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THE SOURCE OF STRATOSPHERIC NO AND N_2O

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SUMMARY

The photodissociation of O_3 has been investigated as part of a program to study possible sources of N_2O production in the stratosphere. Photolysis was conducted at 1576 Å to generate the excited O_2 states that we propose may react with N_2 to form N_2O. We ascertained that, at this wavelength, there is a quantum yield of two for prompt production of oxygen atoms, which is a consequence of the existence of two photodissociative channels giving comparable yields. One of these channels gives $O(^1D)$ and $O_2(b^1\Sigma_g^+)$, with a quantum yield of 0.6, whereas the other results in fragmentation of the O_3, with production of three ground state oxygen atoms. The $O_2(b)$ is generated with vibrational excitation, and we have so far determined that there are comparable populations in levels 0-3. These observations are the first to show $O_2(b)$ production from <u>any</u> photodissociative process, and they were made under conditions in which the kinetics of vibrationally excited $O_2(b)$ can be studied. It appears that O_3 photodissociation at 1576 Å is not a good system for generating the higher electronic states of O_2; it is likely that better results will be obtained at 1930 Å.

A search was made, by vuv absorption, for N_2O production during 1576 Å O_3 photodissociation in the presence of N_2. Consistent with the fact that the relevant 4-5 eV states of O_2 are not generated, no N_2O formation was observed. This study was extended to an investigation of the interaction between highly vibrationally excited OH and N_2 as a possible N_2O source, and it was established that an upper limit of 3×10^{-4} can be set for the reaction yield. Such a yield would still correspond to a large local stratospheric source of N_2O, so it is important to attempt to improve the experiment in order to get an actual yield or to decrease the upper limit.

Earlier experiments on 2537 Å photolysis of N_2O-O_3-N_2 mixtures were repeated to confirm and investigate the apparent N_2O loss that had been noted. With an improved analytical technique, no loss was observed, so the previous results were not confirmed.

The following points can be made concerning the present status of the stratospheric N_2O production problem. Excited O_2 states other than $O_2(a^1\Delta_g)$ are produced in O_3 photodissociation at wavelengths shorter than the Hartley band. Wavelength-dependent studies are needed to further our understanding of products and yields, and to determine whether they act as N_2O sources. The

interaction between vibrationally excited OH and nitrogen is not excluded as an N_2O source, although we were not able to detect N_2O. The question of whether the interaction between $N_2(A^3\Sigma_u^+)$ and O_2 generates N_2O is still an open one, and at present depends on reaching a consensus on the rate coefficient for the $N_2(A)$ pooling reaction.

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INTRODUCTION

The single most important molecule in the stratosphere is ozone, because of its multifunctional character. The absorption of radiation in the Hartley band prevents destructive 2000-3000 Å light from reaching the earth. In this absorption process, O_3 generates $O(^1D)$, a ubiquitous intermediate in stratospheric and tropospheric chemistry. O_3 is also active as a reactant, and its reactions with H, OH, and NO are all important processes.

It is therefore interesting to find that relatively little is known about O_3 photodissociation below 2000 Å, particularly in terms of the products formed. Just as $O(^1D)$ is a reactive photodecomposition product in the Hartley band, it is important not to neglect processes taking place at shorter wavelengths, even though in terms of solar flux, much more radiation is available above than below 2000 Å.

Although both the solar flux and the O_3 photoabsorption cross sections are high in the Hartley band, there are yet other parameters to be considered. Examples are yields of photoproducts and their subsequent histories. Although $O(^1D)$ is a very reactive species and is produced with a yield close to unity from O_3 at 2000-3000 Å, it is an extremely inefficient reactant because it is almost entirely quenched by O_2 and N_2. Therefore, only a minute fraction is available to react with N_2O, H_2O, and CH_4 to produce the important species NO and OH. Thus, it is possible for a reactive species that is produced with a far lower yield than $O(^1D)$ to be an important atmospheric ingredient if it is used more efficiently. Such could be the case either by low quantum yield production of a species from O_3 photoabsorption in the Hartley band, or by generation of such a species at wavelengths below 2000 Å, where the solar flux is relatively weak.

The photoproducts from O_3 in the Hartley band are[1]

$$\begin{aligned} O_3 &\rightarrow O(^1D) + O_2(a^1\Delta_g) \qquad \Phi = 0.85\text{-}0.90 \\ &\rightarrow O(^3P) + O_2(X^3\Sigma_g^-) \qquad \Phi = 0.10\text{-}0.15 \end{aligned} \tag{1}$$

However, because the $O\text{-}O_2$ bond is very weak (1.1 eV), there are many thermodynamically accessible product channels. Those that are spin-allowed are listed in Table 1 with their threshold wavelengths.

TABLE 1

O_3 PHOTODISSOCIATION THRESHOLDS

Atom	Molecule	Threshold Wavelength (Å)
$O(^3P)$	$O_2(X^3\Sigma_g^-)$	11250
$O(^1D)$	$O_2(a^1\Delta_g)$	3060
$O(^1D)$	$O_2(b^1\Sigma_g^+)$	2638
$O(^3P)$	$O_2(A'^3\Delta_u)$	2318
$O(^3P)$	$O_2(A^3\Sigma_u^+)$	2275
$3\ O(^3P)$	----	1997
$O(^1S)$	$O_2(a^1\Delta_g)$	1981
$O(^1S)$	$O_2(b^1\Sigma_g^+)$	1794
$O(^1D)$	$O_2(c^1\Sigma_u^-)$	1741
$O(^3P)$	$O_2(B^3\Sigma_u^-)$	1717

We have previously[2] investigated the yield of $O(^1S)$ below 2000 Å and have found it to be below 0.5%, at least down to 1400 Å. Thus, it is the possibility of generating excited O_2 states that raises interesting questions about the details of O_3 photodissociation below 2000 Å.

To date, there has been no demonstration of photoproduction of O_2 states from O_3 other than the ground state and $O_2(a^1\Delta_g)$. In fact there is no known photodissociative process that generates these higher states ($b^1\Sigma_g^+$, $c^1\Sigma_u^-$, $A'^3\Delta_u$, $A^3\Sigma_u^+$) from any molecule, although recombination of oxygen atoms both in the laboratory and in the airglow is a well-known source.

Our interest in investigating O_3 photodissociation has to do with the possibility that a highly excited O_2 molecule could in principle react with the dominant atmospheric molecule, N_2, to generate N_2O,

$$O_2^* + N_2 \rightarrow N_2O + O(^3P) \quad \Delta H = 3.4 \text{ eV} \qquad (2)$$

The candidate O_2 states are $A'^3\Delta_u$ and $A^3\Sigma_u^+$ at 4.25 and 4.35 eV, respectively. The $c^1\Sigma_u^-$ state is excluded because of the spin requirements of Reaction (1).

Current models of the troposphere and stratosphere[3,4] assume that N_2O is generated by biogenic soil processes, rises through the atmosphere, and is destroyed by photodissociation and reaction with $O(^1D)$. However, Zipf[5] and Zipf and Prasad[6] have suggested several ways of generating N_2O <u>in situ</u>. The first idea was that $N_2(A^3\Sigma_u^+)$ is produced in the upper stratosphere by N_2 absorption of solar radiation at ~2000 Å and that this N_2 state reacts rapidly with O_2 to produce N_2O. It is certain that $N_2(A)$ is removed exclusively by O_2, but it is less clear whether the reaction product is N_2O. Zipf claims that the reaction efficiency is 60%, Iannuzzi et al.[7] find it to be less than 2%, and our measurements on the first year of this contract[8] indicated an upper limit of 8%. However, our value depends on the figure adopted for the $N_2(A) + N_2(A)$ pooling reaction rate coefficient; if it is as fast as Zipf claims, our efficiency becomes compatible with his, whereas if it lies closer to the value measured at SRI several years ago,[9] then we have agreement with Iannuzzi et al. Thus, the final answer on this reaction scheme awaits more experimentation.

More recently, Zipf[10] observed that interaction between $OH(A^2\Sigma^+)$ and N_2 appears to generate N_2O. The OH(A) can be produced in the stratosphere by solar pumping of ground state OH, which is a much more efficient process than pumping of N_2, but is offset by the rapid radiation of OH(A), and the low density of OH. In a private communication,[10] Zipf also discussed generation of N_2O from interaction of highly vibrationally excited OH with N_2, the OH(vib) being produced in the stratosphere at v=9 by the reaction between H atoms and O_3. From H and O_3 atmospheric models, one may calculate the OH(v=9) production rate and determine that even a small efficiency for its reaction with N_2 to produce N_2O would perturb current source models. In the present study, we have evaluated N_2O production both for interaction of N_2 with the products of ozone photodissociation at 1576 Å and for the OH(v=9)-N_2 interaction.

The overall approach to the study has been two-fold: to investigate O_3 photodissociation below 2000 Å and to determine whether N_2O is produced by any of the mechanisms discussed above. A secondary goal has been to follow up some results reported in the first year of the present contract,[8] which had indicated that photodissociation of an N_2O-O_3-N_2 mixture at 2537 Å leads to the partial destruction of N_2O. These results are difficult to understand on the basis of our knowledge of the O_3 photoproducts, the high quenching efficiency of $O(^1D)$ by N_2, and the transparency of N_2O at 2537 Å.

EXPERIMENTAL METHODS

The major part of this study has been performed with the use a Lumonics Model 861T-3 F_2 laser as a photodissociation source. With this instrument, which delivers 10 mJ pulses of 1576 Å radiation at a repetition rate of up to 100 Hz, we have been able to obtain adequate signal levels in the more difficult experiments, which involved signal averaging for as many as 2×10^4 shots.

For the measurements of product yields from O_3, experiments were performed in a flowing system, with a Pyrex reaction cell. At right angles to the incoming laser beam, a photomultiplier (EMI 9558) was mounted, and in the orthogonal direction, radiation entered a 0.3-m McPherson 218 monochromator, at the exit of which was mounted a solar-blind phototube (EMR 542-08-18). Measurements of O_2 emissions were made with the EMI tube; there was insufficient radiation to detect, except for the O_2(b-X) 0-0 band, after passage through the monochromator. A series of 100 Å wide interference filters were used to measure the radiation, between 7600 and 7900 Å.

For detection of oxygen atoms, an oxygen lamp was mounted on the system, orthogonal to both the laser beam and the monochromator axis. This microwave-powered lamp was run with a flow of 1% O_2 in helium and was a source of 1302-1306 Å resonance radiation. The resonantly scattered light from this lamp was a measure of oxygen atoms and was detected after passage through the monochromator by the solar-blind tube.

All the transient data were processed and recorded with a Nuclear Data ND-100 signal averager, generally using the smallest channel width, 10 μs.

For the experiments involving N_2O generation, concentrations of products were determined by vuv absorption, using either an H_2 discharge lamp or a high pressure argon lamp. Initially, analyses were performed by developing a set of absorption spectra for the various system components, N_2O, O_3, O_2, and H_2O, then trying to reconstruct an experimental spectrum by summing these individual spectra, with computer assistance. This procedure was reasonably successful, but it was never possible to eliminate the spurious signals inherent in such a procedure to the point where the required sensitivity could be attained.

When we ascertained that the system components could be separated by trapping at low temperature, it became obvious that this was the preferable procedure. At the pressures used, neither O_2 nor O_3 condenses at 77 K, whereas N_2O does, although it does not condense at 196 K, where H_2O is completely trapped. Thus, it was a simple matter to separate N_2O from the other gases and measure it alone, a much more straightforward and accurate procedure than the one we had originally tried.

The O_3 was prepared in an ozone generator and held in a molecular sieve trap at 196 K. Once a day the slowly evolving oxygen was pumped off, and during a run the O_3 (swept into the system by a helium flow) was O_2-free, as demonstrated by lack of O_2 bands in the absorption spectrum and by the temporal behavior of the $O_2(b-X)$ emission, which was very sensitive to the presence of O_2.

The H_2O used in the experiments was added by bubbling He through water, but the outgassing rate was so high that adding H_2O was unecessary. The problem was to remove the water, which was accomplished with the above-mentioned trap.

For the studies at 2537 Å, a mercury discharge lamp was used, the output of which was on the order of 10^{17} quanta s^{-1}, capable of destroying O_3. The 40-cm-long reaction vessel used in this experiment was water-jacketed, both to keep the walls cool to prevent heterogeneous reactions, and to prevent any 1849 Å radiation from entering the cell.

Pressures were measured with a Baratron gauge, and the small concentrations of O_2 and N_2O that were used were added as 1% or 10% mixtures in helium. O_3 pressures were determined in various ways: by 2537 Å absorption, by 1216 Å absorption, and by the decay rates of $O(^1D)$ and $O_2(b)$, for which O_3 quenching rate coefficients are known.

ACCOMPLISHMENTS

O_3 Photodissociation at 1576 Å

Two types of measurements were made in this first detailed study of vuv O_3 photodissociation: determination of the identity and yield of the initial atomic oxygen fragments and determination of the yield of $O_2(b^1\Sigma_g^+)$. Although this O_2 state will not react with N_2 to generate N_2O, its investigation is essential for understanding the photodissociation dynamics. Obviously, if it is produced with a quantum yield of unity, a search for higher excited O_2 states becomes less interesting.

The oxygen atom yields from O_3 are measured absolutely by comparison with the yields from O_2, where at 1576 Å the sole process generates $O(^1D) + O(^3P)$.[11] The atoms are measured as $O(^3P)$ by 1304 Å resonance fluorescence; thus to get a total yield, $O(^1D)$ must be quenched to $O(^3P)$. This is accomplished by N_2 addition. Figure 1 shows the resonance fluorescence signals obtained from photodissociation of O_2 and O_3. The 2 torr N_2 quenches $O(^1D)$ within 0.5 μs, much less than the 10 μs/channel averaging time, so the jump in signal when the laser is fired represents total oxygen atoms produced. The signal ratio, $I(O_2)/I(O_3)$, is given by

$$\frac{I(O_2)}{I(O_3)} = \frac{[O_2]}{[O_3]} \cdot \frac{\sigma(O_2)}{\sigma(O_3)} \cdot \frac{\Phi(O_2)}{\Phi(O_3)} \cdot f \qquad (3)$$

or

$$\Phi(O_3) = \frac{2I(O_3)}{I(O_2)} \cdot \frac{[O_2]}{[O_3]} \cdot \frac{\sigma(O_2)}{\sigma(O_3)} \cdot f \qquad (4)$$

where $\sigma(O_2)/\sigma(O_3)$ is the ratio of photoabsorption cross sections at 1576 Å, and Φ is the atom yield. The correction term, f, is used because at the probe wavelength of 1304 Å the O_3 absorbs some radiation, thereby decreasing the atom detection efficiency, an effect not occurring with O_2. At 11.8 mtorr O_3, f = 1.12 for the geometry used.

The O_2 pressure was measured directly, and the O_2 cross section of 6.3×10^{-18} cm^2 at 1576 Å was obtained by interpolation from the data of Ogawa and Ogawa.[12] The cross-section ratio was determined by measuring the attenuation of wall-scattered 1576 Å light through the monochromator, with the O_3 pressure being measured by 2537 Å absorption. A value of $[\sigma(O_2)/\sigma(O_3)]_{1576} = 4.3$ was found, just the figure reported by Tanaka et al.[13] Substituting into

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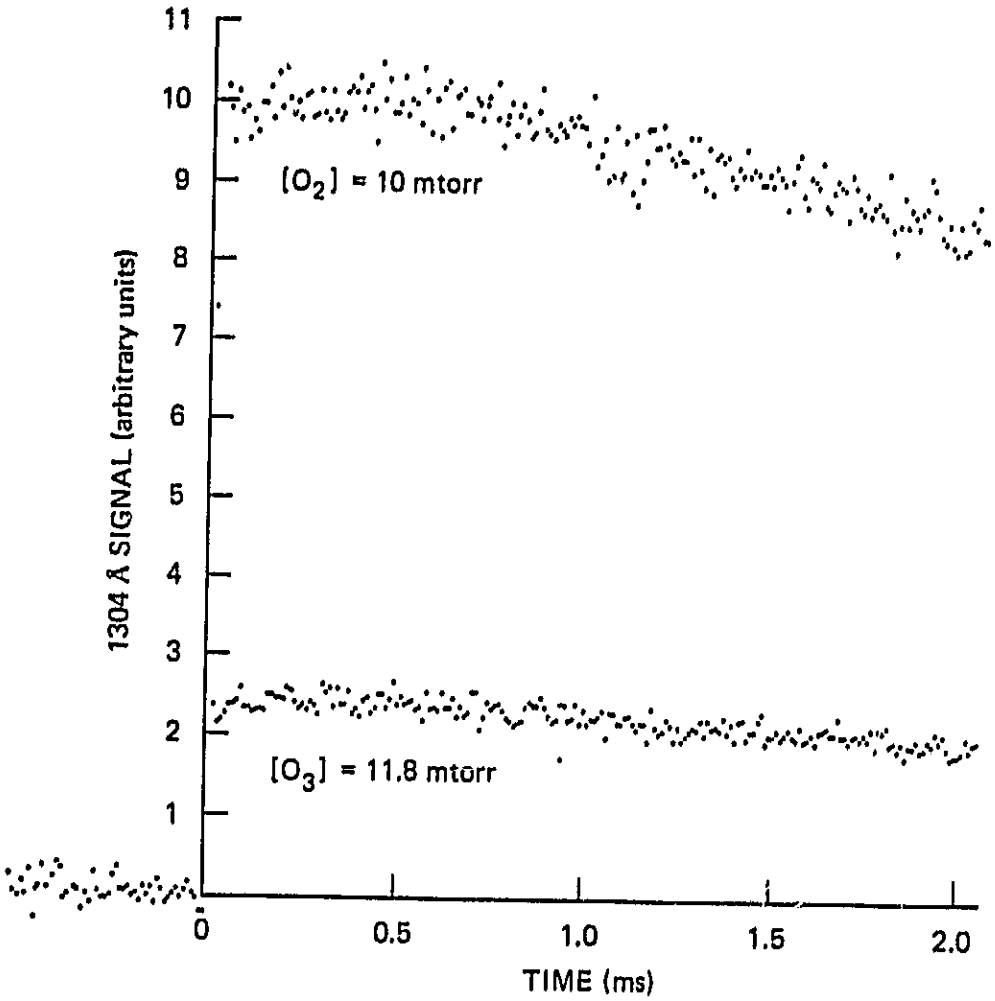

FIGURE 1 $O(^3P)$ YIELD FROM 1576 Å PHOTODISSOCIATION OF O_2 AND O_3
[He] = 17 torr, $[N_2]$ = 3 torr, 3500 laser shots

equation (3), we find that $\Phi(O_3) = 2.0 \pm 0.1$, i.e. each O_3 photodissociation process results in production of two prompt oxygen atoms.

More information is available if the N_2 is left out because then $O(^1D)$ does not appear immediately as $O(^3P)$, and the slower production then gives differentiation between prompt $O(^3P)$ and slow $O(^3P)$ from $O(^1D)$ relaxation, enabling us to evaluate the $O(^1D)/O(^3P)$ ratio. With a total $O(^1D) + O(^3P)$ yield of 2.0, this ratio then gives absolute yields for each state.

Figures 2 and 3 show the results of this determination. The initial jump represents prompt $O(^3P)$, as before, and Figure 2 shows that for O_2 photodissociation, the magnitude of the subsequent rise is approximately the same, indicating that equal amounts of $O(^1D)$ and $O(^3P)$ are produced. In the O_3 data of Figure 3, however, the slower rise is considerably smaller than the initial jump, showing that the $O(^3P)$ yield is larger than that of $O(^1D)$. Amimoto et al.[14] have shown that when $O(^1D)$ interacts with O_3, one $O(^3P)$ is produced for every $O(^1D)$ consumed, but it seems unlikely that the process is

$$O(^1D) + O_3 \rightarrow O(^3P) + O_3. \qquad (5)$$

Instead, we believe that two other channels are involved:

$$O(^1D) + O_3 \rightarrow O_2 + O_2 \qquad \Phi_1 \qquad (6)$$

$$\rightarrow 2O(^3P) + O_2 \qquad \Phi_2 \qquad (7)$$

where $\Phi_1 = \Phi_2$. This results in an effective unity quantum yield for $O(^3P)$ production. However, we find that the total $O(^3P)$ yield from O_3 is slightly decreased by the presence of N_2, indicating that Φ_2 is slightly larger than Φ. At the O_3 pressure used in Figure 3, the $O(^1D) \rightarrow O(^3P)$ conversion requires 40 μs, consistent with the data.

The ratio of prompt $O(^3P)$ to $O(^3P)$ produced from $O(^1D)$ is approximately 70:30 from Figure 3 which we adjust to 75:25 on the basis of the above discussion. Because the total $O(^3P)$ yield is two, we conclude that the yield for prompt $O(^3P)$ is 1.5 and that the yield for $O(^1D)$ is 0.5. Since it is obviously not possible to have a photodissociative process in O_3 that yields

two atoms, such a yield can be explained only by a process that generates three atoms, i.e., complete fragmentation of O_3. If this takes place, then the yield for that process is 0.5, making the total O_3 photodestruction yield unity and making explicable the observation that the atom quantum yield is two. Thus, the data are explained by hypothesizing two channels, occurring with similar probabilities,

$$O_3 \rightarrow O(^3P) + O(^3P) + O(^3P) \qquad \Phi = 0.5 \qquad (8)$$

$$\rightarrow O(^1D) + O_2(\text{singlet}) \qquad \Phi = 0.5 \qquad (9)$$

Interestingly, this interpretation leaves no room for any other processes; in particular, no excited triplet O_2 can be formed. However, the fragmentation process is best thought of in two steps in which a highly excited triplet O_2 molecule is produced, which then dissociates or predissociates.

The identity of the excited singlet O_2 is very important for understanding the overall mechanism, and the candidates are $a^1\Delta_g$, $b^1\Sigma_g^+$, and $c^1\Sigma_u^-$. We were not able to look for the emission from $a^1\Delta_g$ in the ir, and emission from the $c^1\Sigma_u^-$ state is difficult to detect because of its long radiative lifetime, estimated to be about 30 s, and its expected rapid quenching by O_3. However, the $b^1\Sigma_g^+$ state is simple to detect, by b-X emission in the near ir, and we were able to show that it is the principal partner of $O(^1D)$.

Figure 4 shows a trace of the signal detected at 7700 Å (the b-X 1-1 band position) from O_3, characterized by the fact that the emission begins promptly during the laser pulse, which is consistent with $O_2(b)$ being a primary fragment. To be certain that there is no ultra-fast collisional process giving the apparent instantaneous production in Figure 4, we added a small amount of O_2 to the cell, which has the effect of generating $O(^1D)$. This $O(^1D)$ can then react with O_2 to give $O_2(b)$ by energy transfer,

$$O(^1D) + O_2 \rightarrow O(^3P) + O_2(b). \qquad (10)$$

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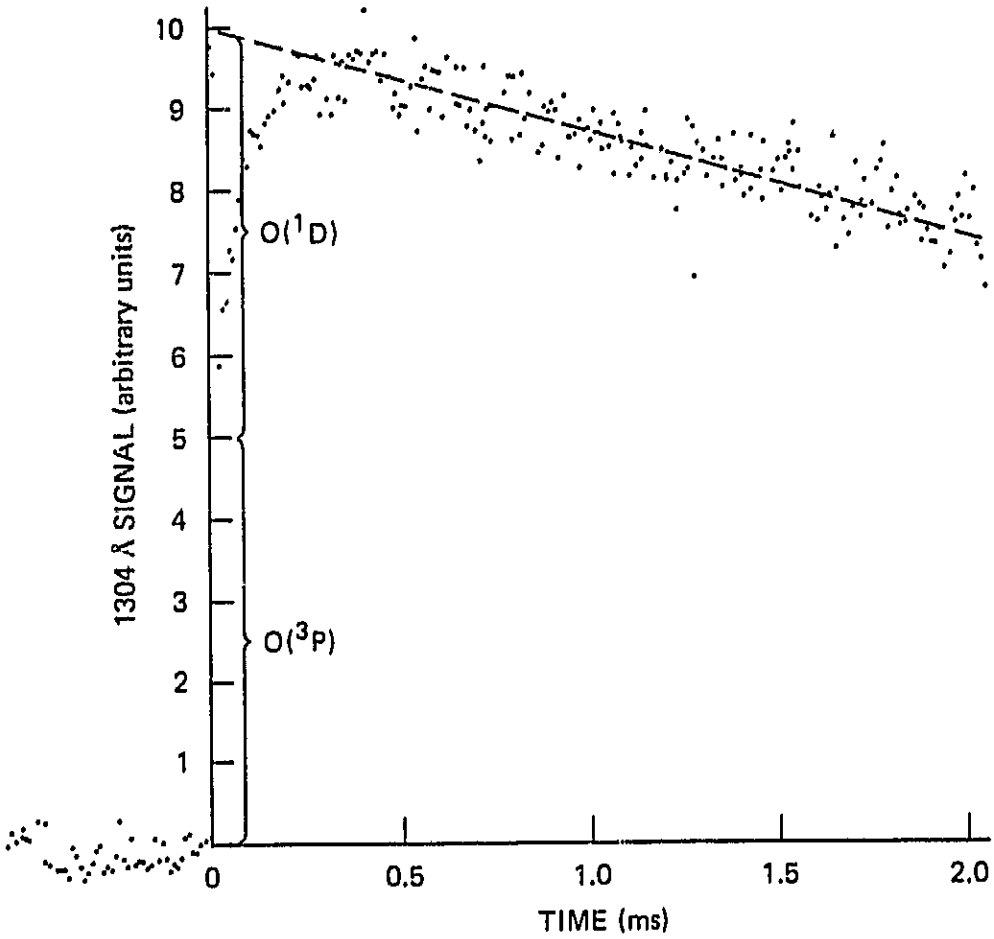

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FIGURE 2 PROMPT AND SLOW $O(^3P)$ YIELDS FROM 1576 Å O_2 PHOTODISSOCIATION
$[O_2]$ = 10 mtorr, [He] = 30 torr, 2000 laser shots

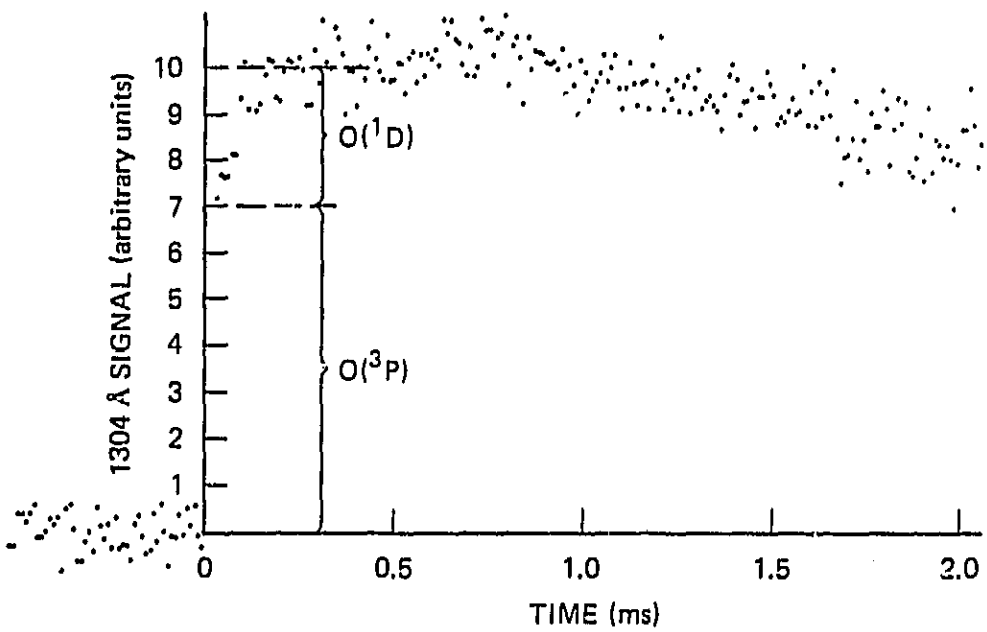

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FIGURE 3 PROMPT AND SLOW $O(^3P)$ YIELDS FROM 1576 Å O_3 PHOTODISSOCIATION
$[O_3]$ = 3 mtorr, [He] = 18 torr, 2000 laser shots

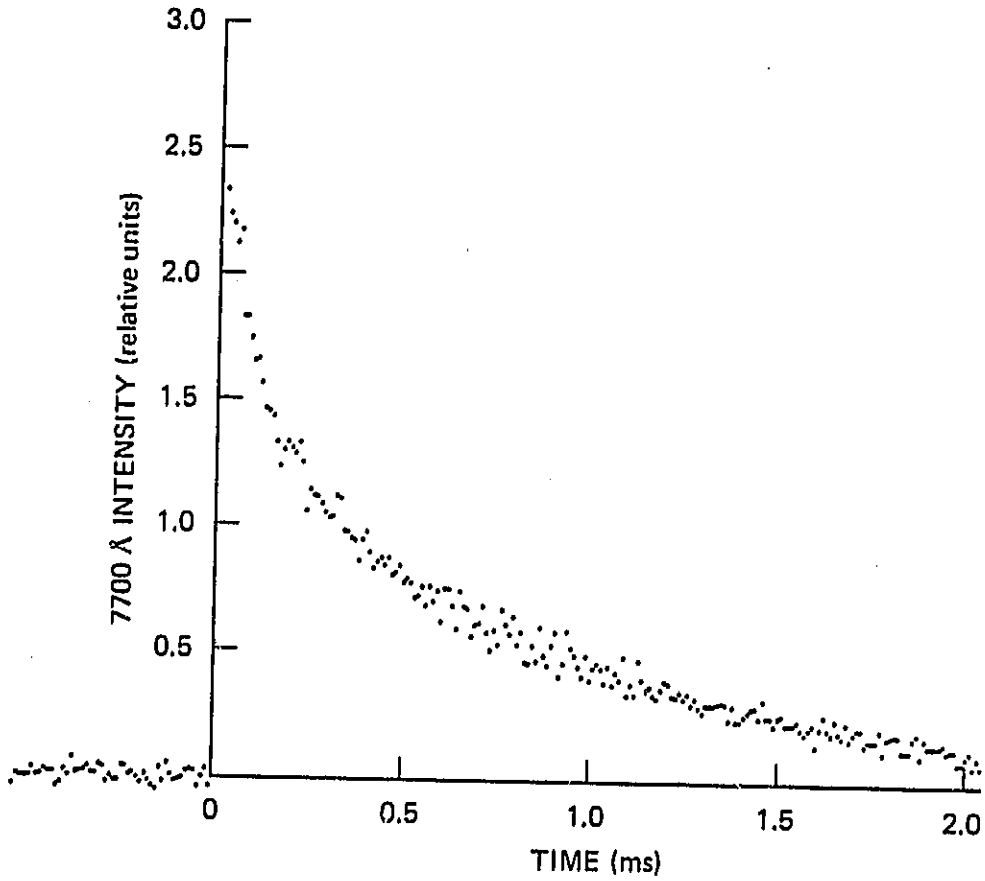

FIGURE 4 O_2 (b-X) 1-1 BAND EMISSION (7700 Å) FROM 1576 Å O_3 PHOTODISSOCIATION
$[O_3]$ = 3 mtorr, [He] = 18 torr, 10,000 laser shots(normalized intensity scale).

The rate at which the signal from this reaction builds up is determined by the $O(^1D)$ removal rate, which is governed not by O_2 but by O_3. Because the rate coefficient[15] for the $O(^1D)-O_3$ interaction is 2.4×10^{-10} cm^3 $molec^{-1}$ s^{-1}, close to collision frequency, a demonstration that the buildup can be discerned will substantiate that the data of Figure 4 indicate that $O_2(b)$ production from O_3 is a primary process.

Figures 5 and 6 show two traces of $O_2(b)$ temporal behavior. Figure 5 shows the effect of adding 4 mtorr of O_2 to the 3 mtorr O_3 used for the run in Figure 4. It is clear that there is now a buildup of signal, and we can therefore be certain that the instantaneous appearance of $O_2(b)$ in Figure 4 is truly a primary process. This is also a demonstration that the $O_2(b-X)$ emission in Figure 4 is not a consequence of a small amount of impurity O_2 in the O_3. Figure 6 shows the temporal behaviour of $O_2(b)$ produced from O_2 alone; the build-up is slower in the absence of O_3, as $O(^1D)$ is removed more slowly by O_2 than by O_3.[15]

Comparing the $O_2(b-X)$ signal in Figure 4 with that in the O_2-O_3 experiment of Figure 5 makes it possible to calculate the quantum yield for $O_2(b,v=1)$ production from O_3, since it is known that the yield from O_2 is 0.3. To perform this calculation, we need to know what fraction of the $O(^1D)$ is quenched by O_2 (0.18 from the known rate coefficients[15]), the 1576 Å cross section ratio for O_2 and O_3 (4.3), and the ratio of signals from O_3 in Figure 4 and from O_2-O_3 in Figure 5. These are t = 0 signals, which requires a short extrapolation for the O_2-O_3 case; the ratio $I(O_2+O_3)/I(O_3)$ is 4.2. With these figures, we determine that the yield for production of $O_2(b^1\Sigma_g^+)$ in the v=1 level from 1576 Å O_3 photodissociation is 0.09.

We have used a series of filters to measure the emissions from O_3, sampling at the positions not only of the 1-1 b-X band but also of the 0-0, 2-2, and 3-3 bands. We find that in each case there is no buildup of emission intensity, indicating primary production, and that the intensities are comparable. Figures 7 and 8 show $O_2(b-X)$ 2-2 band results at 7800 Å. By determination of filter factors, phototube sensitivities, and using published Franck-Condon factors, we have determined absolute nascent populations of each level. These are presented in Table 2, and show roughly comparable values for each level with a slow increase with increasing level. Given that the $O(^1D)$ yield is 0.5, we should not exceed this value for the $O_2(b)$ quantum yield;

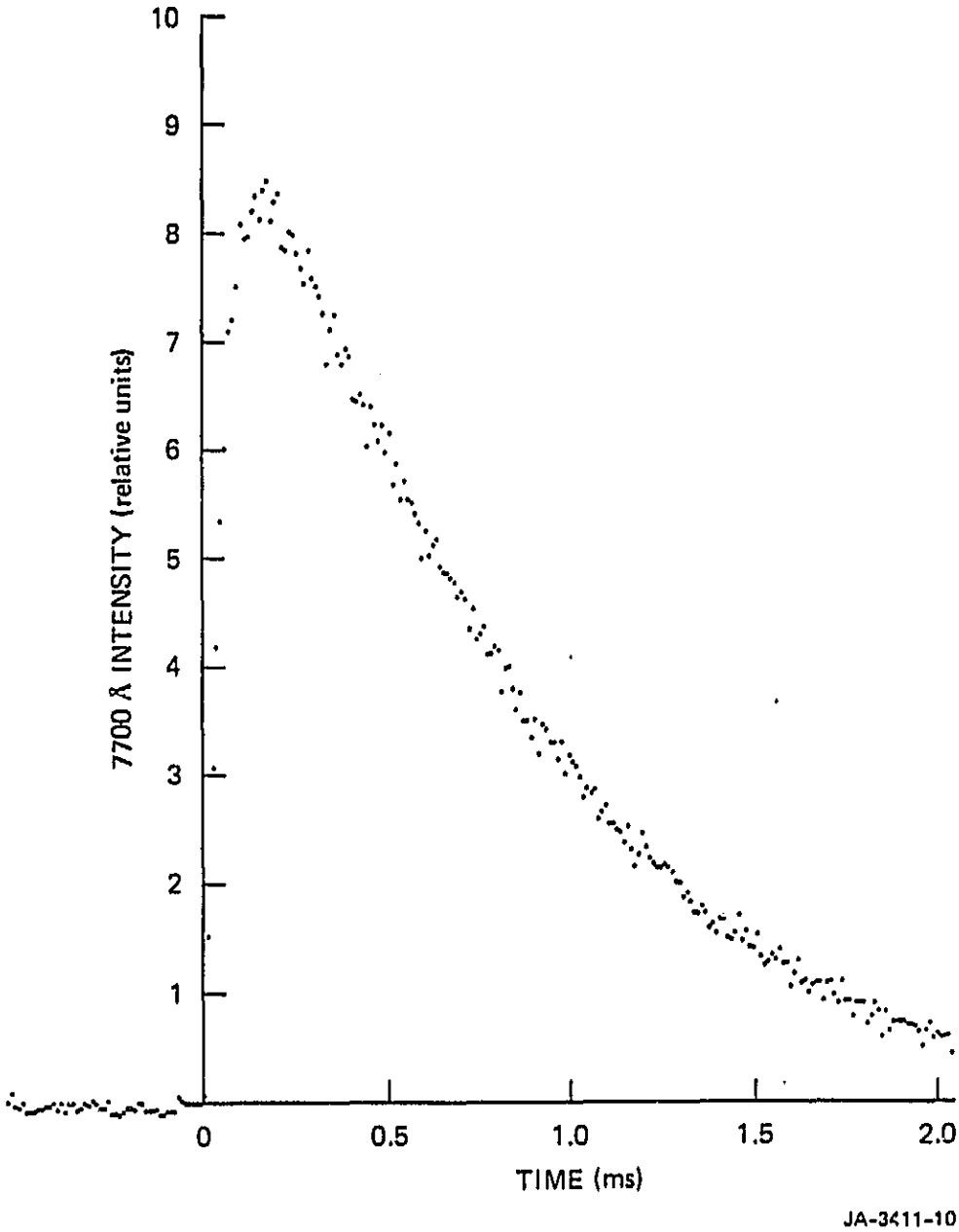

FIGURE 5 O_2 (b-X) 1-1 BAND EMISSION (7700 Å) FROM 1576 Å PHOTODISSOCIATION OF $O_2 + O_3$
$[O_2]$ = 4 mtorr, $[O_3]$ = 3 mtorr, 2200 laser shots (normalized intensity scale).

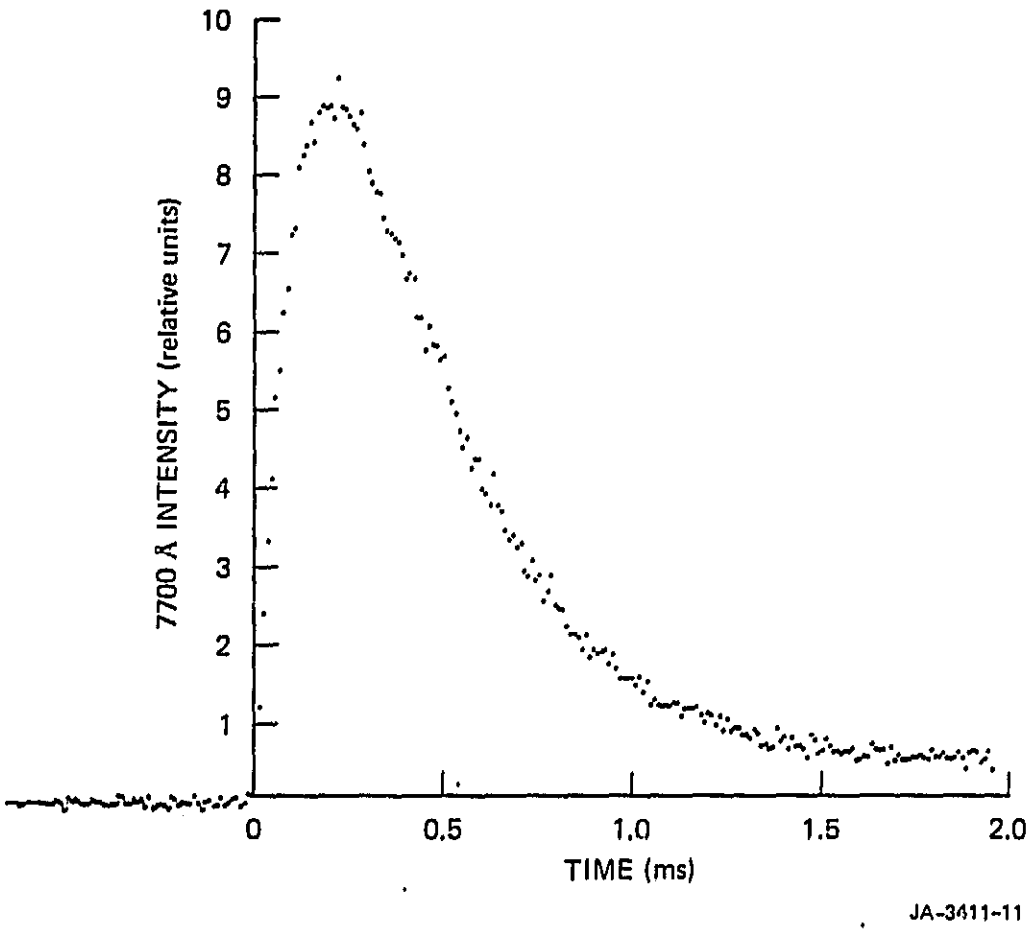

FIGURE 6 O_2 (b-X) 1-1 BAND EMISSION (7700 Å) FROM 1576 Å PHOTODISSOCIATION OF O_2
$[O_2]$ = 4 mtorr, [He] = 10 torr, 2000 laser shots

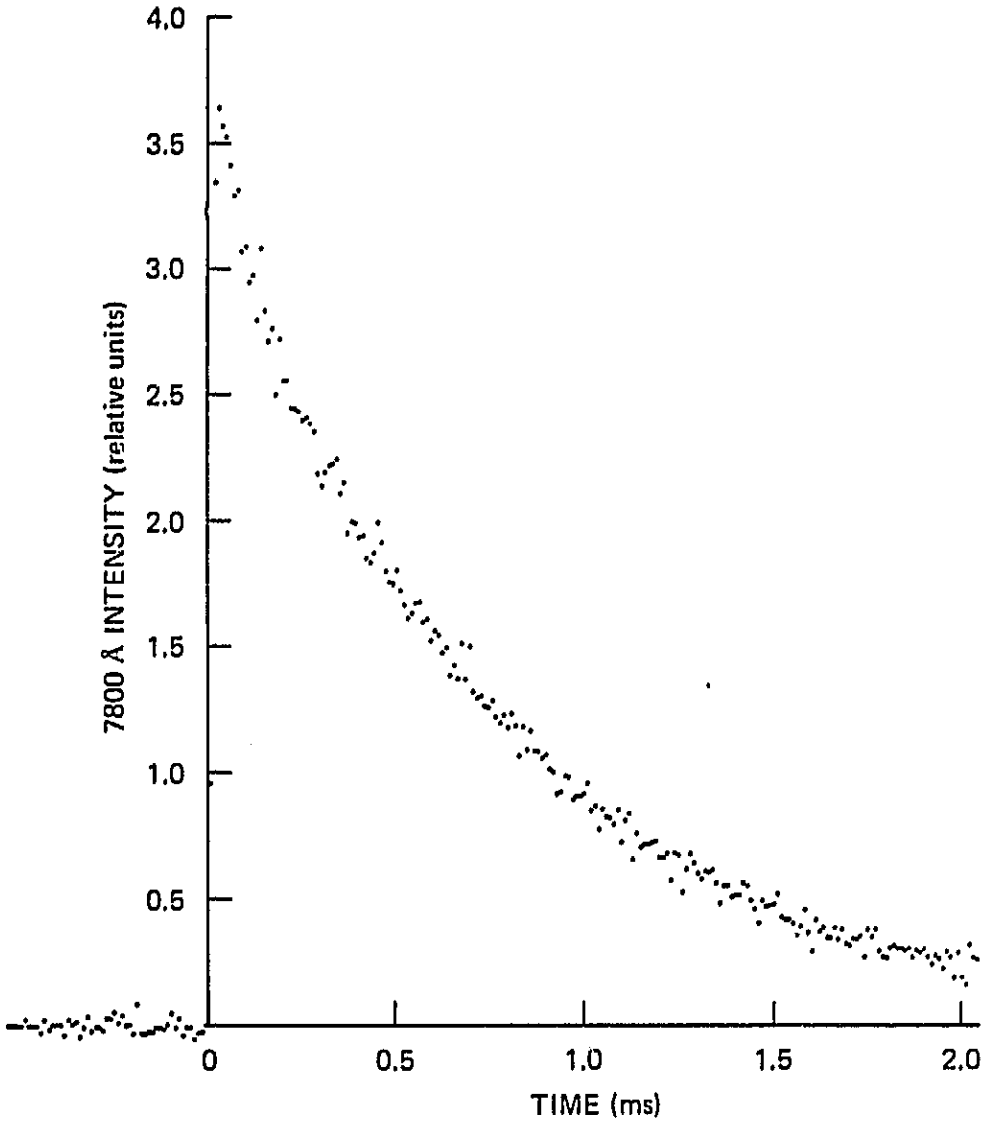

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FIGURE 7 O_2 (b-X) 2-2 BAND EMISSION (7800 Å) FROM 1576 Å O_3 PHOTODISSOCIATION $[O_3]$ = 3 mtorr, [He] = 18 torr, 10,000 laser shots (normalized intensity scale).

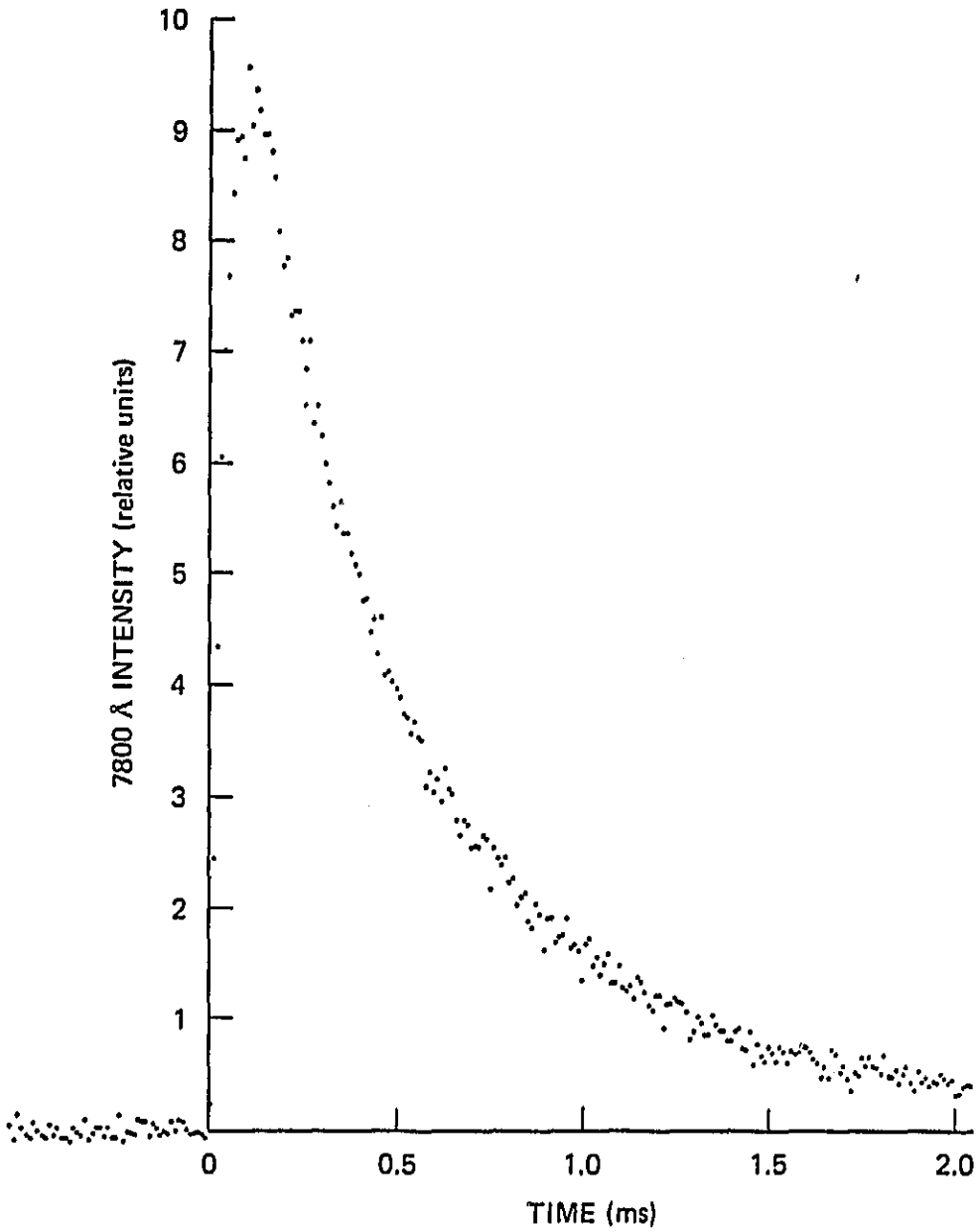

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FIGURE 8 O_2 (b-X) 2-2 BAND EMISSION (7800 Å) FROM 1576 Å PHOTODISSOCIATION OF $O_2 + O_3$ $[O_2]$ = 4 mtorr, $[O_3]$ = 3 mtorr, [He] = 18 torr, 2200 laser shots (normalized intensity scale).

Table 2

Level	Yield
0	0.11
1	0.09
2	0.12
3	0.15

the sum of the values in Table 2 is 0.47.

A frustrating conclusion of these experiments is that, although we have been able to perform a self-consistent analysis of the O_3 photodissociation products, we find ourselves unable to answer the initial question: Do O_2 excited states, formed from O_3 photodissociation, react with N_2 to produce N_2O? This uncertainty arises because we have accounted for all the products, but find that at 1576 Å none of the relevant O_2 states (those between 4 and 5 eV), are formed. This is perhaps to forceful a statement, since 10% yields could be hidden in the data, but from the indirect evidence of $O(^3P)$, $O(^1D)$, and $O_2(b)$ yields, there is little room for $O_2(A,A',c)$ production. However, the three-atom fragmentation process is likely to have a much lower yield at longer wavelengths (its threshold is 1997 Å), so that measurements at the ArF laser wavelength, 1930 Å, which is in any case more relevant to stratospheric photoabsorption, may show substantial yields of the O_2 triplet excited states.

These studies constitute the first report of the photolytic production of any electronically excited O_2 state other than $O_2(a^1\Delta_g)$. Furthermore, previously reported laboratory emission studies of vibrationally excited $O_2(b)$ above v=1 have been limited to spectroscopic observations[16,17] because they were performed under conditions ($CO-O_2$ explosions, for example) where kinetic studies were not possible.

The direction of further work on this system is self-evident. Although the emissions that we observe are sufficiently characterizable by their kinetic behavior (buildup and decay times), it is important to produce an actual spectrum. This task is not trivial because the rapid quenching by O_3 and the long radiative lifetime of $O_2(b)$, 12 s, mean that a very small fraction of the molecules radiate. At 3 mtorr O_3, this fraction is less than 10^{-4}.

It would be interesting to learn more about the fragmentation in which three atoms are produced. This would need to be a time-of-flight experiment, and given that one could discriminate against detection of $O(^1D)$, the ground state atoms would show two-thirds having the same velocity and one-third having a different velocity. However, before embarking on such a program, we should extract the maximum amount of information from optical experiments.

One of the most important issues is to study the photodissociation process as a function of wavelength. This is a far easier task with a laser source than with conventional vuv light sources, at least for $O_2(b)$ detection, but we anticipate that, if the experiments are repeated with an ArF laser at 1930 Å, the results may be very revealing. Although the O_3 photoabsorption cross section is smaller by a factor of three at this wavelength than at 1576 Å,[13] the available laser intensity is at least ten times greater, so that to obtain the same signal levels, we ought to be able to work with less O_3 (and thus limit quenching). As mentioned above, it may be possible to access higher O_2 states at 1930 Å because with 1.5 eV less energy available for dissociation, the three fragment process may be suppressed, with the excited triplet molecule surviving. Even if we cannot get information on the excited molecular species in the absence of laser excitation, measurements of $O(^3P)$ yields should be possible at different vuv source wavelengths: 1470, 1236, and 1216 Å. Such data will at least be a guide to unravelling the processes that occur.

N_2O Loss in N_2O-O_3-N_2 2537 Å Irradiation

In the measurements made last year,[8] in which N_2O loss was observed in 2537 Å radiation of O_3-N_2O-N_2 mixtures, analysis was complicated by the need to take reaction mixture samples to another laboratory to be analyzed by electron capture gas chromatography. We were concerned about undesirable handling of the samples as well as the possibility that O_3 might react further at some point, making the results spurious. Thus, the present study was designed around analysis of the reaction mixtures *in situ*, by vuv absorption, with the species to be measured being O_3, N_2O, O_2, and H_2O. The last was included because we suspected that there might be both outgassing and water driven off the walls during photolysis.

The experiment to test the earlier conclusion, that N_2O was destroyed by 2537 Å irradiation of an N_2O-O_3-N_2 mixture, was performed in a straightforward manner. The 40-cm-long absorption cell, containing 100 mtorr O_3, 20 mtorr N_2O, and 250 torr N_2, was irradiated with a mercury discharge lamp for 15 minutes, during which time the O_3 reached an equilibrium value of roughly 15 mtorr. However, this O_3 loss does not represent photon input because O_3 is reformed rapidly by recombination of the $O + O_2$ products. We estimate that,

with the geometry used, the photon absorption rate into the system was well above 10^{17} s^{-1}, for a total of more than 10^{20} photons absorbed during a

Figure 9 shows two N_2O absorption spectra, taken before and after 253[illegible] Å irradiation. Because we wish to look only at the N_2O optical depth, each of these spectra has had a blank spectrum (containing no N_2O) subtracted from it. For the irradiated sample, this had the effect of generating the same amount of O_2 as was made when N_2O was present, so the absorption bands of neither O_2 nor O_3 appear in the final spectrum. There are some differences in the two spectra, particularly at long wavelengths where the system becomes optically thick due to O_2 generation, resulting in inaccuracy in taking differences in optical depth. However, the basic conclusion is that, within reasonable error limits, there is no loss of N_2O during 2537 Å irradiation. If anything, the spectrum taken after irradiation contains slightly more N_2O than the one taken before, but the difference is probably not significant.

Figure 10 shows the same sort of data taken with argon substituted for nitrogen. Again, there is little difference between the two spectra, with slightly more N_2O being indicated after irradiation. Because in this case N_2O generation is not possible, we conclude that these differences represent the precision of the analysis system. It therefore appears that, when N_2O is measured <u>in situ</u> under these conditions, there is no evidence for its photodestruction and that the earlier conclusions are not confirmed.

N_2O Production in O_3-N_2 Photolysis at 1576 Å

After completion of this phase of the work, we returned to the initial problem, which was to ascertain whether the high-lying states of O_2 could produce N_2O upon reaction with N_2. It was presumed that O_3 photodissociation at 1576 Å would provide a good source of these states, although it is evident from Table 1 that the thresholds lie at much longer wavelengths. As described earlier, it now appears that the O_3 photoproducts do not include the relevant O_2 states, although that is not yet a rigorous conclusion.

We had noticed that H_2O was generated by outgassing in the closed reaction cell used in the 2537 Å experiments, but because it does not absorb at that wavelength, we did not feel that its presence was an issue. This is

Figure 9

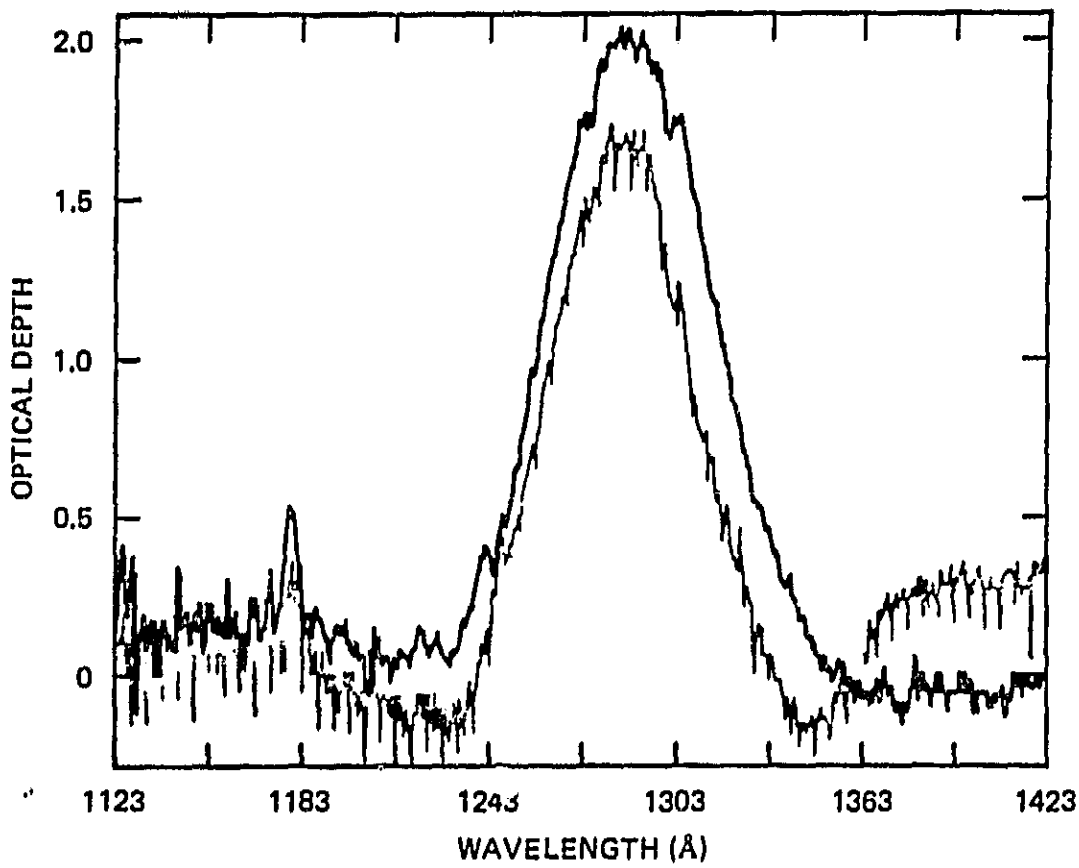

FIGURE 9 EFFECT OF 15 MINUTE 2537 Å IRRADIATION OF N_2O-O_3-N_2 MIXTURE ON $[N_2O]$
$[N_2O]_o$ = 20 mtorr, $[O_3]_o$ = 100 mtorr, $[N_2]$ = 250 torr
Light Line - Before Irradiation
Dark Line - After Irradiation

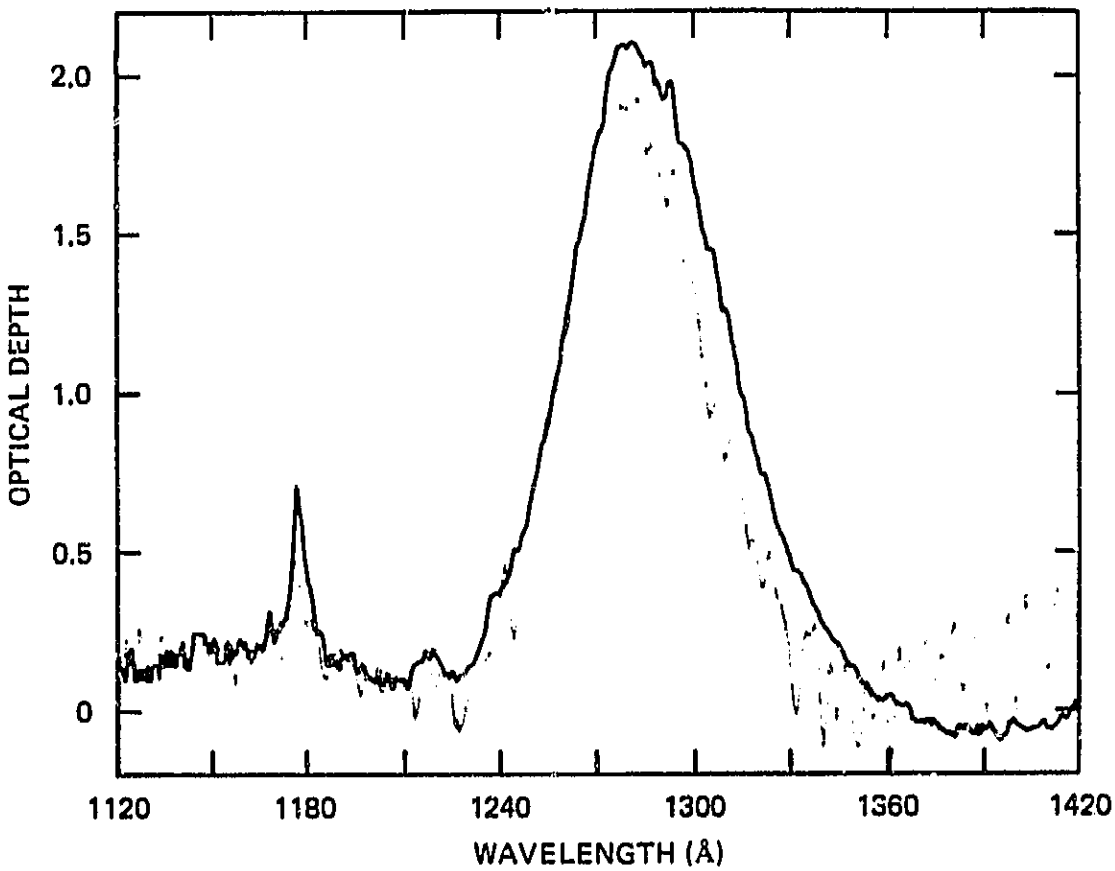

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FIGURE 10 EFFECT OF 15 MINUTE 2537 Å IRRADIATION OF N_2O-O_3-Ar MIXTURE ON $[N_2O]$
$[N_2O]_o$ = 20 mtorr, $[O_3]_o$ = 100 mtorr, [Ar] = 250 torr
Light Line - Before irradiation
Dark Line - After irradiation

not true at 1576 Å, however, so in setting up the laser experiment, we equipped the smaller cell with a trap, above the laser beam path, which effectively removed H_2O at dry ice temperatures and, when operated with liquid nitrogen, removed N_2O as well. With water removed, we could conduct the desired study, which consisted of photolyzing O_2-N_2 mixtures, the necessary O_3 rapidly being produced from O-O_2 recombination. In the presence of H_2O, an entirely different study became possible, discussed below, in which we could explore the question of the interaction of OH(v=9) with N_2.

The fact that we have an approximate material balance of states, i.e. that the photodecomposition products are basically accounted for, does not mean that N_2O cannot be produced. Even a 1% yield of an O_2 state that could react efficiently with N_2 could result in considerable N_2O generation. Thus, the experiment was performed with the intention of setting the N_2O detectability limit as low as possible. Figure 11 shows an absorption spectrum of N_2O at a pressure of 6 mtorr. This spectrum was produced by putting O_3, O_2, H_2O, N_2O, and N_2 into the cell, trapping the N_2O and H_2O with liquid N_2, pumping out the O_3, O_2, and N_2, warming the trap to room temperature, then trapping at 196 K with dry ice-acetone. This procedure has the effect of (1) calibrating the absorption peak and showing that it has the magnitude expected, (2) showing that such a procedure results in full recovery of the N_2O added, and (3) determining if there are any interfering absorptions.

The peak absorption cross section[18] in the N_2O 1285 Å band is 2470 cm^{-1} atm^{-1}. For the 14-cm absorption path, an optical depth of 0.27 is therefore expected, and this is close to the value shown in Figure 11. The only additional features seen are the two strong O_2 bands at 1205 and 1243 Å; presumably there is some occlusion of O_2 in the condensing vapor, but it does not interfere with N_2O detection. The amount of O_2 corresponds to a few mtorr.

Figure 12 shows the results of the same procedure conducted with 2-hour irradiation of an O_3-O_2-N_2 mixture to search for evidence of N_2O production. The trap was kept at 77 K to remove any outgassing H_2O and to remove any N_2O as it was formed. The only discernible features are weak O_2 bands. There is no 1285 Å N_2O band, and a reasonable limit of detectability corresponds to an optical depth of 0.02 and a pressure of 0.4 mtorr, or 10^{13} N_2O molecules/cm^3.

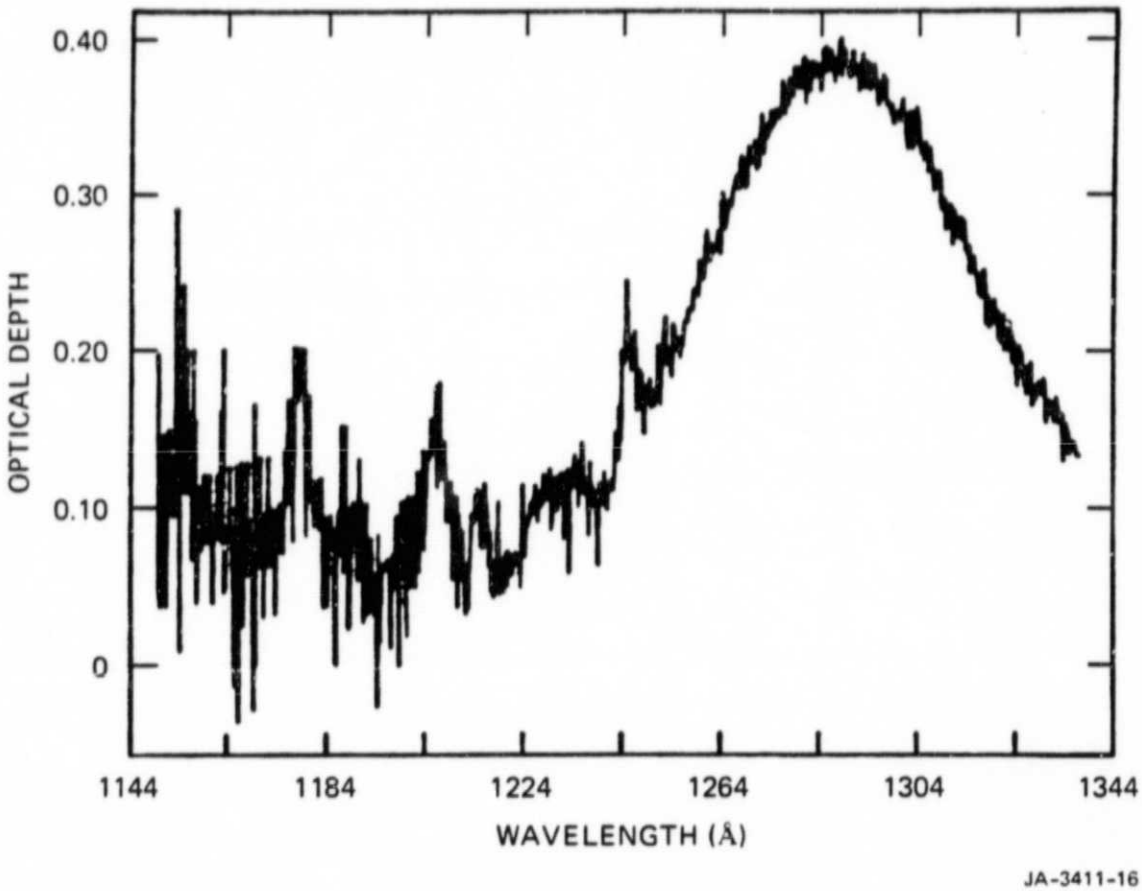

FIGURE 11 N_2O ABSORPTION SPECTRUM
$[N_2O]$ = 6 mtorr

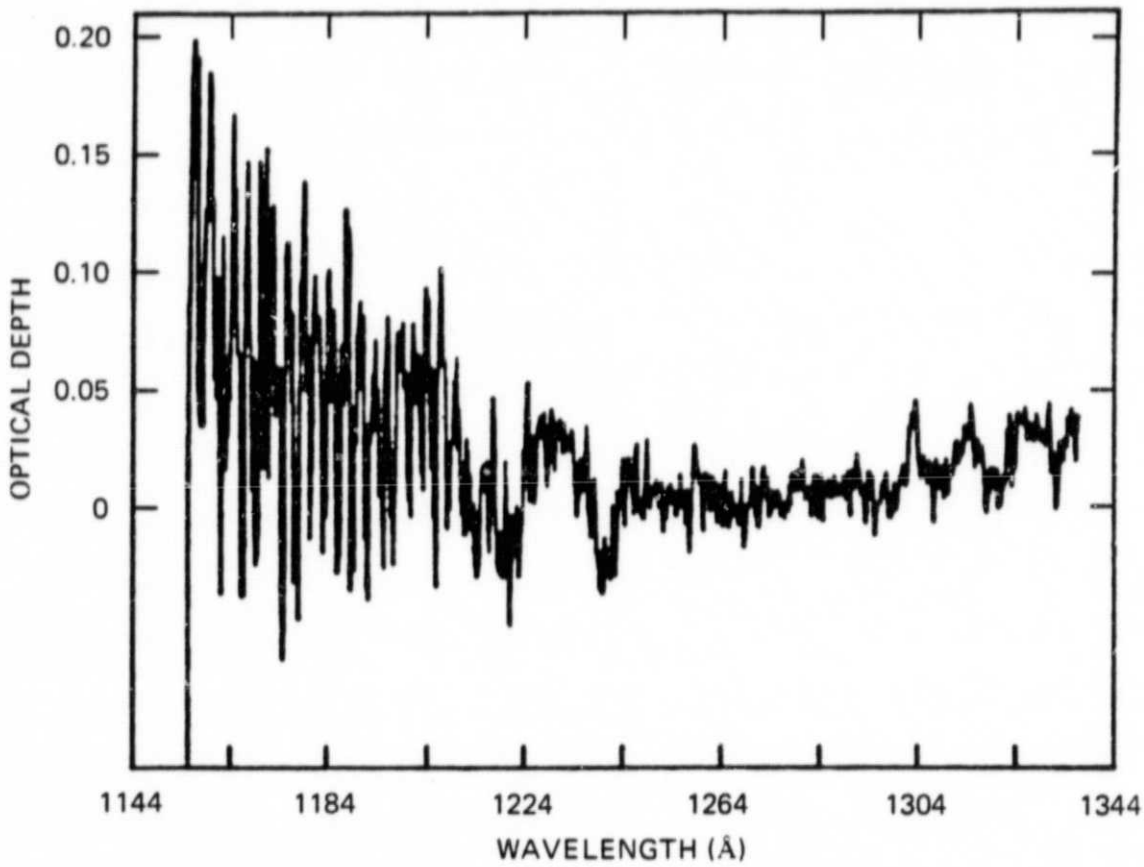

FIGURE 12 ABSORPTION IN N_2O 1285 Å BAND REGION AFTER 120 MINUTES 1576 Å IRRADIATION OF O_2-N_2 MIXTURE

$[O_2]$ = 250 mtorr, $[N_2]$ = 250 torr

To ascertain the significance of this limit, we may calculate the number of O_3 molecules that have been dissociated during the 2-hour irradiation period. We find experimentally that the O_3/O_2 ratio at equilibrium is ~0.15. The photoabsorption cross section ratio favors O_2 by a factor of 4. Half of the incoming 1576 Å photons are absorbed, so we conclude that 2% of the laser photons dissociate O_3. The total laser photon flux is 5×10^{20} hr^{-1}; thus, 2×10^{19} O_3 molecules are dissociated during the 2-hour experiment, resulting in $<10^{16}$ N_2O molecules produced (the cell volume is one liter).

If N_2, the preponderant mixture component by three orders of magnitude, is the principal deactivator of the relevant excited O_2 state, we conclude that less than 0.1% of the O_2^*-N_2 deactivating collisions lead to N_2O production, if the O_2 state in question is produced with a unity quantum yield. We already know that the second issue is moot: the quantum yields of the c, A, or A' states of O_2 are produced, if at all, with yields far less than unity from O_3 at 1576 Å. On the first issue, it is probable, from what is known about $O_2(A)$ and $O_2(c)$ deactivation,[19] that a 3 to 4 order-of-magnitude excess of N_2 over O_2 and O_3 will assure that a large fraction of O_2^* quenching is by N_2. For example, $O_2(A)$ quenching by N_2 has a rate coefficient[20] on the order of 10^{-14} cm^3 $molec^{-1}$ s^{-1}, so that even if that for O_3 were 10^4 times faster, half the quenching would still be due to N_2. In most cases, the O_2 and N_2 rate coefficients are likely to be similar, certainly not differing by as much as the 10^3 pressure ratio of the experiment.

If we say that the yield of the high O_2 states does not exceed 10%, it is reasonable to conclude that the yield of N_2O from $O_2^* + N_2$ is less than 1%. However, this is not a useful conclusion because O_3 photodissociation at 1576 Å is evidently not a good way of accessing these states. It remains to be seen whether dissociation at longer wavelengths, which is in any case more aeronomically interesting, will generate these states of O_2. Judgement on the question of N_2O production from $O_2^* + N_2$ will have to be held in abeyance until such a time.

N_2O Production from OH(v=9) + N_2

Stronger conclusions can be drawn about the OH(v=9)-N_2 interaction. We

find ourselves able to study this reaction because H_2O photodissociation at 1576 Å generates H atoms with a quantum yield close to unity.[21] The fate of these atoms in an O_3-O_2-H_2O-N_2 mixture will be to react with O_3, producing OH(v=9) almost exclusively. Although the relative rates of OH(v=9) quenching by the four components are a matter in some dispute,[22,23] it is expected that N_2 will in fact be the dominant quencher, being in excess of the other components by at least 10^3. At the pressure conditions used, 15% of the photons are absorbed by H_2O, and half of the total laser output is absorbed in the cell. At a flux of 5×10^{20} photons hr^{-1}, the H atom production rate is 4×10^{19} hr^{-1}, which is equal to the production rate of OH(v=9). If this is entirely quenched by N_2 to produce N_2O, the final N_2O concentration would be 1.3 torr.

Figure 13 shows the results of an experiment similar to that described above, except that H_2O was one of the added components and it was not trapped during irradiation. We again seen no evidence for N_2O, with the limit corresponding to an optical depth of 0.02, or 0.4 mtorr. We are thus able to set an upper limit of 3×10^{-4} on the yield of N_2O from the interaction between OH(v=9) and N_2, and this time there is no ambiguity about the production rate of the N_2 collision partner.

The thermodynamics of this system has been investigated from the point of view of the reverse reaction

$$N_2O + H \rightarrow OH + N_2 \qquad (11)$$

which is known to have an activation energy of 15 kcal/mole.[24] The exothermicity of the forward reaction, with OH(v=9), is 12.6 kcal/ mole, thus falling slightly short of the required energy. This is not a significant issue when considering a reaction that must in any case have a low yield. However, it is not clear how efficiently vibrational energy can be used in surmounting the barrier; sometimes there is equivalence of vibrational and translational energy, and other times vibrational energy is relatively inefficient. For low yield processes it is best to rely on experimental determinations on the system in question.

To show how our results impact atmospheric processes, we have calculated the production rate of OH(v=9) as a function of altitude, determined from an H

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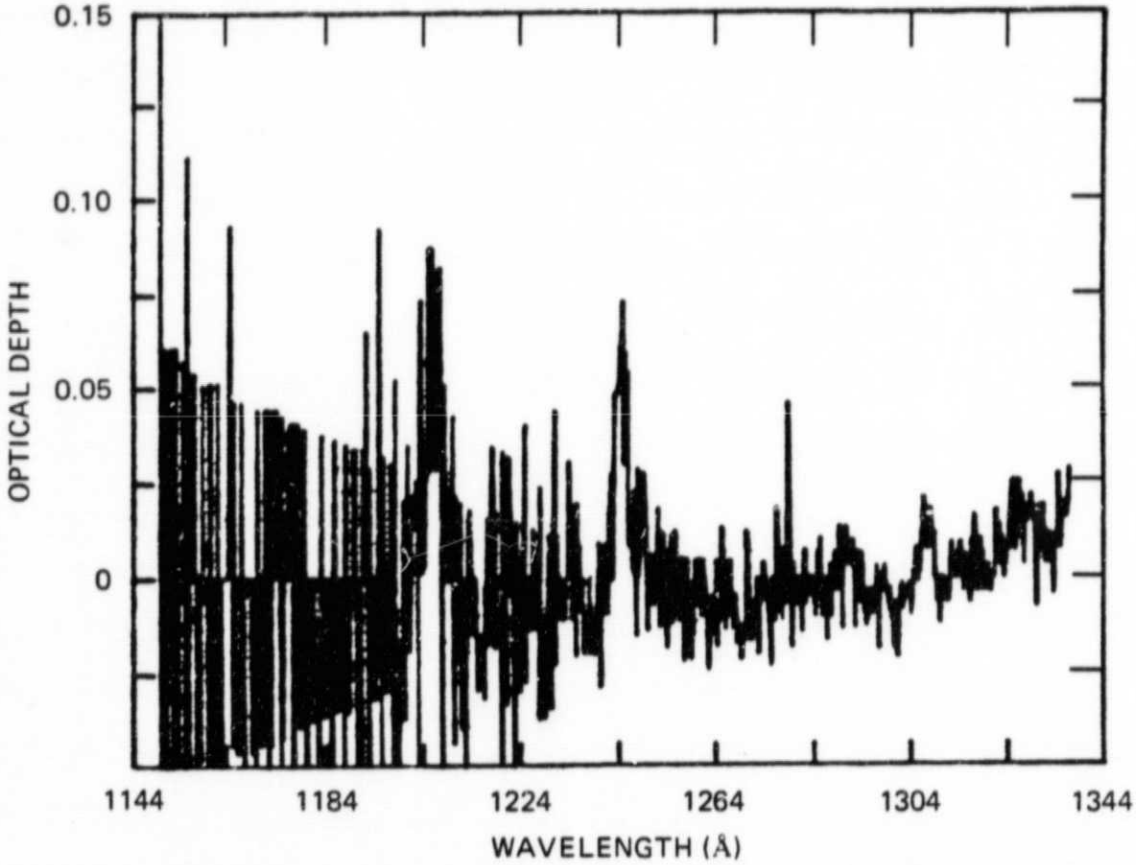

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FIGURE 13 ABSORPTION IN N_2O 1285 Å BAND REGION AFTER 60 MINUTES 1576 Å IRRADIATION OF O_2-H_2O-N_2 MIXTURE
$[O_2]$ = 250 mtorr, $[H_2O]$ = 65 mtorr, $[N_2]$ = 250 torr

and O_3 model given by Nicolet[25] and using as an interaction rate coefficient[26] the value of 2.9×10^{-11} cm^3 $molec^{-1}$ s^{-1}. At the top of the stratosphere, at 50 km, the N_2 density is 3×10^{16} cm^{-3}, and if we take the OH(v=9) + N_2 rate coefficient to be 5×10^{-13} cm^3 $molec^{-1}$ s^{-1}, as given by Streit and Johnston,[27] then all OH(v=9) quenching is by N_2. For our limiting efficiency factor, the N_2O production rate is then 1×10^3 cm^{-3} s^{-1} at that altitude. To put this figure into perspective, we can use the analysis performed by Zipf and Prasad[6] on the $N_2(A^3\Sigma_u^+)$ + O_2 reaction as a source of N_2O, in which they found that a production rate of 100 cm^{-3} s^{-1} at 50 km was of nonnegligible proportions compared with known sources. Thus, a source that is ten times stronger would severely perturb existing models, and since our value is only a limit, it is evident that an order-of-magnitude decrease in the experimental sensitivity for N_2O is needed before the OH(v=9)-N_2 reaction can be ruled out as an N_2O source. Zipf[10] in fact claims to have evidence that some N_2O is produced by this reaction, but the efficiency is not yet available. As an experimental problem, an order-of-magnitude increase in sensitivity should not be difficult to achieve because we can increase photolysis times, increase the H_2O/O_2 ratio, and reconfigure the cell so that analysis can be performed at a higher N_2O optical depth than is generated during irradiation.

PRESENT STATUS OF N_2O SOURCE PROBLEM

This study has demonstrated that there are still a variety of questions to be addressed before the possibility of finding in situ stratospheric N_2O sources is clarified. We have shown that at wavelengths shorter than the Hartley band, an O_2 state higher than $O_2(a)$ is in fact produced, and it is important to continue this line of investigation, as there is reason to believe that even more energetic states will be found at wavelengths around 1900 Å. Whether they can interact with N_2 to make N_2O can only be determined experimentally. The issue of whether vibrationally excited OH can react with N_2 to form N_2O is still open, since even our limiting yield of 3×10^{-4}, if an actual figure, would severely perturb present models. Progress in this area will also involve obtaining improved rate coefficient data on quenching of OH (v=9). The question of the N_2O yield from the $N_2(A) + O_2$ reaction is still not definitively settled, and at present revolves around the question of the $N_2(A)$ energy pooling rate.

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