MEDIUM- AND LONG-WAVELENGTH INFRARED EMISSION FROM A LASER-PRODUCED OXYGEN PLASMA(U) AIR FORCE GEOPHYSICS LAB HANSCOM AFB MA J B LURIE ET AL. 31 DEC 85

UNCLASSIFIED AFGL-TR-8341
Medium- and Long-Wavelength Infrared Emission From a Laser-Produced Oxygen Plasma

JONATHAN B. LURIE
JAMES C. BAIRD

31 December 1985

Approved for public release; distribution unlimited.
This technical report has been reviewed and is approved for publication.

LAILA DZELZKLNS
IHWC Scientist

W. BLUMBERG, Acting Chief
Infrared Dynamics Branch

FOR THE COMMANDER

RANDALL E. MURPHY, Director
Infrared Technology Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify AFGL/DAA, Hanscom AFB, MA 01731. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.
Medium- and Long-Wavelength (cont.)

Experiments on a laser-produced oxygen plasma were observed by medium-wavelength (MWIR) and long-wavelength (LWIR) infrared emission. This research is part of a continuing series of LINES (Laser Induced Nuclear Excitation) experiments starting in the short-wavelength infrared (SWIR) and extended to longer wavelengths to continue studies on highly excited oxygen atom states produced by three-body recombination in a highly ionized, laser-produced plasma. The first observations of emission in the 5- to 8-µ region from a recombining oxygen plasma are reported, including the first experimental observation of the 3050 Å (3.05 µm) oxygen atom emission. The observed line widths of these MWIR emissions are discussed using a Stark line shape analysis.

<table>
<thead>
<tr>
<th>FIELD/GR</th>
<th>SUB-GR</th>
<th>infrared emission</th>
<th>Stark effect</th>
<th>Laser plasma</th>
<th>Oxygen atom</th>
<th>Lineshape</th>
</tr>
</thead>
<tbody>
<tr>
<td>04</td>
<td>01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ABSTRACT:**
Experiments on a laser-produced oxygen plasma were observed by medium-wavelength (MWIR) and long-wavelength (LWIR) infrared emission. This research is part of a continuing series of LINES (Laser Induced Nuclear Excitation) experiments starting in the short-wavelength infrared (SWIR) and extended to longer wavelengths to continue studies on highly excited oxygen atom states produced by three-body recombination in a highly ionized, laser-produced plasma. The first observations of emission in the 5- to 8-µ region from a recombining oxygen plasma are reported, including the first experimental observation of the 3050 Å (3.05 µm) oxygen atom emission. The observed line widths of these MWIR emissions are discussed using a Stark line shape analysis.
Acknowledgements

The authors gratefully acknowledge the support of the Air Force Office of Scientific Research and the Defense Nuclear Agency.
Contents

1. INTRODUCTION 1
2. EXPERIMENTAL 2
3. RESULTS 3
4. DISCUSSION 4
   4.1 Linewidth 6
   4.2 Stark Lineshape Theory 8

REFERENCES 23

Illustrations

1. Experimental Apparatus for Infrared Emission Studies 13
2. 5.5μ - 8μ Emission Spectrum of a 150 Torr Laser-Produced Oxygen Plasma With a 10 μs Delay 14
3. 7.43μ Emission Linewidth vs Total Oxygen Pressure at τD = 6μs 15
4. 7.43μ Emission Linewidth vs τD at 176 Torr Oxygen Pressure 16
5. 7.43μ Emission Line Area vs Total Oxygen Pressure at τD = 6μs 17
6. 7.43μ Emission Line Area vs τD at Total Oxygen Pressure of 176 Torr 18
7. Simulated Emission Spectrum in the 5.5 μ - 8.0 μ Region Using Coulomb Approximation Intensities, 40 cm⁻¹ Widths for the 6g and 6h States and 12 cm⁻¹ Linewidths for the Rest of the Transitions

8. Synthetic Spectrum of 5.5 μ - 8μ Emission Region for a Stark Field Corresponding to 10¹⁴ e's/cm³, a 6g - 5f, 6h - 6g Component Linewidth of 40 cm⁻¹

9. Synthetic Spectrum of 5.5 μ - 8μ Emission Region for a Stark Field Corresponding to 10¹⁵ e's/cm³, a 6g - 5f, 6h - 6g Component Linewidth of 40 cm⁻¹

Tables

1. Infrared Emission Lines Observed in Oxygen From 5.5 μ to 14 μ

2. Emission Lines Predicted to Be Within the Experimental Width of the 7.43 μm Emission Line at τ_D = 6 μs, P_O₂ = 176 Torr
1. INTRODUCTION

Oxygen atom short wavelength infrared (SWIR) transitions observed in previous Laser-Induced Nuclear Simulation (LINUS) studies\(^1\) originate in states which lie more than 6800 cm\(^{-1}\) below the ionization limit at 109837.02 cm\(^{-1}\). These states are produced by collisional deactivation of higher-lying atomic states produced by three-body recombination of O\(^+\)(\(^4\)S\(^0\)) with electrons. For several reasons, spectroscopic observation of these higher-lying atomic states in a high-electron density, high-temperature plasma presents a formidable experimental challenge. Insofar as the plasma may be described by a time dependent temperature of some kind, the atomic state population will decrease as the principal quantum number \(n\) increases for a given orbital and spin angular momentum configuration. Since the energy separation between states decreases as \(n\) increases, collisional deactivation processes will be more efficient for higher-lying states than for lower-lying states. Even without the small separations in energy, higher-\(n\) states might have a larger cross-section for deactivation than lower states, due to the increasingly extended nature of their electronic wave functions. Infrared emission lines between O-atom states where \(n > 4\) are expected to lie at progressively longer wavelengths, occurring in regions where detector technology is less well-developed than for the SWIR. The sum of these considerations has resulted in the lack of observations of any O-atom emission lines at wavelengths longer than 5 \(\mu\) in either plasmas or discharges. Although line positions and oscillator strengths have been calculated for O-atom infrared transitions based on experimentally and theoretically determined energy levels, an experimental comparison with these calculations is a matter of considerable importance for the understanding of the infrared radiation processes which might occur in the disturbed upper atmosphere. We report here the first time-resolved observations of transitions in the MWIR and LWIR in the 5 \(\mu\) - 14 \(\mu\) region from a recombining oxygen plasma. Assignments have been made for the

Received for publication 27 Dec 1985
transitions using experimental and calculated energy levels from the literature. The strongest of the observed emission features occurs at 7.43 $\mu$m. This feature has been studied as a function of background gas pressure and delay time, $\tau_D$. The longest-wavelength infrared line transitions identified positively are $6h^3\ell_5 - 5g^3\ell_5^0$ and $6g^3\ell_5^0 - 5f^3\ell_5^f$ calculated to be at 7.450 $\mu$m and 7.426 $\mu$m respectively. The oscillator strengths calculated by Biemont and Grevesse, and Sappenfield employing the Coulomb Approximation (CA) and our own hydrogenic calculations, are considered for a qualitative discussion of the relative intensities of these emission lines. The observed 7.43 $\mu$m emission feature occurs at the calculated position within experimental resolution. The observation of the $6g$ and $6h$ states suggests that lower-lying states which are predicted to give rise to LWIR emission are also populated, although we have not yet observed these lines for technical reasons.

2. EXPERIMENTAL

Figure 1 illustrates the experimental apparatus used for the MWIR emission studies. A Quanta-Ray Nd:YAG laser (model DCR 1A, $\lambda = 1.064 \mu$m, 10 ns FWHM multilongitudinal pulse, 10 Hz repetition rate) was focussed with a 56 mm f.l. biconvex lens into a gas cell containing pressures of 50 to 250 torr $O_2$. The laser was propagated parallel to the monochromator entrance slit. A typical average laser power of 4 W created an estimated intensity of $2 \times 10^{-13}$ W cm$^{-2}$ in the focal region.

The radiation from the laser-produced plasma was collected at $90^\circ$ to the axis of the laser beam and collimated and focused on the spectrometer entrance slit using two 100 mm f.l. ZnSe lenses. In order to block all radiation except the wavelengths of interest from reaching the detector, a Corion Industries filter transmitting the wavelengths 5.3 - 9.0 $\mu$m.
was placed just inside the entrance slit. The Spex 1870 spectrometer (0.5 m f.l.) was fitted with a 150 grooves/mm grating blazed at 6.0 μ. Use of this grating with 3 mm slit widths yielded an overall resolution of 0.04 μ. The detector was a Santa Barbara Research Center (SBRC) HgCdTe photoconductive chip mounted in a side-looking dewar cooled to 77 K, used in conjunction with a SBRC A110 preamplifier providing gain of 80 db. The system time response was 0.5 μs. Signal processing was done with a PAR 162-165 boxcar averager using a 1.5 μs gate. The output of the boxcar was recorded on a strip chart recorder.

The wavelength accuracy of the spectrometer was checked by collecting 1.064 μ laser radiation scattered in 5th and higher orders. An additional check of MWIR line positions was carried out by replacing the MWIR bandpass filter with a germanium window which transmitted wavelengths > 1.8 μ. This made possible the simultaneous viewing of SWIR lines in 2nd order along with the (much weaker) MWIR lines. The spectrum was calibrated using the line at 5.97 μ and the 7th order of the 1.0642 μ laser radiation with the 7.45 μ line. LWIR scans were carried out using a 75 grooves/mm grating blazed at 10 μ and a LWIR pass filter. The optical path was flushed with dry nitrogen or helium when spectra are taken in regions where water absorption is considered a problem. A search for emission lines using pure nitrogen gas in the same spectral region and under the same experimental conditions showed only continuum radiation. This negative result helps to confirm the origin of the oxygen plasma emission features as due to oxygen atoms and not artifacts of the gas handling system.

3. RESULTS

Figure 2 illustrates the 5.5 μ - 8 μ emission spectrum of a 150 torr laser-produced oxygen plasma with a 10 μs delay, uncorrected for the spectral response of the system, with 0.04 μ resolution. In spite of the relatively slow time response of the detector, the setting of the 1.5 μs boxcar gate at 10 μs after the laser pulse proved to be sufficient to gate out th
early-time continuum emission. All observed lines originate in the O-atom levels with \( n = 4,5,6 \). The plasma temperature was estimated using the relative populations calculated from the intensity ratio of the 6.62 \( \mu \) and 5.97 \( \mu \) lines and found to be 4,000 \( \pm \) 1,000 K. This estimate of a "temperature" is the only one available to us from our limited data. No line emission was detected above 7.45 \( \mu \). Table I lists the observed infrared emissions along with observed linewidths, \( \Sigma gf \) factors and line assignments.

Measurements were made on the 7.43 \( \mu \) emission as a function of delay after the plasma initiation and as a function of pressure. The linewidth (full width at half maximum, FWHM) obeys the following empirical relationship:

\[
\Gamma(t,P) = 0.177P(\text{torr}) - 3.31\tau_D(\mu\text{s}) + 36.20 \ \text{cm}^{-1}
\]

with a standard deviation \( \sigma = 1.39 \ \text{cm}^{-1} \), where \( \Gamma(t,P) \) is the linewidth in cm\(^{-1}\), \( P \) is the pressure in torr, and \( \tau_D \) is the observation delay time in \( \mu \)s, and where 50. \( < P(\text{torr}) < 200 \), \( 4 < \tau_D(\mu\text{s}) < 20 \). The linewidth data as a function of pressure and delay time are summarized in Fig. 3 and Fig. 4 for the 7.43 \( \mu \) transition.

1. DISCUSSION

These results constitute the first MWIR observations of line emission in a recombining oxygen plasma and the first observation of the \( 6h^35H - 5g^35G^0 \) emission. Several general conclusions may be drawn from the experimental observations:

1. The observed lines may be assigned exclusively to transitions between high-lying O-atom states. No emission attributable to \( O_2 \) or ionic oxygen is observed. Infrared emission between vibrational levels of ground states \( O_2 \) is electric dipole-forbidden. The plasma temperature is apparently sufficiently low so that very high-lying states of \( O^+ \) which might give rise to MWIR emission are not populated at our observation times. The ozone emission with origin at 9.5 \( \mu \) is absent. Emission is not observed from O-atom states with an \( O^+ \)
(2D°) core configuration.

2. The positions of the lines at 5.97 \( \mu \), 6.61 \( \mu \), 6.84 \( \mu \), and 7.43 \( \mu \) correspond to calculated values to well within experimental resolution. The 5.74 \( \mu \) line center is slightly displaced from the calculated value of the 5d\(^{5}D^{0} \rightarrow 5p\(^{5}P\) transition (5.68 \( \mu \)). The line center position is not reproducible from spectrum to spectrum because of poor signal-to-noise.

3. All of the observed lines are predicted to be strong by the CA calculations. No lines are observed which have low CA oscillator strengths. In addition, we might expect CA calculations to be even more justified for MWIR lines originating in \( n = 5,6 \) than for SWIR lines originating in \( n = 4 \). Therefore, we believe that CA calculations used in conjunction with tabulated energy levels differentiate accurately between strong and weak MWIR lines.

The preliminary nature of these data precludes addressing accurately the quality of the CA calculations for each of the individually observed lines. However, some qualitative discussion of the results along with some speculation may be offered. The "temperature" calculated from the 6.61 \( \mu /5.97 \mu \) intensity ratio gives a temperature of about 4,000 K. These lines were chosen for the temperature estimation since their upper states are subject to no known perturbations, allowing more reliance on the CA oscillator strengths. However, the np\(^{3}P\) states are known to be perturbed by close-lying levels.\(^2\) The 5p\(^{3}P\) and 5p\(^{5}P\) states are separated in energy by 244 cm\(^{-1}\), with the triplet state at higher energy, and would be expected to contain nearly equal populations under these temperature conditions. Since the 5p\(^{3}P\) state is observed to contain a lower population than the 5p\(^{5}P\) state by a factor of 0.6, we believe the true oscillator strength for the 5p\(^{3}P\) – 5s\(^{3}S\) transition at 6.84 \( \mu \) ought to be lower than the calculated CA oscillator strength. Additional evidence for perturbation of the 5p\(^{3}P\) state is obtained by the lack of observation of the 5d\(^{3}D^{0} \rightarrow 5p\(^{3}P\) transition at 6.49 \( \mu \). This transition (\( \Sigma g f = 13.1 \)) ought to be observed nearly as strongly as the 5d\(^{5}D^{0} \rightarrow 5p\(^{5}P\) transition at 5.68 \( \mu \) in the absence of perturbations, yet is apparently missing. These data suggest that further attention taking account of detailed state-to-state
perturbations should be devoted to the calculation of all infrared oscillator strengths for lines
which either originate or terminate in a np \(^3P\) state.

The broad emission feature centered at 7.43 \(\mu\) is assigned predominantly to the
6g\(^3,5\)G\(^0\) \(-\) 5f\(^3,5\)F and 6h\(^3,5\)H \(-\) 5g\(^3,5\)G\(^0\) transitions. The calculated oscillator strengths for
these transitions are extremely high (\(\Sigma gf = 66.1\) and 127 respectively) and the transitions
are expected to appear quite strongly in spite of the high energy of the 6g\(^3,5\)G\(^0\) and 6h\(^3,5\)H
states. These transitions are expected to be particularly sensitive to Stark broadening
effects, due to the high \(n, l\) values of the states involved, the nearness of perturbing levels
and the large polarizabilities of the states.

The position of the 6h\(^3,5\)H term can be estimated using polarization theory.\(^9\) The
result is 106,788.515 \(\text{cm}^{-1}\) or about 0.6 \(\text{cm}^{-1}\) above the 6g\(^3,5\)G\(^0\) state. We may check this
estimate by computing the position of the 5g\(^3,5\)G\(^0\) term, at 105,445.962 \(\text{cm}^{-1}\) previously
assigned by Saum and Benesch\(^4\). Our estimate is 105,446.259 \(\text{cm}^{-1}\). Using this calculated
value for the term energy of the 6h\(^3,5\)H state the 6h\(^3,5\)H \(-\) 5g\(^3,5\)G\(^0\) transition is predicted
to lie at 7.450 \(\mu\), well within the envelope of the experimentally observed emission feature.

1.1 Linewidth

The range of observed linewidths for the emission lines is from 12 \(\text{cm}^{-1}\) to 51 \(\text{cm}^{-1}\) at a
pressure of 176 torr and a delay time of 6 \(\mu\)s. The emissions at 5.97 \(\mu\) and 6.61 \(\mu\) are
assigned as the single transitions 5p\(^5\)P \(-\) 5s\(^5\)S\(^0\) (17 \(\text{cm}^{-1}\)) and 5p\(^3\)P \(-\) 5s\(^3\)S\(^0\) (15 \(\text{cm}^{-1}\)),
while the emission line at 7.43 \(\mu\) is assigned as an envelope of a number of transitions
dominated by the 6g\(^3,5\)G\(^0\) \(-\) 5f\(^3,5\)F and 6h\(^3,6\)H \(-\) 5g\(^3,5\)G\(^0\) transitions. These widths are
well outside the spectrometer resolution of about 2 to 4 \(\text{cm}^{-1}\). The major contribution to the
linewidth is expected to be due to interactions between the neutral atom and the electron
density of the plasma. Therefore, a study and understanding of linewidths and shapes
should lead to estimates of the electron number density in the plasma. Contributions to the
observed linewidths will be discussed in this section. First, a synopsis of line broadening will be given to establish notation.

4.1.1. HOMOGENEOUS BROADENING

The natural width of a particular transition is given in terms of the oscillator strength and wavelength by \( \Gamma_{ki}(\text{cm}^{-1}) = \frac{|f_{ki}|}{450 \lambda_{ki}^2(\mu)} \), where \(|k>\) represents the upper state and \(|l>\) the lower state of the atom. \( f_{ki} \) represents the emission oscillator strength and is related to the absorption oscillator strength by \( f_{ki} = \frac{g_i}{g_k} f_{ik} \) and to the transition matrix element by \( |<i|r|k>|^2 = 10.97 \lambda_{ki}(\mu) f_{ki} \text{ a.u.} \). The \( g_i \) and \( g_k \) are lower state and upper state degeneracies respectively. The line strength is \( S_{ik}(\text{a.u.}) = 32.92 g_i f_{ik} \lambda(\mu) \) and its relation to the Einstein coefficient is \( A_{ki}(s^{-1}) = 2.03 \times 10^6 S_{ik}/g_k \lambda^3(\mu) \) where \( S_{ik} \) is in atomic units. The intensity in watts/atom-steradian is defined as \( J_{ki} = (3.013 \times 10^{-13} \lambda^4(\mu)|<i|r(\text{a.u.})|k>|^2) \). The sum of all the allowed transitions between the \( 6g^5G_J \) and the \( 5f^5F_J \) states gives \( |f_{ki}| = 4.705 \) yielding a width \( \Gamma = 0.002 \text{ cm}^{-1} \), a lifetime \( \tau_o = 176 \text{ ns} \) and a half-life \( \tau_{1/2} = 122 \text{ ns} \).

We may estimate the cross-section necessary to account for lifetime broadening due to non-radiative processes using estimated properties of a typical plasma system. For velocities corresponding to temperatures of 2500 K to 4500 K, \( n_e = 10^{16} \text{ electrons/cm}^3 \) and a linewidth of 12 cm\(^{-1} \) the cross-section would have to be approximately \( 10^{-13} \text{ cm}^2 \).

4.1.2. INHOMOGENEOUS BROADENING

Within the observed line profile of the 7.43 \( \mu \) emission there are a number of possible transitions so that we might consider the emission profile as an electron broadened composite of these. Table II lists these transitions. Figure 7 shows a simulation of the lines from 5.5 \( \mu \) to 8.0 \( \mu \) using CA intensities, an instrument resolution of 4 cm\(^{-1} \), a linewidth of 12 cm\(^{-1} \) for all lines except the 6h-5g and 6g-5f transitions which were assigned a 40 cm\(^{-1} \) width.
4.2 Stark Lineshape Theory

In order to gain further understanding of the broadness of the 7.45 μ feature, we have synthetically constructed an emission profile based on computed oscillator strengths and a simple non-degenerate Stark broadening theory. The matrix elements computed in this theory may be used later in a more extensive theory of line broadening. We assume that the emitting atom experiences an average electric field which is computed using the electron density as a parameter. For simplicity we ignore the Holtsmark distribution function. This average field splits the J-sublevels of a given term to second order in the Stark effect.

The Stark shift \( \Delta E_{nJLS} \) is given in second order by

\[
\Delta E_{nJLS} = \sum_{n'J'L'} \frac{|<n'J'L'S|R(1)|nJLS>|^2}{E^{(0)}_{n'J'L'S} - E^{(0)}_{nJLS}}
\]

where a sum over spatial orientation has already been performed and a sum over 17 terms for each multiplicity has been taken. The matrix elements,

\[
|<n'J'L'S|R(1)|nJLS>|^2 = ((2J + 1)(2J' + 1)(2L + 1)(2L' + 1))
\]

\[
x|<(n'L')||R(1)||nL>|^2 \left( \begin{array}{c} S J' L' \\ 1 L J \end{array} \right) \left( \begin{array}{c} L' 1 L \\ 0 0 0 \end{array} \right)^2
\]

where \( <(n'L')||R(1)||nL> \) represents the integration over the radial wave function of the atom and the usual notation for 3j and 6j symbols is used. These matrix elements are calculated using hydrogenic wave functions and agree reasonably with the CA results. The width, \( \Gamma \), and shift, \( \Delta \), of each J-component in each term is assumed to be due to electron collision processes. We may scale the temperature and electron number density dependence of this width using
\[ \Gamma = (1 + 1.75a(n_e)(1 - 0.75R(n_e))) \Gamma_0 \]
\[ \Delta = \frac{\Delta_0 \Gamma_0}{\Gamma} + 2.0a(n_e)(1 - 0.75R(n_e))) \Gamma_0 \]

where \(a(n_e)\) = the quasi static ion broadening parameter, \(R(n_e)\) = the Debye shielding parameter, and where \(a\) scales as \(n_e^{1/4}\) and \(\Delta\) and \(\Gamma\) scale as \(n_e\). Alternatively, a width parameter set by the observed width of a single, isolated transition may be introduced. The energies of the perturbing levels are taken from Bashkin, Saum and Benesch, Erickson and Isberg, Isberg and Russell-Saunders coupling is assumed. It should be noted that the 6g\(^{3}G^0\) state is only 0.6 cm\(^{-1}\) below the 6h\(^{3,5}H\) level and 2.8 cm\(^{-1}\) above 6f\(^{3,5}F\). We also assume that the effective electric fields have no preferred direction in space. The second-order Stark effect connects levels by way of dipole matrix elements. These have been calculated using hydrogenic wave functions and the matrix elements compared with previous calculations. The Stark calculation estimates the perturbation of each J-sublevel in a given term and computes the wavelengths and energies for transitions between terms. The relative intensities for each J-component are used to make up the line profile and the line shift comes about from the shift in the center of gravity of the resulting transitions. In this model, the 7.43 \(\mu\) emission feature is composed of the Stark splitting of each of the lines listed in Table II using the electron density as a parameter. Synthetic spectra are composed of Gaussian lineshapes having a width as previously described. An obvious feature of the synthetic spectra is the sensitivity on electric field strength. This is due to the presence of nearby perturbing levels. Results for electron densities of \(10^{14}\) and \(10^{15}\) cm\(^{-3}\) are presented in Figures 8 and 9. Clearly, the line positions of the calculated transitions are strongly influenced by the presence of an electric field. Since we observe no shift of line position from the zero-field predictions we conclude that either the electric field strength at the site of the emitting atoms is negligible, or that there is significant mixing of states so that a degenerate broadening theory should be used. The observed broadness of the 7.43 \(\mu\) feature must be due to a process essentially unrelated to the Stark J-level.
splitting approach used for our spectral simulations.

Lifetime broadening could conceivably account for much of the observed width of the 7.43 \( \mu \) feature. A width of 50 cm\(^{-1}\) corresponds to a lifetime of \( 10^{-13}\) s. This implies the existence of an extremely efficient electron-emitter collision process. The decrease in linewidth with increasing time delay and decreasing pressure are consistent with this suggestion. Since the 6f, 6g and 6h states lie within an extremely narrow (3 cm\(^{-1}\)) energy range, the cross-section for collisional transfer between these states might be expected to be several orders of magnitude greater than gas-kinetic. Although it is difficult to assess the form of the potential which might be responsible for such rapid collisional state scrambling, it might prove significant that the hydrogenic matrix elements \(<6f|r|6g>\) and \(<6g|r|6h>\) are extremely large. In a sense, electron broadening is such a collision process. We are therefore applying a more rigorous lineshape theory to the near degenerate state situation found in the upper levels of atomic oxygen.

We have searched for O-atom line emission in the 8 \( \mu \) - 12 \( \mu \) region, with negative results. The CA oscillator strengths predict transitions in the 10.4 \( \mu \) and 11.7 \( \mu \) regions with oscillator strengths similar to the transitions observed in this experiment. These transitions originate in the levels 6d\(^5\)D, 5p\(^3\)P and 6d\(^3\)D. Since we observe 6g \(-\) 5f transitions in the MWIR, lower populations of levels giving rise to LWIR transitions should not be the cause of the failure to observe these lines, since the 6g levels lie higher in energy than the other levels. Rough calculations taking into account the lower energy of the LWIR transitions and the increase toward longer wavelengths of 300K background radiation viewed by the detector indicate that an increase in signal-to-noise ratio of at least a factor of 10 might be necessary for the laboratory observation of these LWIR emission lines. Several experimental parameters might be altered in order to obtain this signal-to-noise improvement. These include trading off detector time response for greater quantum
efficiency, increasing the laser repetition rate, lengthening the time width of the boxcar gate and performing slower spectrometer scans.
observed linewidth transition calculated
emission wavelength
\( \lambda (\mu m) \) \( \Gamma (\text{cm}^{-1}) \) transition \( \Sigma g_{ki}^\prime \) \( \lambda (\mu m) \) \( \Sigma g_{ki}^\prime \)
5.74 51 \( 5d^3D^0 \rightarrow 5p^3P \) 5.6813 19.3
5.971 12 \( 4p^3P \rightarrow 3d^3D^0 \) 5.9713 3.9
6.607 17 \( 5p^3P \rightarrow 5d^3S^0 \) 6.6248 9.4
6.841 15 \( 5p^3P \rightarrow 6s^3S^0 \) 6.8567 5.8
7.447 48 \( 6g^3P^0 \rightarrow 5f^3F \) 7.4281 66.1
7.4501 127 \\

Table I. Infrared emission lines observed in oxygen from 5.5 \( \mu m \) to 14 \( \mu m \). Wavelengths and widths were measured at a pressure of 176 torr in pure oxygen with a 6 \( \mu s \) delay.

<table>
<thead>
<tr>
<th>( \lambda (\mu m) )</th>
<th>transition</th>
<th>( \Sigma g_{ki}^\prime )</th>
<th>( J_{ki} )</th>
<th>lower state energy ( \times 10^{-13} ) ( \text{cm}^{-1} )</th>
<th>short wavelength channel</th>
<th>( \lambda (\mu m) )</th>
<th>final state</th>
<th>( \tau (\text{ns}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1419</td>
<td>( 5d^3D^0 \rightarrow 6f^2F )</td>
<td>18.7</td>
<td>440</td>
<td>105,385</td>
<td>1.0679</td>
<td>( 3d^3D^0 )</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>7.1739</td>
<td>( 5p^3P \rightarrow 6s^3S^0 )</td>
<td>6.4</td>
<td>151</td>
<td>103,627</td>
<td>0.5437</td>
<td>( 3p^3P )</td>
<td>328</td>
<td></td>
</tr>
<tr>
<td>7.2664</td>
<td>( 5d^3D^0 \rightarrow 6f^2F )</td>
<td>11.7</td>
<td>280</td>
<td>105,409</td>
<td>1.0754</td>
<td>( 3d^3D^0 )</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>7.426</td>
<td>( 6s^3P^0 \rightarrow 5f^3F )</td>
<td>41.4</td>
<td>1012</td>
<td>105,442</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.450</td>
<td>( 6h^3H \rightarrow 5g^3G^0 )</td>
<td>24.7</td>
<td>604</td>
<td>105,442</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.5052</td>
<td>( 7f^3F \rightarrow 11d^3D^0 )</td>
<td>.057</td>
<td>1.4</td>
<td>107,595</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.5236</td>
<td>( 6f^3F \rightarrow 6d^3D^0 )</td>
<td>.20</td>
<td>4.9</td>
<td>106,785</td>
<td>0.5131</td>
<td>( 3p^3P )</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.550</td>
<td>( 5f^3F \rightarrow 6d^3D^0 )</td>
<td>.614</td>
<td>15.3</td>
<td>105,442</td>
<td>0.0973</td>
<td>ground</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.5683</td>
<td>( 6f^3F \rightarrow 6d^3D^0 )</td>
<td>.40</td>
<td>10</td>
<td>106,785</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.6323</td>
<td>( 5f^3F \rightarrow 6d^3D^0 )</td>
<td>1.2</td>
<td>30.2</td>
<td>105,442</td>
<td>0.4967</td>
<td>( 3p^3P )</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>7.7186</td>
<td>( 5p^3P \rightarrow 6s^3S^0 )</td>
<td>4.0</td>
<td>101</td>
<td>103,870</td>
<td>0.0951</td>
<td>ground</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

Table II. Emission lines predicted to be within the experimental width of the 7.43 \( \mu m \) emission line at \( \tau_D = 6 \mu s \), \( P_{O_2} = 176 \) torr.
Figure 1. Experimental Apparatus for Infrared Emission Studies
Figure 2. 5.5 \( \mu \) - 8 \( \mu \) emission spectrum of a 150 torr laser produced oxygen plasma with a 10 \( \mu \)s delay.
Figure 3. \( \lambda \) emission linewidth vs. total oxygen pressure at \( T_D = 6 \mu s \).
Figure 4. 7.43 μm emission linewidth vs. T. D. at 176 torr oxygen pressure.
Figure 6. 7.43 μ emission line area ∝ τ_D at total oxygen pressure of 176 torr.
Figure 7. Simulated emission spectrum in the 5.5 μ - 8.0 μ region using Coulomb Approximation intensities, 40 cm⁻¹ widths for the 6g and 6h states and 12 cm⁻¹ linewidths for the rest of the transitions. (a) Equal population of states assumed. (b) A Boltzmann distribution at a temperature of 4000 K is assumed among 36 terms of interest.
Figure 8. Synthetic spectrum of 5.5 $\mu$ - 8 $\mu$ emission region for a Stark field corresponding to $10^{14}$ e$/$cm$^2$, a 6g - 5f, 6h - 6g component linewidth of 40 cm$^{-1}$.
Figure 9. Synthetic spectrum of 5.5 $\mu$ - 8 $\mu$ emission region for a Stark field corresponding to $10^{15}$ e's/cm$^3$, a 6g - 5f, 6h - 6g component linewidth of 40 cm$^{-1}$. 
References


7. B. Isberg, Arkiv Förfysik 35, 495 (1967)

8. D. Sappenfield, private communication


END

DTIC

8-86