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Interferometric spectra of the Earth's airglow (1·2 to 1·6 μm)

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The principal emission in the Earth's airglow at wavelengths between 1 and $2\,\mu$m is the $\Delta v = 2$ sequence of the hydroxyl vibration-rotation bands (Gush & Vallance Jones 1955; Shemansky & Vallance Jones 1961). The hydroxyl emission, whose bands extend from the visible region to $4\,\mu$m, is present in both the day and night airglow and is probably produced by the chemiluminescent reaction between atomic hydrogen and ozone (Wallace 1962)

$$\mathrm{H} + \mathrm{O}_3 \to \mathrm{OH}(v' \leqslant 9) + \mathrm{O}_2.$$
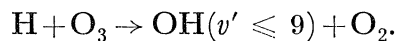
The application of the multiplex Fourier spectroscopy to the study of this region of the spectrum (Connes & Gush 1960; Gush & Buijs 1964) has increased the resolving power attainable by nearly an order of magnitude, making possible the resolution of the rotational structure of the bands and allowing more precise determination of the rotational temperature.

During the day, the brightness of the hydroxyl bands is exceeded by that of the infrared atmospheric system of oxygen ($^1\Delta_g - {}^3\Sigma_g^-$) whose most intense bands are the 0–0 at $1\cdot27\,\mu$m and the 0–1 at $1\cdot58\,\mu$m. Ground-level observations of this system have been limited to the 0–1 band since the 0–0 band is strongly absorbed by the oxygen of the lower atmosphere (Vallance Jones & Harrison 1958). Observations of the 0–0 band intensity throughout the day have been made, however, from an aircraft at $13\cdot7$ km (Noxon & Vallance Jones 1962; Noxon 1967) and from a balloon at 30 km (Evans, Llewellyn & Vallance Jones 1967). The emission was also detected in the night airglow by Gush & Buijs (1964) from a balloon at 30 km. The emission during the day probably is caused by the photodissociation of ozone (Wayne 1967)

$$\mathrm{O}_3 + h\nu \to \mathrm{O}_2(^1\Delta_g) + \mathrm{O},$$
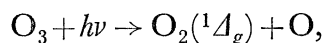
but the excitation mechanism during the night is not established. The $^1\Delta_g$ state has a radiative half-life of about 45 min (Badger, Wright & Whitlock 1965) which, in the absence of collisional deactivation, would produce a long decay of the brightness of the emission during evening twilight. Ground-level observations of the evening twilight decay of the brightness of the 0–1 band (Vallance Jones & Gattinger 1966) indicate a much faster decay with a time constant of 10 to 15 min.

In the present work, a dynamic Michelson interferometer equipped with a germanium detector has been used to obtain spectra from $1\cdot2$ to $1\cdot6\,\mu$m at better resolution and higher signal/noise ratios than was possible in earlier work with lead sulphide detectors.

Method

The interferometer used in this work is a copy of the one used by Gush & Buijs in their balloon-borne airglow studies and described by them. The instrument incorporates a reference interferometer using the mercury line at 5461 Å to provide a precise measure

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of path difference which is varied continuously at the rate of four mercury green line fringes per second. The maximum path difference attainable is 4 mm corresponding to a resolving power of over 3000 at a frequency of 8000 cm^{-1}. The detector is a germanium photodiode with a sensitive area 0·2 cm^2, cooled with liquid nitrogen and having a noise equivalent input power of 5×10^{-15} W at a wavelength of 1·4 μm in a 1 Hz bandwidth at 15 Hz. A silicon field lens is used both to focus on the detector and to act as a filter preventing all frequencies above 9000 cm^{-1} from reaching the detector. The detector output, after amplification, is sampled twice per cycle of the mercury green reference fringes by an integrating digital voltmeter and recorded on perforated paper tape.

The interferograms are pretreated before Fourier transformation by the method of Forman, Steel & Vanasse (1966) to correct for phase errors and to eliminate frequencies outside the range 6100 to 9000 cm^{-1} from the spectrum. At the same time the number of points in the interferogram is reduced by a factor of 6 to reduce the amount of computation required in the transformation.

Results

The spectrum obtained from an interferogram taken on the night of 7 August 1966 is shown in figure 1. The resolving power is about 3000. The zenith angle of observation was 45° and the duration of recording was 60 min. The spectrum is not corrected for the variation in sensitivity of the instrument.

The main features of the spectrum are the 4–2, 3–1, 8–5, 7–4 and 6–3 hydroxyl vibration-rotation bands whose Q-branches lie at 6316, 6642, 7748, 8249 and 8741 cm^{-1} respectively. Absorption by water vapour obscures the region from 6800 to 7500 cm^{-1} where the 2–0 and 9–6 hydroxyl bands should occur. The signal/noise ratio is significantly better than obtained in earlier work and the structure of the bands of the $\Delta v = 3$ sequence is shown here for the first time. Rotational temperatures of 185 ± 6 and 182 ± 9 °K were obtained from the 3–1 and 8–5 bands respectively, using the lines from the Q, P_1, and P_2 branches in the analysis. Similar temperature measurements taken throughout the year 1966 show that such low temperatures prevail only during the summer with 215 °K being typical throughout the rest of the year.

The only features in the spectrum which can not be ascribed to OH are the structure near 7880 cm^{-1} and the much weaker feature at 6327 cm^{-1}, just resolved from the $Q(1)$ line of the 4–2 hydroxyl band. These emissions are identified as the 0–0 band and 0–1 infrared atmospheric bands of oxygen respectively. The presence of the 0–0 band was most surprising because of earlier work of Vallance Jones & Harrison (1958) who failed to detect it, even during evening twilight, and who calculated the transmission to be 0·06 % for the strongest lines.

No emission other than the hydroxyl and oxygen bands can be identified in the spectrum. An upper limit of 2 kR can be put on the brightness of any narrow airglow emission yet to be discovered in this region.

Since the 0–0 $^1\Delta_g$–$^3\Sigma_g^-$ oxygen band was found in the spectrum obtained well after sunset, an attempt was made to observe the brightness of this feature as a function of time during evening twilight. Spectra for this purpose were taken at a reduced resolving power in order to obtain better time resolution of the brightness decay through reduction of the

observing time required for each interferogram. Three spectra illustrating the decay of the band during evening twilight are shown in figure 2. Each spectrum required 12 min of observing time and the resolution is 15 cm^{-1}. At this resolution the 0–1 oxygen band at 6327 cm^{-1} is overlapped by the Q-branch of the 4–2 hydroxyl band. There is considerable
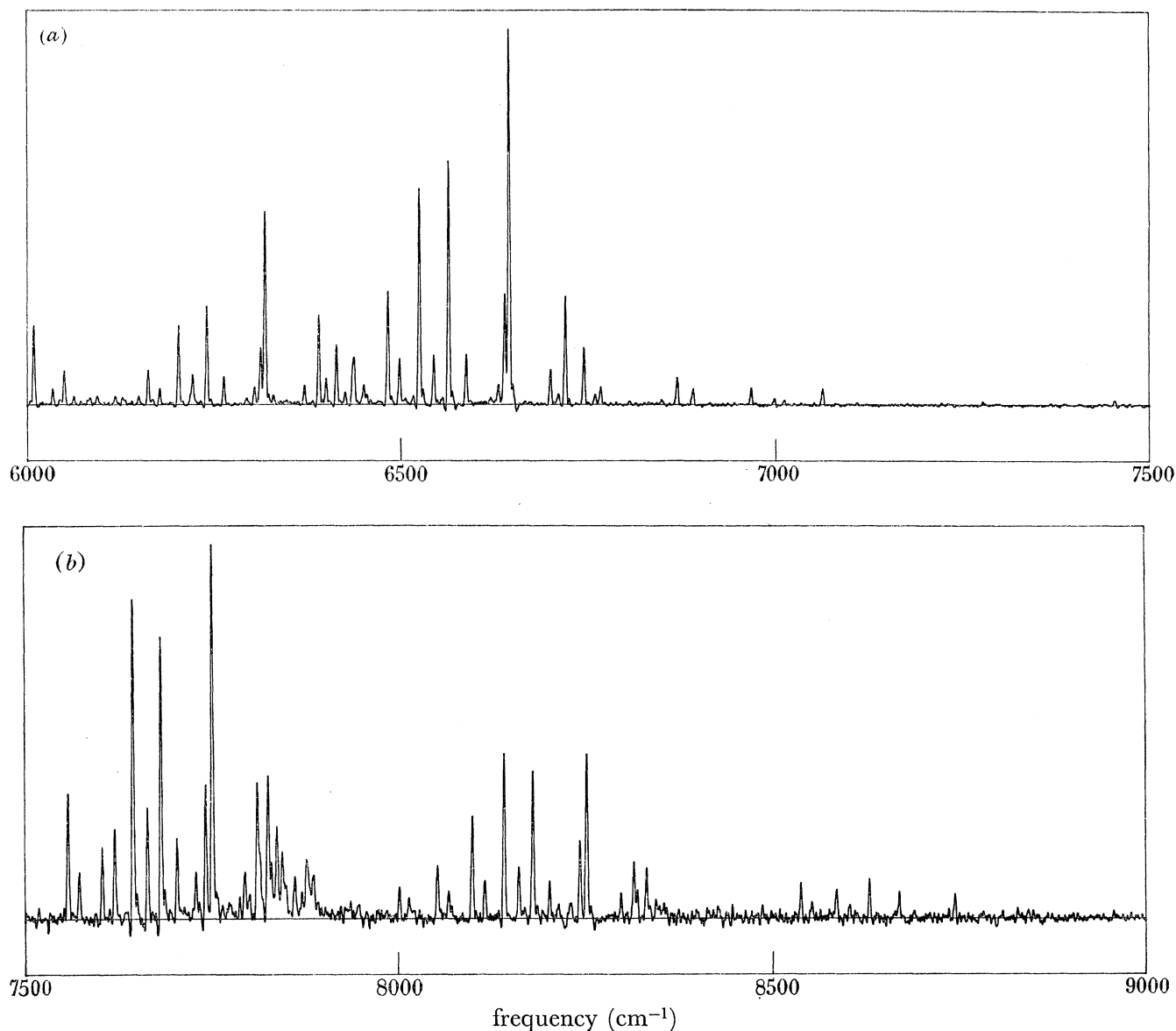

Figure 1. Spectrum of night airglow, 6/7 August 1966, 23.42 to 00.40 h Eastern Standard Time.
(a) 6000 to 7500 cm^{-1}. (b) 7500 to 9000 cm^{-1}, gain $\times 6$.

contribution from scattered sunlight in the first spectrum. The presence of this scattered sunlight makes the measurement of the brightness of the 0–0 oxygen band in emission difficult since the scattered light spectrum shows the same band in absorption.

The decay of the brightness of the 0–0 oxygen band on the three nights in 1966 is illustrated in figure 3 (a). In the absence of an absolute calibration of the interferometer,
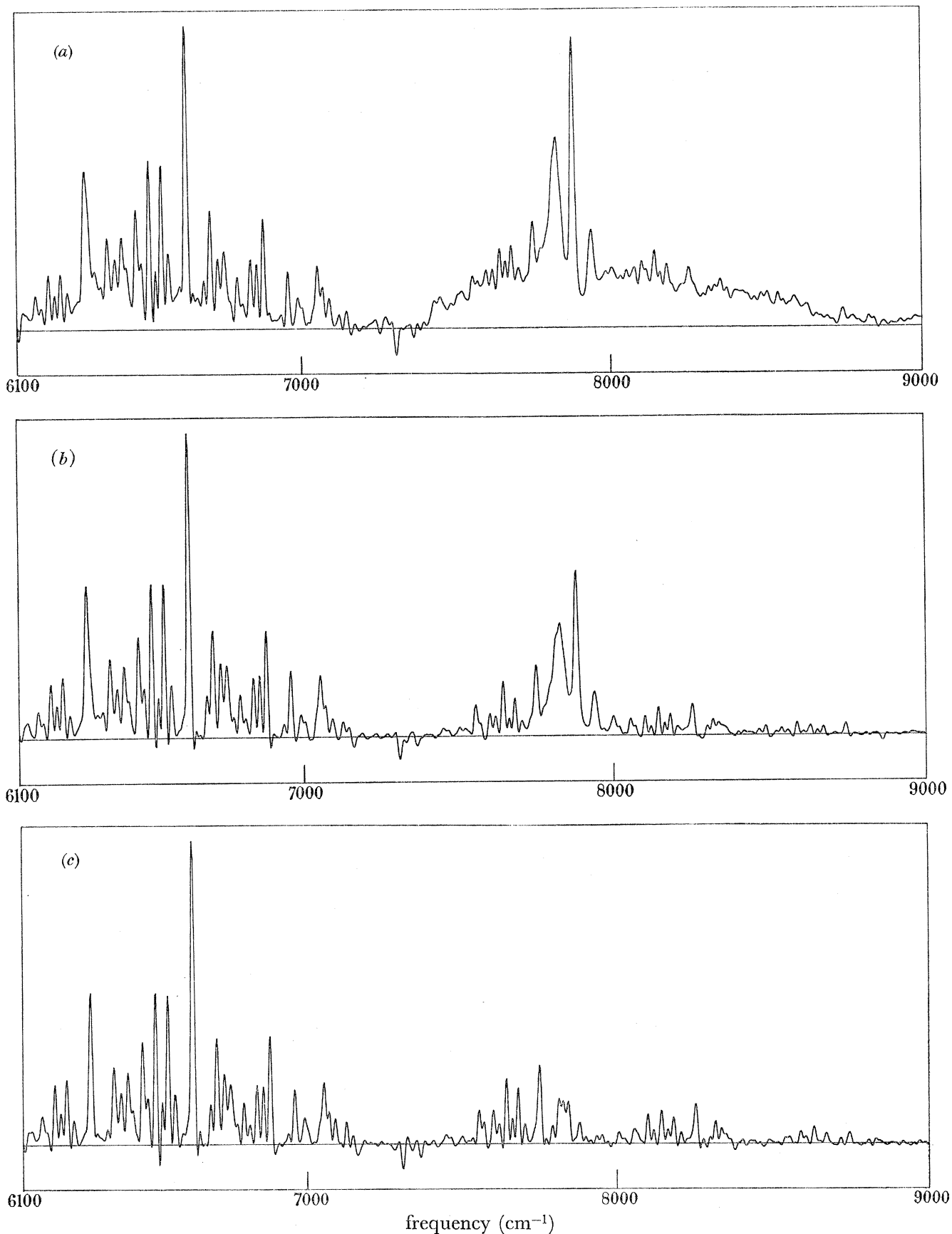
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FIGURE 2. Spectra of twilight airglow, 15 November 1966. (a) 16.57 to 17.09 h EST; (b) 17.09 to 17.21 h EST; (c) 20.31 to 20.43 h EST. Time of ground level sunset 16.11 h EST.

the brightness was measured with respect to that of the 8–5 OH band which is assumed to be constant throughout the period of observation. The emission reaches a constant brightness about 4 h after sunset. In order to show better the rate of decay of the emission, this constant brightness was subtracted from the observed values and the results plotted in
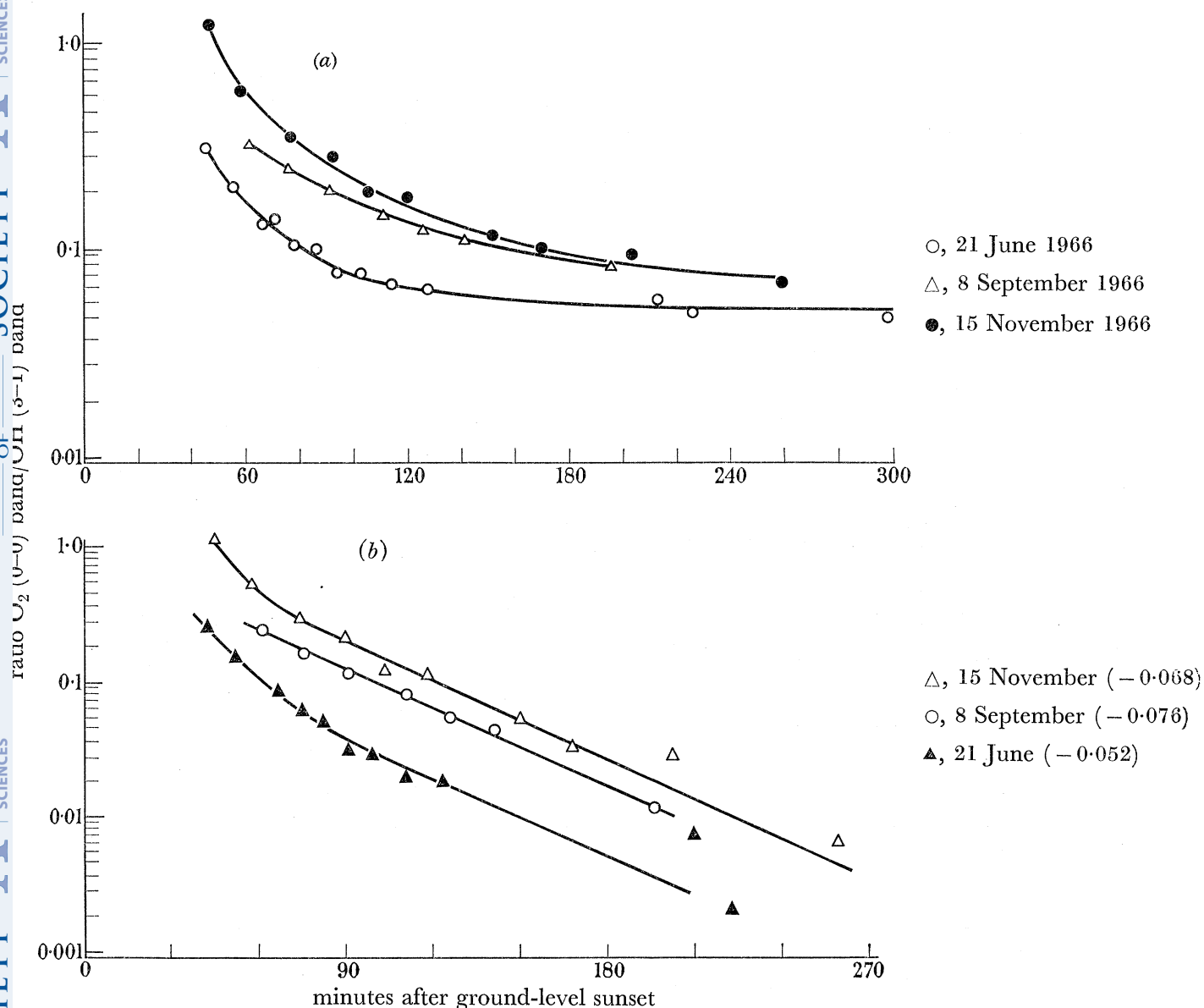

FIGURE 3. Evening twilight decay of brightness of 0–0 band of oxygen at 7880 cm⁻¹. Ordinate scale not corrected for instrument sensitivity. (a) Observed relative brightness. (b) Observed relative brightness corrected for assumed constant nightglow brightness. The numbers in parentheses following the dates indicate the magnitude of the corrections.

figure 3 (b). Starting about 1 h after sunset, the results are well fitted by an exponential decay with a time constant of 45 min which is in reasonable agreement with the measured radiative half-life of the $^1\Delta_g$ state. Earlier than an hour after sunset a faster decay is observed. The results also show a seasonal variation in the evening twilight brightness with

the value on 21 June approximately six times less than that on 15 November. The seasonal variation is again predicted on the assumption that the 8–5 OH band has a constant brightness throughout the year.

The transmission of the atmosphere for the 0–0 band has been estimated in two ways. First, the relative brightness of the 0–0 and 0–1 band was measured and compared with the emitted relative intensity of 60:1 measured in our laboratory by Dr F. Findlay. Secondly, the observed brightness at ground level well after twilight was compared with the value of 80 kR obtained by Gush & Buijs (1964) for the brightness measured at an altitude of 30 km. The ground level value was obtained by assuming that the brightness of the 8–5 OH band was 16 kR (Chamberlain & Smith 1959). Both methods give $4(\pm 1)$ % for the transmission at a zenith angle of 45°.

Discussion

The combination of a highly sensitive germanium detector with the multiplex advantage and the great light-gathering power of a Michelson interferometer has enabled us to obtain a spectra of the region 6100 to 9000 cm^{-1} at better resolution and higher signal/noise ratio than previously attainable. The rotational temperatures obtained from the 3–1 and 8–5 hydroxyl bands are consistent with the temperature of the region in which the emission is supposed to take place, contrary to the observations discussed by Krassovski & Shefov (1965). The annual variation of rotational temperature is not inconsistent with that proposed by Murgatroyd (1957), although it is not established that the height of the hydroxyl emission remains constant throughout the year.

The observed brightness of the 0–0 band of the infrared atmospheric system of oxygen at ground level indicates that previous calculations of the absorption of this band by the lower atmosphere are seriously in error. This error is probably the result of the change in the pressure broadening of the absorption line with altitude being incorrectly allowed for. The observed decay of brightness during evening twilight suggests that a large fraction of the emission takes place at altitudes where non-radiative deactivation of the $^1\Delta_g$ state is important. This observation, which is inconsistent with earlier ground-level measurements, explains the morning–evening asymmetry in the brightness of the emission and should permit simplification of the photochemical theory of the emission which previously was complicated by the necessity of finding suitable deactivation reactions over a wide range of altitudes. The presence of a seasonal variation in intensity as suggested earlier by Vallance Jones & Gattinger (1966) is apparently confirmed on the basis of three nights of observation, but more extensive observations over the course of a full year will be required to establish fully the nature of seasonal effect.

The results presented in this paper are the product of the first 6 months of an observational programme which is continuing on a regular basis. It is to be expected that a clearer picture of the variation of rotational temperature and the intensity of the infrared atmospheric band will be obtained when data for a period of 18 to 24 months are available.

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