-1}$, $2.0 \text{ R } \text{Å}^{-1}$, $19 \text{ R } \text{Å}^{-1}$, $30 \text{ R } \text{Å}^{-1}$, $48 \text{ R } \text{Å}^{-1}$ and $62 \text{ R } \text{Å}^{-1}$ at 2760 Å, 5030 Å, 5310 Å, 5577 Å, 7150 Å, 7330 Å and 7619 Å, respectively when it was brightest at a height of about 102 km. The spectral feature of this particular emission looks like something different from a continuum, because it is much weaker at 5030 Å and 5310 Å than at other wavelengths. It probably came from the atmosphere heated by shock waves in the region of the wake of the rocket, and we speculate the emitting species to be O₂ Herzberg (6,2) and (7,2) bands and N₂ Vegard-Kaplan (0,6) band at 2760 Å, OI 5577 Å at 5577 Å, N₂ First Positive (7,5) band at 7150 Å, N₂ First Positive (5,3) band, OII 7319–30 Å and OH Meinel (8,3) band at 7330 Å and O₂ Atmospheric (0,0) band at 7619 Å.

4. Result

Figure 1 represents the height variation of the 5577 Å emission in terms of vertical column intensity. The 5577 Å emission rate was deduced by subtracting the continuum component from the 5577 Å photometer output. This subtraction was made with the output signals averaged for 0.7 s every exchange of filters. Accordingly, in calculating vertical column intensity, an average value was also used for secant of the zenith angle of the photometer's FOV. The data in the heights below 80 km in the ascent and below 90 km in the descent may include some errors in determining zenith angle since the rocket attitude at these heights was significantly different from its regular coning motion seen above about 100 km.

The solid curves of Fig. 1 are best-fit smooth curves. Those for the ascent and the descent are identical within fitting error. The total column intensity is about 180 R both in the ascent and the descent. On the other hand, the ground-based observation simultaneously made at TAO Kiso Observatory (35°48'N, 137°38'E; about 800 km away from Uchinoura) obtained an intensity of 200 ± 5 R. This difference of 20 R probably originates from an experimental error and/or spatial variability of the

Fig. 1. OI 5577 Å emission rates as in a vertical column observed in the ascent and the descent of S310.10 rocket.

airglow. However, it is noteworthy that a small residual emission of the 5577 Å is found above 110 km in Fig. 1, and that its intensity is much smaller than the normal one originating from the ionospheric *F* region. This may imply that our present reduction of the rocket data includes a negative bias as much as -20 R.

Figure 2 represents the height profiles of vertical column intensity of the Herzberg bands. The data values are sampled at an integration time of 50 ms and converted to vertical column intensity with a subtraction of the star background. They are represented in terms of the total intensity of the Herzberg I system, by using a model distribution of the band emission rates after DEGEN (1977).

Scatter of the data in Fig. 2 is mainly due to shot noises of the photomultiplier. The total intensity is found to be 430 ± 60 R in the ascent and 500 ± 60 R in the descent. These values are smaller than an intensity of 600–700 R measured by rocket observations so far (STECHE, 1965; HENNES, 1966; LLEWELLYN *et al.*, 1979; R. J. THOMAS and YOUNG, 1981). However, they agree with an intensity of 490 R obtained in the rocket observation by L. THOMAS *et al.* (1979), and are within a range of variability of 300–600 R observed on board a satellite (REED and CHANDRA, 1975). These different values are thought to be consequences of natural variability; however, another interpretation cannot be ruled out. Different observations sensed different bands of the Herzberg I system; therefore, if the model intensity distribution among

Fig. 2. The same as Fig. 1 but for the O_2 Herzberg bands.

different bands was wrong, then different values would be evaluated with respect to the total intensity of the Herzberg I system.

It should be noted that the star background has been subtracted in the emission intensities given in Fig. 2. The star background at $2760 \text{ \AA}$ was measured to be $0.36 \text{ R \AA}^{-1}$ toward Milky Way and $0.12 \text{ R \AA}^{-1}$ away from it.

Figure 3 shows vertical column intensity of the Atmospheric (0,0) $7619 \text{ \AA}$ band. The data were sampled at an interval of 100 ms and corrected to obtain the vertical column intensity by knowing the zenith angle of the look direction of the photometer. Dispersive data points are found in the heights below 77 km in the ascent and below 90 km in the descent. This may be mainly due to the error in determining the direction of the spin axis of the rocket.

The total column intensity of the (0,0) $7619 \text{ \AA}$ band is found to be 6.1 kR in the ascent measurement and 7.2 kR in the descent. These values are in agreement with 6.3 kR measured by WITT *et al.* (1979). The Herzberg band emission also exhibits a similar difference: a 16% excess in the descent. Considering that the observing location in the descent was about 150 km southeast from that in the ascent, it is highly

Fig. 3. The same as Fig. 1 but for the O_2 Atmospheric (0,0) band.

probable that the larger intensity in the descent is a consequence of an inhomogeneity of the airglow layer. However, it is hard to rule out a possibility of contamination to the photometers for the Herzberg and Atmospheric bands at the heights 85–95 km during the descent.

Differentiation of the vertical column intensity profiles gives the volume emission rates. In the case of the Atmospheric band, differentiation was made point by point with 3-points differentiation method, and a smoothed curve was fit to the difference values. The fitting error is $\sim \pm 150\%$, $\pm 16\%$, $\pm 12\%$ and $\pm 34\%$ at heights 85 km, 90 km, 95 km and 100 km, respectively. Direct differentiation of the 5577 Å and Herzberg bands profiles has a difficulty, so that smoothed curves were fit to the intensity profiles and differentiation was made with these curves. Errors in evaluating the volume emission rates were estimated in terms of fitting errors: $\sim \pm 140\%$, $\pm 50\%$, $\pm 14\%$, $\pm 11\%$ and $\pm 16\%$ at heights 85 km, 90 km, 95 km, 100 km and 105 km, respectively for the 5577 Å in the ascent; $\pm 22\%$, $\pm 6\%$, $\pm 7\%$ and $\pm 16\%$ at heights 90 km, 95 km, 100 km and 105 km, respectively for the 5577 Å in the descent; and $\pm 20\%$, $\pm 11\%$, $\pm 14\%$ and $\pm 55\%$ at heights 90 km, 95 km, 100 km and 105 km, respectively for the Herzberg bands both in the ascent and descent.

The volume emission rates are presented in Fig. 4. The peak of the volume emission rate comes to a height of 96 km for the 5577 Å, 97 km for the Herzberg bands and 94 km for the Atmospheric band. These values agree with the average feature of previous observations. See OFFERMANN and DRESCHER (1973) and references

Fig. 4. Height distributions of the volume emission rates of OI 5577 Å, O₂ Atmospheric and Herzberg bands obtained in this observation.

therein for the 5577 Å; L. THOMAS *et al.* (1979), LLEWELLYN *et al.* (1979), R. J. THOMAS and YOUNG (1981) and references therein for the Herzberg bands; WITT *et al.* (1979), WATANABE *et al.* (1981) and references therein for the Atmospheric band.

It is evident in Fig. 4 that the Herzberg and Atmospheric bands exhibit larger emission rates in the bottomside of the emission layer in the descent than in the ascent. This is the reason why the column intensity was more intense in the descent than in the ascent, and suggests a variation of the atomic oxygen density in a horizontal scale of 150 km at around the height 90 km. On the other hand, the 5577 Å profiles in Fig. 4 do not show this difference. Experimental error in the 5577 Å measurement was relatively large at heights around 90 km, and the scatter of the measured values probably made this difference obscure.

5. Discussion

5.1 Emission rate ratio

Figure 5 represents the ratios of volume emission rates of the Herzberg and Atmospheric bands to the 5577 Å. It is remarkable that the ratio of the Herzberg bands to the 5577 Å is approximately constant with height at a value of about 2.6, and that the ratio of the Atmospheric band to the 5577 Å varies with height in proportion to the atmospheric density. Uncertainties of these ratios are evaluated to be $\pm 60\%$, $\pm 20\%$, $\pm 20\%$ and $\pm 70\%$ at heights 90 km, 95 km, 100 km and 105 km, respectively for the ratios of the Herzberg bands to the 5577 Å, and $\pm 300\%$, $\pm 50\%$, $\pm 20\%$ and $\pm 40\%$ at heights 85 km, 90 km, 95 km and 100 km, respectively for the ratio of the Atmospheric band to the 5577 Å. These features confirm the historical data indicating

Fig. 5. Ratios of the volume emission rates calculated from Fig. 4: Herzberg bands vs. 5577 Å and Atmospheric band vs. 5577 Å. The solid curve is proportional to the atmospheric density.

that the emission layers of the Herzberg bands and the 5577 Å are located at the same height, and that the Atmospheric band extends to lower heights than the other two.

PACKER (1961) first measured the height profiles of these three emissions of the night airglow. Height resolution was coarse in that measurement, but the height of the Herzberg band emission agreed roughly with that of the 5577 Å, and that of the Atmospheric band extended to lower heights than the above two. Later, LLEWELLYN *et al.* (1979) and WITT *et al.* (1979) also measured the profiles of these three emissions simultaneously, but they analyzed the Herzberg bands separately from other emissions. Simultaneous measurements of the airglow profiles are available for the Herzberg bands and the 5577 Å from the observations by L. THOMAS *et al.* (1979) and R. J. THOMAS and YOUNG (1981), who also measured atomic oxygen density simultaneously. WITT *et al.* (1984) obtained two simultaneous profiles of the Atmospheric band and the 5577 Å.

The ratios of emission rates from these data sets are plotted in Figs. 6 and 7. A good agreement is found in those of the Atmospheric band to the 5577 Å with respect to the height variation and the ratio values themselves. In particular, different data sets for the emission ratios of the Atmospheric band to the 5577 Å lead to the same result at different latitudes of 31°N (Uchinoura), 57°N (South Uist) and 68°N (Kiruna). We are confident that this feature is inherent in the excitation process of the airglow.

In the case of the emission ratios of the Herzberg bands to the 5577 Å, they apparently differ from observation to observation, but if we look at the data points only in the heights 96 ± 5 km where the data are of highest reliability, each observation seems to exhibit a constant ratio with respect to height. The ratio values are different with different observations: ~ 7 for L. THOMAS *et al.* (1979), ~ 4 for LLEWELLYN *et al.* (1979) plus WITT *et al.* (1979), ~ 6 for R. J. THOMAS and YOUNG (1981) and ~ 2.6 for our present observation. The calibration error in absolute sensitivity of photometers may be a source of this difference; however, the calibration of the 5577 Å photometers is accurate enough judging from the agreement of the emission ratios of the Atmospheric band to the 5577 Å in different observations. The 5577 Å emission rates at the height of their peak emissions varied with different observations by a factor of 2 probably due to natural variability. The Herzberg band photometer is less accurate in calibration than the 5577 Å photometer because of a technical difficulty in the ultraviolet region, but the calibration error normally should not exceed the range of the above difference of a factor of 3.

The most probable source of the above difference is the conversion factor from the measured emission intensity to that of the total Herzberg I system. Different observations sensed different bands of the Herzberg system. L. THOMAS *et al.* (1979) measured the (3,4), (4,4) and (5,4) bands at the wavelength region of about 3200 Å, LLEWELLYN *et al.* (1979) for the (2,6) and (4,7) bands at 3640 ± 45 Å, R. J. THOMAS and YOUNG (1981) for the (4,4), (5,4), (6,4), (3,3), (4,3) and (5,3) bands at 3060 ± 180 Å, and our present observation mainly for the (6,2) and (7,2) bands at 2760 ± 80 Å. The conversion of the emission intensity of the total Herzberg system was made by using the band intensity distribution from the DEGEN model (1977). The different

Fig. 6. Ratios of the volume emission rates, Herzberg bands vs. 5577 Å taken from other researches. Solid circles from LLEWELLYN *et al.* (1979) combined with WITT *et al.* (1979), open circles from L. THOMAS *et al.* (1979) and open triangles and squares from R. J. THOMAS and YOUNG (1981).

Fig. 7. Ratios of the volume emission rates, Atmospheric band vs. 5577 Å taken from WITT *et al.* (1979, 1984). The solid curve is proportional to the atmospheric density.

observations sensed the emission bands from different vibration levels in the upper electronic state $O_2(A^3\Sigma_u^+)$. Consequently the above difference in the emission ratios may be an artifact that the relative population in the vibrational levels of $O_2(A^3\Sigma_u^+)$ has been incorrectly determined in the model. Yet, we cannot rule out a possibility that the vibrational population of $O_2(A^3\Sigma_u^+)$ differs from observation to observation according to a change in the atmospheric condition.

5.2 Inference on excitation processes

The above relations between emission rates seem to originate from the characteristics of excitation processes, and therefore may provide us a constraint in discussing possible excitation processes of oxygen airglows involved in recombination of atomic oxygen.

BATES (1981) wrote a review paper on the history and recent development of the 5577 Å excitation theory. He favors the 2-step excitation of $O(^1S)$ in the recombination of atomic oxygen according to the evidences both from rocket observations and chemical kinetics. The set of relevant reactions is represented as follows:

where M is N_2 and/or O_2 , k_i is the rate coefficient of i -th reaction in units of $\text{cm}^3 \text{s}^{-1}$ and $\text{cm}^6 \text{s}^{-1}$ for 2-body and 3-body reactions, respectively and A_i is the spontaneous transition probability of i -th process. O_2^* is the precursor leading to $O(^1S)$ and is an electronically excited state of O_2 . According to BATES (1981), a vibrationally excited level of $c^1\Sigma_u^-$ is the most promising candidate for O_2^* . However, identification of O_2^* is beyond the scope of this paper.

L. THOMAS *et al.* (1979) and R. J. THOMAS (1981) have obtained evidences for the 2-step excitation of $O(^1S)$ from rocket measurements of both the 5577 Å airglow and atomic oxygen density. R. J. THOMAS (1981) has inferred that the collisional quenchings of $O(^1S)$ due to reactions (7) and (8) are small and that reaction (4) is most important in quenching O_2^* . A small quenching of $O(^1S)$ is supported by recent results from laboratory experiments (see Appendix), so that we may neglect reactions (7) and (8) in our present discussion. Neglecting reactions (2) and (3) as compared with reaction (4), and reactions (7) and (8) as compared with reaction (6), the 5577 Å emission rate is approximately represented by

$$I(5577 \text{ Å}) = k_1[O]^2[M] \frac{k_2[O]}{A_5 + k_4[M]} \quad (9)$$

where [] denote the number density of species shown in the bracket. By using the value of $k_4/A_5 = 7 \times 10^{-14} \text{ cm}^3$ obtained by R. J. THOMAS (1981), a rough approximation is possible:

$$I(5577 \text{ \AA}) \approx \frac{k_1 k_2}{k_4} [\text{O}]^3. \quad (10)$$

In analyzing the data from rocket measurements of both the Herzberg airglow and atomic oxygen density, L. THOMAS *et al.* (1979) and R. J. THOMAS (1981) adopted the direct excitation of $\text{O}_2(\text{A}^3\Sigma_u^+)$ in the 3-body recombination of atomic oxygen, i.e.,

Their rocket data are consistent with reactions (11) and (12), but $\text{O}_2(\text{A}^3\Sigma_u^+)$ should be quenched significantly by M,

Actually, R. J. THOMAS (1981) derived $k_{13}/A_{12} = 1.1 \times 10^{-12} \text{ cm}^3$ for O_2 or $2.75 \times 10^{-13} \text{ cm}^3$ for N_2 from his data set, and $k_{13}/A_{12} = 3.05 \times 10^{-13} \text{ cm}^3$ for N_2 from the data set of L. THOMAS *et al.* (1979).

If the above analysis is correct, the emission rate of the Herzberg I airglow is represented as

$$I(\text{Herzberg}) = \frac{k_{11}[\text{O}]^2[\text{M}]}{1 + k_{13}[\text{M}]/A_{12}} \quad (14)$$

which can be further approximated by

$$I(\text{Herzberg}) \approx \frac{k_{11}A_{12}}{k_{13}} [\text{O}]^2. \quad (15)$$

Consequently, we have an approximate relation

$$\frac{I(\text{Herzberg})}{I(5577 \text{ \AA})} \approx \frac{k_4 k_{11} A_{12}}{k_1 k_2 k_{13}} \cdot \frac{1}{[\text{O}]}. \quad (16)$$

The rate coefficients k_1, k_2, k_4, k_{11} and k_{13} do not vary significantly with height even if considering their temperature dependency, because the height variation of atmospheric temperature is believed to be small in the height region 90–100 km. Relation (16) indicates that the emission rate ratio varies with height as $[\text{O}]^{-1}$, and it is a

consequence of the analysis by R. J. THOMAS (1981). This relation is also consistent to the constant ratio of the Herzberg band to the 5577 Å emissions obtained by us and L. THOMAS *et al.* (1979) if [O] does not vary significantly with height in the height region 90–100 km. Rocket observations of atomic oxygen seem to imply that [O] is roughly constant in the heights 90–100 km as represented in the review by OFFERMANN *et al.* (1981).

However, the above discussion is not conclusive, if considering the values of the quenching rate of $A^3\Sigma_u^+$ obtained by laboratory kinetics experiment as shown in Appendix. The value of k_{13} obtained by R. J. THOMAS (1981) is much larger than those laboratory values, since the Herzberg band measured by L. THOMAS *et al.* (1979) and R. J. THOMAS (1981) were those originating mainly from $v'=3, 4$ and 5. On the other hand, according to the results of laboratory experiments, atomic oxygen seems most effective in quenching $A^3\Sigma_u^+$, $v' \leq 5$; however it cannot fit the height variation of the quenching factor of the Herzberg band measured by R. J. THOMAS (1981).

The above problem may be resolved if we adopt a 2-step excitation process of $O_2(A^3\Sigma_u^+)$ as suggested by LLEWELLYN *et al.* (1979). The quenching factor of $O_2(A^3\Sigma_u^+)$ calculated from the data shown in Appendix does not change significantly with height, so that the large quenching factor derived by R. J. THOMAS (1981) may be interpreted as that for the precursor of $O_2(A^3\Sigma_u^+)$ in a 2-step excitation process. In order to fit a relation of nearly constant ratio of the Herzberg band to the 5577 Å emission, the precursor of the $O_2(A^3\Sigma_u^+)$, O_2^* which is excited in the recombination of atomic oxygen, should be transferred to $O_2(A^3\Sigma_u^+)$ by O collisions, and the quenching of O_2^* should occur mainly due to M:

and the emission rate of the Herzberg band is represented as

$$I(\text{Herzberg}) \propto k_{17}[O]^2[M] \cdot \frac{k_{18}[O]}{k_{19}[M]} \propto [O]^3. \quad (20)$$

It seems curious in this 2-step process that the energy transfer from O_2^* to $O_2(A^3\Sigma_u^+)$ occurs through collisions only with O but not with M. However, we cannot rule out this possibility.

In the case of the Atmospheric band, a direct excitation in the 3-body recombination of atomic oxygen may interpret our rocket result.

The emission rate of the Atmospheric band is given by

$$I(\text{Atmospheric}) = k_{21}[\text{O}]^2[\text{M}] \frac{A_{22}}{A_{22} + k_{23}[\text{M}] + k_{24}[\text{O}]} \quad (25)$$

Since the quenching factor of $\text{O}_2(\text{b}^1\Sigma_g^+)$ due to (23) and (24) is not large and does not vary significantly with height in the height region 90–100 km (see Appendix), the height variation of $I(\text{Atmospheric})$ may be approximately represented as

$$I(\text{Atmospheric}) \propto [\text{O}]^2[\text{M}]. \quad (26)$$

As a result, we have

$$\frac{I(\text{Atmospheric})}{I(5577 \text{ \AA})} \propto \frac{[\text{M}]}{[\text{O}]} \quad (27)$$

This relation is consistent to our rocket result, allowing the height variation of $[\text{O}]$ to be negligible in the height region 90–100 km.

On the other hand, WITT *et al.* (1979) have suggested that the reaction of vibrationally excited hydroxyl molecules with atomic oxygen is important in the excitation of $\text{O}_2(\text{b}^1\Sigma_g^+)$, and GREER *et al.* (1981) have suggested a 2-step excitation process in the atomic oxygen recombination. WITT *et al.* (1984) have assumed a 2-step excitation of $\text{O}_2(\text{b}^1\Sigma_g^+)$ in their analysis of the emission rate of the Atmospheric band and the simultaneously measured atomic oxygen density. According to their analysis, the quenching of the precursor of $\text{O}_2(\text{b}^1\Sigma_g^+)$ occurs mainly due to O_2 in the height below 100 km. This result is consistent to the laboratory kinetics experiment by OGRYZLO *et al.* (1984) who also favor a 2-step excitation of $\text{O}_2(\text{b}^1\Sigma_g^+)$. However, the quenching of the precursor of $\text{O}_2(\text{b}^1\Sigma_g^+)$ by O_2 will make the emission rate of the atmospheric band identical to (26). It should be noted again that the simultaneous data set of the Atmospheric band and the 5577 Å obtained by WITT *et al.* (1979, 1984) shows the same relation of emission rates as ours (Fig. 7).

Our present rocket result does not seem to need a 2-step excitation process nor vibrationally excited hydroxyl in the $\text{O}_2(\text{b}^1\Sigma_g^+)$ excitation; however, it is also consistent to a 2-step excitation, if the quenching of the precursor of $\text{O}_2(\text{b}^1\Sigma_g^+)$ occurs mainly due to O_2 or M. Consequently, it may be hard to discriminate between a direct excitation and a 2-step excitation from a simultaneous data set of the airglow and atomic oxygen measured on board a rocket, unless these measurements are very accurate.

6. Concluding Remark

The height profiles of OI 5577 Å, O₂ Herzberg bands and O₂ Atmospheric band were measured simultaneously on board a rocket at 31°N latitude. Though this measurement was not accompanied by a measurement of atomic oxygen, the data provided us with useful information for discussing the excitation processes.

A 2-step excitation process is favorable to the 5577 Å, but the emission rate must be approximately proportional to [O]³, which is identical to a consequence of a direct excitation through $O + O + O \rightarrow O_2 + O(^1S)$.

In the case of the Herzberg bands, a direct excitation process needs a large quenching factor of O₂(A³Σ_u⁺) by M. This has a difficulty in the fact that a large quenching of O₂(A³Σ_u⁺) does not agree with recent laboratory kinetics experiments. A 2-step excitation of O₂(A³Σ_u⁺) is still another candidate to be examined in detail.

A direct excitation of O₂(b¹Σ_g⁺) may be applicable to the Atmospheric band; however a 2-step excitation in which the quenching of the precursor of O₂(b¹Σ_g⁺) occurs mainly due to M is also plausible.

Accurate observations of the emission profiles along with atomic oxygen profiles simultaneously are highly necessary to make the excitation processes further clear. Laboratory kinetics study should be encouraged to obtain the useful and accurate data on the excitation and quenching processes involved in the recombination of atomic oxygen.

APPENDIX

We can evaluate the quenching effects on O(¹S), O₂(A³Σ_u⁺) and O₂(b¹Σ_g⁺) based on laboratory data of the rate coefficients (Table 1) along with spontaneous transition probabilities of the excited states; i.e., $A_6 = 1.1 \text{ s}^{-1}$ for O(¹S) (KERNAHAN and PANG, 1975), $A_{12} = 6 \text{ s}^{-1}$ for O₂(A³Σ_u⁺) $v' = 3, 4, 5, 6$ or 7 (DEGEN, 1977) and $A_{22} = 0.085 \text{ s}^{-1}$ for O₂(b¹Σ_g⁺) $v' = 0$ (BURCH and GRYVNAK, 1969).

The quenching of O(¹S) by O has been found to be much smaller than previous values, which are now ascribed to those by O₂(a¹Δ_g). Therefore, the quenching of O(¹S) by O as well as N₂ and O₂(a¹Δ_g) are negligible in the lower thermosphere (SLANGER and BLACK, 1981). O₂ may play a role in quenching O(¹S), but its effect is small, leading to an emission efficiency of 0.63 at a height of 90 km and 0.81 at 95 km.

The quenching of O₂(A³Σ_u⁺) is affected mainly by O and O₂ while the effect of N₂ is negligible in the lower thermosphere. The O₂(A³Σ_u⁺) emission efficiency is evaluated to be about 0.4–0.5 in the heights 90–100 km, if the atomic oxygen distribution is such that it gives [O] = $4 \times 10^{11} \text{ cm}^{-3}$ at 95 km. The rate coefficient may be larger for higher vibrational levels of O₂(A³Σ_u⁺) (SLANGER *et al.*, 1984).

O₂(b¹Σ_g⁺) is quenched mainly by N₂ and O; yet, the emission efficiency is 0.61, 0.51 and 0.38 at heights of 100 km, 95 km and 90 km, respectively. Its quenching by O₂ is negligible in the lower thermosphere.

Table 1. Typical values of the rate coefficients of $O(^1S)$, $O_2(A^3\Sigma_u^+)$ and $O_2(b^1\Sigma_g^+)$ quenching reactions reported in recent publications. The values are those at temperature 300 K unless temperature dependency is given.

Species	Quenching agents	Rate coefficients ($\text{cm}^3 \text{s}^{-1}$)	References
$O(^1S)$	N_2	$<5 \times 10^{-17}$	ATKINSON and WELGE (1972)
	O_2	$4.9 \times 10^{-12} e^{-885/T}$	ZIPF (1979)
	$O_2(a^1\Delta_g)$	2.6×10^{-10}	KENNER and OGRYZLO (1982)
	O	$<2 \times 10^{-14}$	SLANGER and BLACK (1981)
$O_2(A^3\Sigma_u^+)$ $v' = 0-5$	N_2	9.3×10^{-15}	KENNER and OGRYZLO (1983b)
	O_2	2.9×10^{-13}	KENNER and OGRYZLO (1980)
	O	9×10^{-12}	KENNER and OGRYZLO (1980)
$O_2(A^3\Sigma_u^+)$ $v' = 2$	O_2	1.3×10^{-13}	KENNER and OGRYZLO (1983a)
	$O_2(a^1\Delta_g)$	8.1×10^{-11}	KENNER and OGRYZLO (1984)
	O	1.3×10^{-11}	KENNER and OGRYZLO (1983a, 1984)
$O_2(A^3\Sigma_u^+)$ $v' = 8$	O_2	$\geq 8 \times 10^{-11}$	SLANGER <i>et al.</i> (1984)
$O_2(b^1\Sigma_g^+)$ $v' = 0$	N_2	2.2×10^{-15}	MARTIN <i>et al.</i> (1976)
	O_2	4.0×10^{-17}	MARTIN <i>et al.</i> (1976)
	O	8.0×10^{-14}	SLANGER and BLACK (1979)

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