On the Zenith Angle Dependence of the Infrared Oxygen Emission of 1.27 μm Airglow Observed from High Altitude

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1. Introduction

In recent years the 1.27 μm band emission in the night airglow has been observed extensively with the help of infrared spectrometers on board stratospheric balloons (GUSH and BUIJS, 1964; MAKINO and HAGIWARA, 1973). This emission belongs to the infrared atmospheric system of oxygen corresponding to the transition, $a^1\Delta_g, v'=0-X^3\Sigma_g^-, v''=0$. Although the transition $^1\Delta_g-^3\Sigma_g^-$ is optically forbidden, the atmosphere of the earth is opaque to the 1.27 μm radiation because of the large abundance of oxygen. In the stratosphere the atmospheric extinction of the emission is reduced significantly, but it is still important when the emission is observed near the horizon.

In the present work the zenith angle dependence of the emission rate of the 1.27 μm airglow is examined using the data from a balloon-borne photometer. We have calculated the extinction in the atmosphere according to the formalism developed by WALLACE and HUNTEN, 1968, and EVANS *et al.*, 1970.

2. Instrumentation and Observational Results

The optical system of the photometer is schematically drawn in Fig. 1 and its specifications are given in Table 1.

The photometer was flown from Sanriku Balloon Flight Centre of the Institute of Space and Aeronautical Science, University of Tokyo, at 2,100 hours JST on Sept. 10, 1972. The balloon with the photometer reached a height of 24 km at 2,230 hours. The observation of the airglow was continued till 0630 hours in the next morning, when the photometer was cut off the balloon for recovery.

The emission intensities averaged for various zenith angles are shown in Fig. 2. Also shown in Fig. 2 is a van Rhijn curve, which is calculated on two assumptions that (i) the observed emission is not attenuated in the lower atmos-

Fig. 1. Photometer.

Table 1. Photometer constants.

Lens	Diameter Focal length	5 cm 5 cm
Detector	PbS	1 cm × 1 cm
Filter*	Central wave length F.W.H.M. Maximum transmission	1.27 μm 400 $\text{\AA}$ 31%
Chopper	Chopping frequency	125 Hz
Scan	Scanning speed	13°/min

* Inclined incidence is included.

Fig. 2. Observational results and the predicted van Rhijn curve.

phere and (ii) the emission layer is at an altitude of 90 km (EVANS *et al.*, 1972). The observed emission is normalized so that its mean value at a zenith angle of 45° is equal to the value at the same angle of the van Rhijn curve.

By comparing the van Rhijn curve with the observational results, it is seen that the latter show a smaller increase away from the zenith than the former. The deviation of the observational results from the van Rhijn curve may be ascribed to the absorption by the atmospheric oxygen and partly to the contamination by the (8-5) band emission of the hydroxyl.

3. Calculation of the Atmospheric Extinction and Correction to the Hydroxyl Emission

The $^1\Delta_g \rightarrow ^3\Sigma_g^-$ transition is known as magnetic dipole radiation. The possible branches are shown in Fig. 3. In the figure the transitions between anti-symmetric levels (broken circles) are absent due to the zero nuclear spin of oxygen. This transition is also allowed as quadrupole radiation, but the quadrupole radiation is only about 10^{-3} – 10^{-4} as strong as the magnetic dipole radiation (VAN VLECK, 1934).

The rotational constants of the $a^1\Delta_g$ state of oxygen are obtained by HERZBERG and HERZBERG (1947). The line strength of the transition (S_J) is given by Van Vleck, which is used to evaluate the intensity of an individual rotational line relative to the total band intensity in Eq. (3).

To evaluate the optical thickness (τ_c) at the centre of each line of the infrared atmospheric band, a formula used by WALLACE and HUNTEN (1968) was employed;

$$\tau_c = \frac{h\nu}{\omega_e} B \cdot N \cdot I(K'')_{\text{rel}} \quad (1)$$

with

ν : wavenumber of the individual line,

ω_e : equivalent width of the line in wavenumbers,

B : Einstein coefficient,

N : number of absorbing molecules/cm²,

$I(K'')_{\text{rel}}$: intensity of the rotational line divided by the total band intensity.

The intensity of an absorption line is given as (HERZBERG, 1950)

$$I_{\text{abs}} = \frac{2C_{\text{abs}}\nu}{Q_r} S_J \exp[-F(J'')hc/kT], \quad (2)$$

where $F(J'')$ denotes the rotation energy of the state J'' of the unexcited O_2 molecule in units of kayser, Q_r the partition function of the rotational states and C_{abs} is the constant of the relevant band system.

Fig. 3. Branches of $1\Delta_g \rightarrow 3\Sigma_g^-$. Transitions between antisymmetric levels (broken circles) are absent due to the zero nuclear spin of oxygen.

If it is assumed that the wavenumbers of the individual lines are constant over the band, $I(K'')_{\text{rel}}$ is written as

$$I(K'')_{\text{rel}} = \frac{S_J \exp[-F(J'')hc/kT]}{\sum_{\text{band}} S_J \exp[-F(J'')hc/kT]} \quad (3)$$

The central optical depth with Doppler and Lorentz broadening (τ_{Cmax}) may be represented by an analytic approximation (WHITING, 1968).

$$\tau_{\text{Cmax}} = \frac{\tau_D \omega_e}{\omega_V [1.065 + 0.447(\omega_1/\omega_V) + 0.057(\omega_1/\omega_V)^2]} \quad (4)$$

where τ_D is the central optical depth for a pure Doppler-broadened line and ω_e is the equivalent width of this Doppler line. ω_1 is the Lorentz width at half height and ω_V is the Voigt width at half height defined by VAN DE HULST and REESINCK (1947) as

$$\omega_V = \omega_1/2 + (\omega_D^2 + \omega_1^2/4)^{1/2} \quad (5)$$

where ω_D is the Doppler width at half height.

As equation (1) is applicable to any type of absorption, τ_{Cmax} may be calculated by replacing τ_D with τ_C . The accuracy of Eq. (4) is estimated to be about 1% (WHITING, 1968).

In the present case the maximum value of the central optical depth arises at a line of $^9\text{Q}(7)$, and is 8.1 for a zenith angle of 83° at an altitude of 24 km. Then, the variation of the optical depth with the wavenumber from the centre of the line is approximated by

$$\begin{aligned} \tau(\nu) = \tau_{\text{Cmax}} \left\{ [1 - \omega_1/\omega_V] \exp[-2.772(\Delta\nu/\omega_V)^2] + [\omega_1/\omega_V] \frac{1}{1 + 4(\Delta\nu/\omega_V)^2} \right. \\ \left. + 0.016[1 - \omega_1/\omega_V][\omega_1/\omega_V] \left\{ \exp[-0.4(\Delta\nu/\omega_V)^{2.25}] - \frac{10}{10 + (\Delta\nu/\omega_V)^{2.25}} \right\} \right\} \quad (6) \end{aligned}$$

This corresponds to Eq. (5) of WHITING's paper, and this approximation agrees with the Voigt profile within 5% at worst. Furthermore, this error is expected to be less than the uncertainties of the Einstein coefficient employed in the present work. The Einstein coefficient and the pressure broadening constant (γ_0) in the Lorentz width employed in the present work are the same as those used by EVANS *et al.*, which had been measured to be $0.070 \text{ erg}^{-1} \text{ sec}^{-1} \text{ cm}^2$ and $0.08 \text{ cm}^{-1} \text{ atm}^{-1}$ defined at half height, respectively (BADGER *et al.*, 1965). Neglecting the temperature dependence of the Lorentz width, the expression for ω_1 is taken as $\omega_1 = \gamma_0 P$ in view of the fact that it does not exceed the experimental uncertainties of γ_0 in the lower atmosphere. P is the local atmospheric pressure in bar.

The original emission spectrum was calculated for a rotational temperature of 200°K , which is the local temperature for neutral molecules at the emission layer height. The line profile (Voigt profile) reduces to the expression for a Doppler line at this altitude. In the region above 50 km, the absorption is neg-

Fig. 4. Intensity distribution of the original emission for a rotational temperature of 200°K and the transmitted intensity for a zenith angle of 58° at an altitude of 24 km. For the sake of clarity RQ , $^Q R$, $^Q P$ and $^P Q$ branches have been omitted in the figure.

Fig. 5. Calculated intensity with the observed intensities. $\pm$: Observed intensity with the standard error. ----: Corrected for the absorption. —: Corrected for the absorption and for the contamination of hydroxyl emission.

ligibly small (the central optical depth for the line of ${}^9\text{Q}(7)$ is 0.04 at a zenith angle of 83°). Therefore, the calculation was carried out for altitudes below 50 km, with spherical shells of 1 km thickness. In the calculation the earth's radius is taken as 6,400 km and the local temperature in ω_D is taken from the data of U.S. Standard Atmosphere, 1962. The atmospheric pressure is expressed as $1.0 \exp[-0.146h]$, where h is the height in km.

The calculated transmission for the zenith observation is 70.3% and for a zenith angle of 58° is 50.4% at an altitude of 24 km, respectively. The transmitted intensity distribution for the zenith angle of 58° (dotted line) at the height of 24 km is shown in Fig. 4 with the original emission distribution (solid line). A calculated intensity curve as a function of the zenith distance is shown in Fig. 5 by the dotted line.

The contamination by the hydroxyl emission of the observed intensities is calculated using the observational results by GUSH and BUIJS, 1964, and the transmission characteristic of the filter employed in the present work. Gush and Buijs have estimated the relative intensity of the (8-5) band emission of hydroxyl to the infrared atmospheric band emission to be (20 kR/70 kR) at an altitude of 90,000 feet (27 km). The relative transmission of the (8-5) band emission to the infrared band emission of the filter is (8%/16%). In the calculation, it is assumed that the hydroxyl emission is not attenuated above 24 km and the emission height is 90 km (EVANS *et al.*, 1972). The calculated intensity for our observation is shown in Fig. 5 by the solid line with the observed intensities.

4. Discussions

The calculated result is in good agreement with the observed intensities except for a point for a zenith distance larger than 80° . Therefore, the intensity distribution of the infrared atmospheric band is interpreted in terms of the absorption of the lower atmosphere. The deviation in the horizontal direction may arise from the re-emission of the 1.27 μm radiation absorbed in the lower atmosphere. Although the 1.27 μm emission is quenched significantly in the lower atmosphere, the re-emission will be still important when it is observed at large zenith angles through the atmosphere. The intensity in horizontal direction will be discussed in detail in a future communication considering the atmospheric quenching of O_2 ($a^1\Delta_g$).

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