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 83 On May 31, 1992, a rocket payload equipped with 10
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A SIMULTANEOUS MEASUREMENT OF THE VERTICAL PROFILES OF SODIUM NIGHTGLOW AND ATOMIC SODIUM DENSITY IN THE UPPER ATMOSPHERE.

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Abstract. On May 31, 1992, a rocket payload equipped with 10 airglow photometers was launched from the Alcântara Launch Center in Northern Brazil. The payload was designed to measure sodium, hydroxyl, atomic and molecular oxygen airglow emissions, in addition to electron density and temperature. At the time of launch, a sodium lidar was operated at the same site, giving vertical profiles of atmospheric sodium density. The measured vertical profiles of the Na D line emission and atomic sodium density are remarkably similar, with sharp boundaries at 81 km and 99 km. On the assumption that the Chapman mechanism is responsible for the Na D emission, the measurements imply an almost constant ozone density of $4 \times 10^{17} \text{ cm}^{-3}$ between 87 and 99 km. The unexpectedness of this height independent ozone concentration suggests that our understanding of the sodium excitation mechanism might be inadequate.

Introduction

Although the photochemistry of atmospheric sodium is poorly understood (Kirchhoff, 1986; Clemesha, 1990) it has generally been accepted that the Chapman (1939) mechanism, $\text{Na} + \text{O}_3 \rightarrow \text{NaO} + \text{O}_2$ in quasi-equilibrium with $\text{NaO} + \text{O} \rightarrow \text{Na}^* + \text{O}_2$, is responsible for production of $\text{Na}(^2P)$, giving rise to the sodium doublet observed in the nightglow. Acceptance of the Chapman scheme has been based mainly on the fact that typical vertical distributions of sodium and ozone are consistent with estimates of the Na D emission profile. Discrepancies between the observed intensity of the emission and calculations based on measured sodium profiles and estimated ozone densities, using laboratory rate coefficients, appear to have been resolved by the recent work of Herschbach et al. (1992). On the other hand, the few vertical profiles of sodium airglow obtained to date are of doubtful accuracy, and no previous simultaneous measurement of the airglow and sodium density profiles has been reported. Thus, up till now, it has not been possible to make a direct comparison between the airglow and density profiles. In this paper we report the results of the first experiment to enable such a comparison to be made.

Measurements and Data Analysis

The MULTIFOT payload was launched from the Alcântara Launch Center (2°S, 44°W) on a SONDA III rocket at 2352 LST on May 31, 1992. In addition to instruments for measuring electron density and temperature, the payload con-

tained 6 forward-looking (longitudinal) and 4 side-looking (transverse) photometers. Launch parameters are given in Table 1. In this paper we analyze only part of the data from the photometers, specifications for which are shown in Table 2; other results will be presented elsewhere. The longitudinal photometers were protected by a conventional split nose cone during launch, and the 4 transverse photometers, situated below the longitudinal instruments, viewed the atmosphere at right angles to the rocket axis through 2" quartz windows inserted into the payload skin.

The payload was designed to study the vertical emission profiles of the O_2 Herzberg, OI 557.7 nm, Na D, OI 630 nm, OH(8,3) and O_2 A emissions. A longitudinal photometer for 578 nm and a transverse instrument for 713 nm were included to estimate the background continuum. Unfortunately, the 713 nm transverse photometer failed shortly after launch, making it difficult to estimate the background for the transverse photometers. This created a serious problem with respect to the analysis of the Na D emission profile, where the background should contribute a significant fraction of the total detected signal. For this reason we used the data from the longitudinal 589.3 nm photometer to determine the Na D profile. In any case, the closer proximity in wavelength of the 578 nm photometer makes the background subtraction more reliable. For the OH(8,3) band, the relative background continuum contribution should be much smaller, and only a fairly small error should be incurred in ignoring it. For the purposes of the present study, where we need to determine the OH profile only for the purpose of estimating the contribution of the OH(8,2) band to the signal registered by the 589.3 nm photometer, the small contribution from the NO_2 continuum can be neglected.

The photon-counting photometers were similar in principle to those described by Takahashi et al. (1987). Data were telemetered at 250 10-bit samples per second for each instrument. A 2-axis magnetometer was used for attitude determination. Absolute laboratory calibrations of all photometers were carried out prior to launch, as described in Takahashi et al. (1987), and each instrument included an in-flight calibration source.

Measurements of the vertical profile of atmospheric sodium density were made using a transportable lidar system, specifications of which are given in Table 3. The lidar included a sodium vapor cell for calibration purposes, and is

Table 1. Launch parameters

Vehicle	SONDA III
Date:	31/05/92
Time:	2352 LST
Location:	Alcântara Launch Center (2°S, 44°W)
Apogee:	282 km
Ground range:	398 km

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Table 2. MULTIFOT Photometer specifications

Wavelength	Bandwidth	PMT	Sensitivity*
Transverse photometers			
589.3 nm	1.75 nm	EMI 9924	84.1
630.0 nm	1.57 nm	EMI 9798	21.6
713.0 nm	10.9 nm	EMI 9798	-
724.2 nm	1.75 nm	EMI 9798	41.4
Longitudinal photometers			
257.0 nm	14.3 nm	EMI 9924	267.6
557.7 nm	1.66 nm	EMI 9924	684.0
578.0 nm	10.95 nm	EMI 9924	165.4
589.3 nm	1.69 nm	EMI 9924	326.9
724.2 nm	1.91 nm	EMI 9798	143.9
762.0 nm	5.69 nm	EMI 9798	43.62

* Counts sec⁻¹ Rayleighs⁻¹.

similar in principle (although not in its mechanical layout) to the São José lidar described in Simonich et al. (1979) and Clemesha (1984). The equipment was installed at the launch site, about 5 km from the ramp, and was operated throughout the campaign. Sky conditions were unfavorable during most of the campaign, and most lidar data were obtained by firing through gaps in the cloud cover. For this reason the signal to noise ratio of the profiles obtained was poor when compared with typical results from modern lidars. On the other hand, on the night of the rocket experiment, adequate profiles were obtained both before and during the launch.

The transverse photometers were included in the MULTIFOT payload because previous photometric experiments, using the SONDA III vehicle, had suffered from strong contamination effects at heights below 87 km. In view of the fact that these contaminating signals appear to have been produced in the shock wave in front of the payload (Clemesha et al., 1987; Clemesha et al., 1988) it was reasoned that side-looking instruments should be much less sensitive to this sort of contamination. It is not clear whether or not this reasoning was justified, because the contamination seen on the longitudinal photometers in the MULTIFOT experiment was very different in nature to that seen in previous payloads using the SONDA III vehicle. On the other hand, none of the side-looking photometers showed contamination signals, whereas the signals from the 2 infrared longitudinal photometers were completely obliterated during the upleg passage through the emitting regions. Fortunately, neither the 589.3 nm nor the 578.0 nm longitudinal photometers suffered serious contamination, and it was possible to use the signals from these instruments to determine the vertical profile of the Na D line emission.

In order to determine the intensity of the Na D emission it is necessary to take into account the NO₂ continuum and the OH(8,2) band emissions within the pass band of the photometer. The continuum contribution was allowed for by subtracting an appropriate fraction of the background signal measured by the 587.0 nm photometer. The OH(8,2) band will contribute to the photometer signal via Q(1)1 and Q(1)2, the former accounting for about 15% and the latter 4% of the total Q branch intensity. It is reasonable to assume that the vertical profile of the (8,2) band was similar to that measured for the (8,3) band, and thus we can calculate the profile of (8,2) band

Table 3. PORTAL lidar specifications

Dye laser transmitter		Receiver	
Wavelength:	589 nm	Fresnel Lens:	0.4 m ²
Bandwidth:	6 pm	Bandwidth:	1 nm
Pulse length:	2 μ s	Ht. resolution:	250 m
Rep. Rate:	1 pps	Efficiency:	1 %

intensity on the basis of estimates for the transition probabilities $A_{8,3}$ and $A_{8,2}$.

The technique used for deriving the vertical profile of volume emission rate from the longitudinal photometer signal was identical to that described by Takahashi et al. (1987), using the incremental straight line fitting technique of Murtagh et al. (1984), with a 4 km fitting length. To determine the OH(8,3) band intensity from the 724.2 nm side-looking photometer signals we applied a suitable inversion process to the observed horizon intensity profile (horizon intensity, in this context, refers to the intensity seen by the photometer when its viewing angle is horizontal). The 2° FOV of the photometer was taken into account by deconvolving the inverted profile with an appropriate instrument function.

The rocket payload was rotating about its axis at 4 rps, and the spin axis was inclined at a mean angle of 26° to the vertical, so the photometer FOV traversed the emitting layer 8 times per second. The horizon intensities were obtained by assuming that instants of maximum intensity correspond to the same vertical viewing angle for both the ascending and descending sweeps of the FOV through the emitting region. Averaging the times of maximum signal gives the instants of maximum and minimum inclination of the photometer FOV, and averaging these latter times gives the instants of horizon crossing.

The payload telemetry system sampled each photometer at 4 mS intervals, so that there were approximately 63 samples for each photometer per rotation of the payload. A simple 3-point parabolic fit was used to determine the instants of maximum intensity and the horizon intensities. In the region of 90 km, the vertical component of vehicle velocity was close to 1800 m s⁻¹, so the 8 horizon crossings per second for each photometer correspond to 4.4 horizon intensity determinations per km of height. The raw data were smoothed by a 10-point running mean, before interpolating at 1 km intervals, giving an effective height resolution of slightly more than 2 km. In order to maximize signal to noise ratio, no attempt was made to analyze opposite horizons separately.

Results and Discussion

The uncorrected horizon signal detected by the 724 nm photometer, in the form of 2-rotation sample averages, is shown in Figure 1. The vertical profile of the OH(8,3) band volume emission rate, obtained as described above, appears in Figure 2. Curve b in Figure 2 represents an estimate of the fraction of the (8,2) band signal which should be seen by the 589.3 nm photometer, to be subtracted from the emission profile determined from the latter. In Figure 3 we show the Na D emission profile, with the OH(8,2) band contribution already subtracted. Also shown in Figure 3 is the lidar profile for ground state sodium. It can be seen that the airglow and

Fig. 1 Horizon brightness as a function of height for 724.2 nm photometer.

Fig. 2 OH profiles: (a) measured OH(8,3) band; (b) estimated contribution of the (8,2) band to the measured Na D intensity.

Fig. 3 Vertical profiles of (a) Na D volume emission rate, and (b) Na density.

density profiles are remarkably similar, with unusually sharp boundaries both at the bottom and the top of the layers. The error bars for the airglow profile are proportional to the standard error in the slopes determined in the 4-km straight line fitting analysis, and the error bars for the lidar profile are based on the channel count statistics in the usual way.

According to the Chapman mechanism, the rapid quasi-

equilibrium between the oxidation and reduction reactions should result in the Na D emission rate being equal to $k_1 f_2 [\text{Na}][\text{O}_3]$, where k_1 is the rate constant for the oxidation reaction, and f_2 is the fraction of Na atoms produced by the reduction reaction in the (^2P) state. Using laboratory values for k_1 and f_2 , we can use our experimental determinations of the sodium density and the Na D volume emission rate to derive an ozone profile. Until recently, laboratory measurements have indicated values for f_2 of less than 0.01; recent work by Herschbach et al. (1992), however, suggests that the oxidation reaction produces NaO in the ($^2\Sigma^+$) state, the reduction of which by atomic oxygen leads to a yield of about $2/3$ for Na(^2P). Using Worsnop et al.'s (1991) value for k_1 , together with the value of 0.67 for f_2 suggested by Herschbach et al.'s work, we get the ozone profile shown in Figure 4. The rapid fall off in ozone density below 87 km results from the an apparent small displacement between the Na and Na D profiles. Remembering that there was a horizontal separation of 60 km between the lidar and the location where the rocket passed through the airglow layer, it is clear that this displacement could well be the result of a small horizontal gradient in the vertical distribution of sodium. We conclude then, that our measurement implies an almost constant ozone concentration between 87 and 99 km, with doubtful evidence for a rapid fall off below 87 km.

We can compare our derived ozone profile with other rocket and satellite measurements and with model calculations. The most extensive set of middle atmospheric ozone measurements to have been published is that of Thomas (1990), based on limb radiance measurements of $\text{O}_2(^1\Delta)$ by the SME satellite. These measurements indicate typical concentrations between 3×10^7 and $1 \times 10^8 \text{ cm}^{-3}$ in the 80 to 90 km height range. Unfortunately, the SME measurements are limited to a maximum height of 90 km, and are for sunlit conditions only. Ulwick et al. (1987) determined ozone densities from 5×10^7 at 80 km to $5 \times 10^8 \text{ cm}^{-3}$ at 90 km, using a rocket-borne infrared spectrometer which measured the $9.6 \mu\text{m}$ $\text{O}_3(\nu_3)$ nightglow intensity. This was a nighttime measurement, and is thus more appropriate for comparison with our profile, but again limited to a maximum height of 90 km. Vaughan (1982) has published a nighttime profile of ozone, obtained from a rocket-borne lunar occultation experiment, showing a peak ozone concentration of $6 \times 10^8 \text{ cm}^{-3}$ at 90 km, falling to about $1 \times 10^8 \text{ cm}^{-3}$ at 80 and 100 km. A model calculation by Allen et al. (1984) shows, for nighttime conditions, a peak of $1 \times 10^8 \text{ cm}^{-3}$ at 86 km, falling to $4 \times 10^7 \text{ cm}^{-3}$ at 81 km and $5 \times 10^6 \text{ cm}^{-3}$ at 100 km.

Both model calculations, such as that of Allen et al. (1984), and experimental determinations of the ozone profile show a minimum in the region of 80 km. This is in agreement with the rapid decrease which we observe below 87 km, but, as mentioned above, this decrease could be the result of a small height difference, between the locations of the lidar and the rocket measurement, in the vertical distributions of sodium.

Although the absolute concentration of ozone determined from our measurement is in reasonable agreement with other experimental results, and with model calculations, our almost constant ozone concentration (within the experimental error) from 87 to 99 km is unexpected. Both modeling studies and experimental results suggest a fairly rapid decrease in ozone density above 90 km. Such a decrease is to be expected, of course, because the production of ozone, via $\text{O} + \text{O}_2 + \text{M} \rightarrow$

Fig. 4. Ozone profile derived from Na density and airglow profiles.

$\text{O}_3 + \text{M}$, must decrease rapidly with increasing height. If we accept the possibility of a small horizontal gradient in the vertical distribution of sodium, our measurements show virtually identical profiles for the sodium density and the Na D airglow. This suggests the possibility that the airglow emission might not be the result of the Chapman reaction, and that it might be produced by some completely different mechanism, where the emission rate is directly proportional to the ground-state sodium concentration. Further discussion of this possibility is beyond the scope of this paper.

Conclusions

The first simultaneous measurement of the vertical profiles of sodium airglow and atomic sodium density shows almost identical height variations for the two parameters, with sharp transitions occurring just above 80 km and just below 100 km. On the assumption that the Chapman mechanism is responsible for the Na D emission, the measurements imply an almost constant ozone density of $4 \times 10^7 \text{ cm}^{-3}$ between 87 and 99 km. The unexpectedness of this height independent ozone concentration suggests that our understanding of the sodium excitation mechanism might be inadequate.

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