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TWILIGHT TRANSITION SPECTRA OF ATMOSPHERIC O₂ IR EMISSIONS

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Abstract. Resolved spectra have been obtained from the ground of the O₂($a^1\Delta_g$) emissions from the upper atmosphere utilizing a wide-field interferometer with a cryogenically cooled germanium detector. The rotational structure of both the (0,0) band at 1.27 μm and the (0,1) band at 1.58 μm are clearly separable from the hydroxyl airglow. The decay rate of the O₂($a^1\Delta_g$) during the twilight transition has been observed.

O₂ IR Atmospheric Band Airglow

The metastable excited state ($a^1\Delta_g$) of molecular oxygen is of considerable importance in aeronomical processes. The state is particularly interesting because its long lifetime of 3.8×10^3 seconds [Badger *et al.*, 1965] makes its 0.98 eV of excitation energy available in atmospheric interactions of many types. These interactions include ionization and charge transfer in addition to photochemical reactions. The high throughput of the wide-field infrared interferometer-spectrometer has made it possible to resolve the spectrum of the infrared atmospheric emission bands of O₂ at 1.27 and 1.58 μm . These bands originate from transitions from the $v' = 0$ energy level of the $a^1\Delta_g$ state to the $v'' = 0$ and $v'' = 1$ levels of the ground state $X^3\Sigma_g^-$.

Extensive radiometric observations of this infrared atmospheric band system have been made as summarized in the fine review articles of Evans and Llewellyn (1970) and Vallance Jones (1973). The O₂(0,1) infrared atmospheric band at 1.58 μm was first discovered in the twilight airglow by Vallance Jones and Harrison (1958) using a grating spectrometer; they observed this band as an asymmetry, which decayed during twilight, in the spectral profile of the Q branch of the (4,2) band of the hydroxyl airglow.

The O₂(0,0) band at 1.27 μm has been observed in laboratory experiments [Whitlow and Findlay, 1967; Becker *et al.*, 1971] a factor of 50 times brighter than the O₂(0,1) band at 1.58 μm . However, unlike the situation at 1.58 μm , the atmospheric absorption at 1.27 μm is severe [Evans *et al.*, 1970]. In fact, the first identification of the ($a^1\Delta_g \rightarrow X^3\Sigma_g^-$) electronic transition in

O₂ was first identified by Herzberg (1934) from observing the strong terrestrial atmospheric absorption of the solar spectrum at 1.27 μm .

Apparently, the O₂ 1.27- μm band was first detected (but not identified) by Goshphstein and Kushpil (1965) on a daytime balloon flight. Positive identification of this band was made in the day and twilight airglow by Noxon and Vallance Jones (1962) who flew a grating spectrometer aboard an aircraft. The (0,0) band at 1.27 μm was first resolved from the ground by Lowe (1969) who used a standard Michelson interferometer.

Observational Technique

The twilight-airglow spectra of the O₂ infrared atmospheric system obtained by Utah State Copyright 1975 by the American Geophysical Union.

University resulted from using a field-widened interferometer-spectrometer developed under grants from the National Science Foundation [No. GA 786] and the Air Force Cambridge Research Laboratories. Two small-angle compensating wedge prisms are used in such a way that incident light rays which may be as oblique as 6 degrees are still accepted by the interferometer even when driven to high resolution. The back surface of the prisms are reflective and serve as the end mirrors of the interferometer. The change of optical path difference to obtain an interferogram is accomplished by driving one of the prisms parallel with its apparent mirror position [Despain *et al.*, 1971]. This instrument uses an electromagnetically driven, gas-lubricated, precision platform for the movable prism. The details of the instrument have been reported elsewhere [Haycock and Baker, 1974].

The detector used for this study was an intrinsic-germanium photoconductor operated at liquid-nitrogen temperature (77°K). The optics of the interferometer were operated at ambient temperature. The interferometer-spectrometer was calibrated using a controlled blackbody source.

Interferograms from the spectrometer were fed into the data system of the *USU Argus* aeronomy observatory. Analog-to-digital (A/D) conversions were made, and fast Fourier transforms (FFT) were computed in near real time as the interferograms were generated.

Figure 1. Zenith spectral radiance at Logan, Utah at 02:19 hrs UT (19:19 hrs local) on September 5, 1975. Spectral resolution = 3 cm^{-1} ; observing time = $1\frac{1}{2}$ min.; viewing field = 0.02 sr. [The instrument response function is normalized to 1.27 μm , to obtain the K/cm^{-1} of the spectrum of any other wavelength divided by the relative instrument response (right-hand scale) at that wavelength.]

Figure 2. Zenith spectral radiance at Logan at 05:35 hrs UT (22:35 hrs local) on September 5, 1974.

Spectral Measurements

The near-infrared interferometer-spectrometer was operated to observe the airglow from a location at Logan, Utah, on September 5, 1974, local time. The latitude of this observing site is $41^{\circ}44'34''$ North, the longitude is $111^{\circ}48'24''$ West, and the elevation is 4790 feet above sea level.

Figures 1 and 2 show the overhead (zenith) spectral radiance at two different times during the evening twilight. The spectral coverage is from 1.1 through 1.7 μm . The optical resolution of each reduced spectrum is 3 cm^{-1} , and the total observing time to obtain the spectrum was $1\frac{1}{2}$ minutes. Four 15-second transformed interferograms were signal averaged (coadded) to obtain each of the two spectrograms shown. In each case, the viewing aspect was the geometrical zenith with the spectrometer operated in this case at a 9-degree full angle field-of-view.

A two-channel radiometer was used to obtain the absolute zenith radiance in selected wavelength bands for continuous monitoring and calibration purposes. One filter was used to measure the radiance of the (0,0) band of $\text{O}_2(\alpha^1\Delta_g)$; a second was used to monitor that part of the $\Delta\nu = 2$ band sequence of OH between 1.57 and 1.70 μm .

Figure 3.

Zenith spectra of the atmospheric solar scattering and airglow emissions around 1.27 μm during the twilight of September 5, 1974, at Logan from 02:10 to 05:35 hrs UT (19:10 to 22:35 hrs LST).

The spectrum of the $\text{O}_2(\alpha^1\Delta_g)$ (0,0) band during the twilight transition from day to night is shown in more detail in Figure 3. The decay of the $\text{O}_2(0,0)$ band at 1.27 μm relative to the surrounding OH bands is clearly evident. At a longer wavelength is the (8,5) band of the OH Meinel sequence, and at a shorter wavelength is the OH(7,4) band. The Q rotational lines of these bands are indicated on Figure 4. The sequence of spectra of Figure 4 are the same twilight transition shown with an expanded ordinate.

Discussion

The dominant twilight airglow emission species in the 1.1 to 1.7- μm spectral region, in addition to the $\text{O}_2(\alpha^1\Delta_g)$ infrared atmospheric system at 1.27 and 1.58 μm (Figure 1), are the first and second overtone rotation-vibration band sequences (Meinel $X^2\Pi_g \rightarrow X^2\Pi_g$) of the ground electronic state of the hydroxyl (OH) molecule. In spite

Figure 4. Zenith spectra of twilight around 1.27 μm (expanded ordinate of Figure 3).

of the atmospheric extinction [Selby and McClatchey, 1972; Baker et al., 1973], clearly evident from left to right in Figure 1, are the (4,2), (3,1), and (2,0) bands of the $\Delta v = 2$ sequence and the (8,5), (7,4), and (6,3) bands of the $\Delta v = 3$ sequence. The location of the Q lines are indicated on the figures for each of these bands.

The $O_2(0,0)$ band (whose dominant Q line is at $1.268 \mu m$) occurs to the right of the Q line of the $OH(8,5)$ band at $1.290 \mu m$. Since the R rotational lines of the $OH(8,5)$ band overlay directly on the $O_2(0,0)$ band, it is evident that exceptional care must be exercised in using fixed bandpass filter radiometers to study $O_2(^1\Delta_g)$ airglow. Valid conclusions drawn about the variations and enhancements of $O_2(^1\Delta_g)$ emissions based only upon radiometric measurements are difficult to achieve.

In the first spectrum of Figure 4, the OH and the O_2 IR emissions can be seen superimposed upon the spectrum of the scattered sunlight as seen through the absorbing lower atmosphere. The subsequent spectra through the twilight transition clearly show the decay of the $O_2(0,0)$ emissions from the high daytime levels. A detailed analysis must, of course, take into account the extinction due to absorption and scattering of the lower layers of atmosphere [Evans et al., 1970]. However, the apparent radiance of the

Table 1. Zenith radiance of $O_2(^1\Delta_g)$ as observed from the ground at Logan on Sep 5, 1974

Universal Time (hrs:min)	Earth Shadow Height (km)	Apparent Radiance (0,0) band (kR)
02:52	95.7	104
03:45	361.5	45
04:30	703.0	35
05:35	1343.0	17

$O_2(0,0)$ band observed from the ground in the zenith at various times during the twilight transition is given in Table 1. The effective time constant of the decay simply modeled as an exponential is about 61 minutes.

Figure 5 shows the twilight transition behavior of the (0,1) Q line $O_2(^1\Delta_g)$ at $1.582 \mu m$. This line lies immediately to the right of the $OH(4,2)$ Q line at $1.583 \mu m$; however, its decay relative to the OH can clearly be distinguished. The effective decay time constant of the $O_2(0,1)$ appears to be 56 minutes. Part of the remainder of the rotational structure of the $O_2(0,1)$ band can be delineated immediately after the solar scattering diminishes.

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Figure 5. Zenith spectra of the atmospheric solar scattering and airglow emissions around $1.58 \mu m$ during the twilight of September 5, 1975, at Logan from 02:13 to 05:35 hrs UT (19:13 to 22:35 hrs LST).

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