Nonequilibrium radiation behind shock waves in oxygen at speeds up to 10 km/s

P V Kozlov, N G Bykova, V Yu Levashev, I E Zabelinskii
Institute of Mechanics Lomonosov Moscow State University, Moscow, Russia

E-mail: kalevala@mail.ru

Abstract. In this work, the radiation characteristics of shock-heated oxygen in the spectral range of 190-700 nm are investigated. The presence of radiation from the Schumann-Runge bands from the nonequilibrium zone of the shock wave for velocities of 5–10 km/s is shown. The magnitude of the emission of oxygen from a nonequilibrium zone was measured. The results of comparison of pure oxygen and air radiations are presented. These data gives the possibility to estimate the contribution of this spectrum region emission to the nonequilibrium emission of air. The emission of some atomic oxygen lines was investigated also in experiment for these conditions.

1. Introduction
There is still great interest in the study of nonequilibrium phenomena in oxygen [1]–[6]. This is due to the importance of these processes for the aero-thermodynamics of hypersonic flight at speeds up to 5 km/s and the assessment of the influence of radiation processes on the surface of spacecraft returned to the Earth during of the breaking maneuver [7], [8]. Wherein the non-equilibrium thermochemical processes in oxygen can be as determining factors at these cases. It should be noted that for practical useful applications the experimental information about non-equilibrium air radiation at large spectral range are needed. The results of the experimental and theoretical study of the molecular oxygen emission and absorption in air and oxygen at the shock waves velocities 3–4 km/s was presented in [1]–[4]. In [9] the results of experiments [10] concerning Schumann-Runge bands contribution to air emission for speeds of 5.56 and 6.94 km/s was analyzed with using two computational models. However the proposed in [9] models give several times overestimated contribution of molecular oxygen radiation. In this paper the estimation of the non-equilibrium and equilibrium Schumann-Runge bands radiation contribution to the air emission was made. The results of experiments in pure oxygen are compared with previously obtained data on the emission of air [11]. The work is a continuation of the cycle of studies of non-equilibrium radiation of air at high speeds of entry of spacecraft into the dense layers of the Earth’s atmosphere [11]–[16].

2. Experimental Setup
The experiments were performed on the Dual Diaphragm Shock Tube – DDST [11]–[12] located at the Institute of Mechanics of Moscow State University. The experimental setup scheme with system registration of the shock-heated gas registration is presented in Figure 1. Experiments on DDST can be carried out no more than once a day; this limitation is due to the rate of pumping of water vapor after the shot of the shock tube. The setup can be serviced by one person and requires a small amount of
expendable materials. The recording system, using 4 spectrographs with different spectral resolutions and the ability to measure both the evolution of radiation over time and the spectral distribution, allows you to quickly adjust the setup for solving various problems.

Figure 1. Experimental setup. System of registration.

3. Results of Experiment
Experimental data for case of pure oxygen (99.99%) and shock wave velocities from 5.8 to 10 km/s are presented below. The experimentally measured volumetric spectral radiance \( B_\lambda \) and its temporal dependence \( J_\lambda \) on the wavelength \( \lambda = 213 \pm 2 \) nm are presented at Figure 2 – Figure 9. The air emission data under similar conditions are presented at these figures for comparison (see black lines). The inscriptions in the figures indicate the number of the experiment, the gas composition, the initial pressure and the velocity of the shock wave correspondingly. The vertical arrows in the Figure 2 show the wavelengths where the temporal dependence of the radiation was recorded. In the figures for the time profile, \( S (\mu J/(cm^2 \cdot sr \cdot \mu m)) \) is the area under the oxygen emission curve for the time interval from 0 \( \div \) 10\( \mu s \) and \( SO_2(S-R) (\mu J/(cm^2 \cdot sr \cdot \mu m)) \) is the area under emission curve for non-equilibrium zone (for example, for case illustrated at the figure 5 this interval is 0 to 0.5\( \mu s \)). The ratio of \( S \) and \( SO_2(S-R) \) allows us to estimate the relative share of equilibrium and non-equilibrium radiations for the shock-heated oxygen.

Figure 2. Volumetric spectral radiance \( B_\lambda \) and temporal dependence of volumetric spectral radiance \( J_\lambda \) on \( \lambda = 213 \pm 2 \) nm for air and oxygen.
The integration time on processing the experimental distributions of the volumetric spectral brightness $B_{\lambda}$ was 10 $\mu$s approximately. Wavelength 213 nm was chosen from the condition of insignificant self-absorption of radiation in pure oxygen [17] and significant radiation of NO in air.

Figure 3. Volumetric spectral radiance $B_{\lambda}$ and temporal dependence of volumetric spectral radiance $J_{\lambda}$ on $\lambda=213\pm2$ nm for air and oxygen.

Figure 4. Volumetric spectral radiance $B_{\lambda}$ and temporal dependence of volumetric spectral radiance $J_{\lambda}$ on $\lambda=213\pm2$ nm for air and oxygen.

Figure 5. Volumetric spectral radiance $B_{\lambda}$ and temporal dependence of volumetric spectral radiance $J_{\lambda}$ on $\lambda=213\pm2$ nm for air and oxygen.
Figure 6. Volumetric spectral radiance $B_\lambda$ and temporal dependence of volumetric spectral radiance $J_\lambda$ on $\lambda=213\pm2$ nm for air and oxygen.

Figure 7. Volumetric spectral radiance $B_\lambda$ and temporal dependence of volumetric spectral radiance $J_\lambda$ on $\lambda=213\pm2$ nm for air and oxygen.

Figure 8. Volumetric spectral radiance $B_\lambda$ and temporal dependence of volumetric spectral radiance $J_\lambda$ on $\lambda=213\pm2$ nm for air and oxygen.
As can see from Figure 2–Figure 9 a distinctive feature of oxygen radiation $J_\lambda$ at speeds $5.8 \pm 10$ km/s is the presence of a peak of non-equilibrium radiation behind the shock wave front. However, its duration is practically independent of the speed of the shock wave, as is the case for the duration of non-equilibrium NO radiation in air [13]. The equilibrium radiation at a wavelength of 213 nm in pure oxygen is stationary for speeds of $5.8 \pm 7.2$ km/s. The same nature of equilibrium pure oxygen radiation behavior was observed for low speeds [2], [14].

The volumetric spectral radiance $B_\lambda$ of pure oxygen for set of different shock wave velocities are presented at the Figure 10. As can see from this figure the spectral radiance value depends on the shock wave velocity significantly at the presented spectral region. The initial oxygen pressure was 1Torr for shock wave velocities $5.81 \sim 7.35$ km/s and 0.25 Torr for case 10 km/s. The type of radiation in the region of 190–300 nm for speeds $5.81$ to $7$ km/s suggests that it is radiation from the Schumann-Runge bands.

With an increase in the velocity of the shock wave above 6 km/s, atomic lines also begin to appear in the spectrum. It is should be noted, the not only atomic lines of investigated gases can be observed in the experimentally recorded spectrum. The atomic lines of carbon (193 and 247 nm) and copper (324 and 326 nm) are observed in the emission spectra in oxygen at speeds greater than 7 km/s. In the region of 310 nm, the radiation of the OH radical is observed. The emission of the Hα (656 nm) and Hβ (486 nm) lines are also observed in the emission spectra at speeds above 7 km/s. These radiations
are due to the presence of residual impurities in the oxygen under investigation and the material of the diaphragms used. Alkali metal radiation (doublets of Na 589; Li 671nm; K 766, 770 nm) is mainly associated with the material of the used optical windows (quartz KU-1). The lines of potassium and lithium were observed by the authors in work [18].

The temporal dependencies of spectral radiance of atomic lines for different wavelengths (394nm, 615nm, 532nm and 645nm) and radiation at 213 nm are presented in Figure 11. As can be seen from Figure 11 the behavior of atomic lines differs significantly from radiation at a wavelength of 213 nm in the non-equilibrium zone. In the equilibrium zone, the characters of the time dependence almost the same coincide. This is true for shock-wave velocities above 7.2 km/s, when the intensity of atomic lines becomes significant, and the contribution to radiation from the Schumann-Runge bands is minimal.

![Figure 11. Temporal dependence of spectral radiance for λ=213 ± 2 nm and atomic oxygen lines. Electronic configurations of the oxygen atom for recorded the radiation are shown in the figure.](image)

4. Discussion

The spectra shown in Figure 2–Figure 9 and the time dependences of radiation in oxygen and air behind the shock wave front allow us to make assumptions about the behavior of both non-equilibrium and equilibrium emission. In the spectral region of 200÷300 nm, the main contribution to air emission is NO up to speeds of 10 km/s, only at higher shock wave velocities the radiation from the attachment of electrons to N and O becomes dominant. This is evident from the shape of the absorption spectra calculated in [19] for air at temperatures above 8000 K and experimental [12] radiation spectra of air for speeds above 10 km/s. Non-equilibrium radiation in molecular oxygen between \( B^3Σ_u^- \rightarrow X^3Σ_g^- \) transitions (these transitions occur in the Schumann – Runge bands systems [17]) at speeds above 5.8 km/s is due to the substantial population of the state \( B^3Σ_u^- \) immediately behind the shock wave front and its short lifetime, and the fact that even at high velocities of the shock wave the oxygen molecules are not yet completely dissociated, while the population of the excited state \( B^3Σ_u^- \) is already large. This is also was noted in work [9], where the calculated maximum of the emission of the Schumann Runge bands in the air always occurs earlier than the maximum of the NO emission. This corresponds to the Zeldovich mechanism [20], the formation of nitric oxide as a result of exchange reactions in the air behind the shock wave front. This also implies that the non-equilibrium radiation of air for shock wave velocities of 6÷10 km/s in the wavelength range of 200÷300 nm is a superposition of NO (\( γ, β, δ, σ \) bands) and Schumann–Runge radiations.

As for the equilibrium radiation in oxygen, up to the velocities of shock waves of 6.5 km/s, the main source of radiation in the spectral region of 200–300 nm is the Schumann–Runge bands. At speeds above 7.2 km/s, the equilibrium temperature behind the shock wave becomes higher than
8000 K, and the equilibrium spectral radiation of the Schumann-Runge bands becomes small, and the radiation from the attachment of electrons to O becomes predominant.

Let us estimate the contribution of the oxygen radiation in the spectral region 200−300 nm to the radiation of shock-heated air. The Figure 12 shows the experimental dependences of the intensity of the non-equilibrium peak and the total radiation of shock-heated oxygen on the velocity of the shock wave.

![Figure 12](image)

**Figure 12.** The intensity of the peak of non-equilibrium radiation $J_{PMT}$ in oxygen at a wavelength of $\lambda=213 \pm 2$ nm and the intensity of the integral signal $J_{CCD}$ from the CCD camera in oxygen at a wavelength of $\lambda=213 \pm 2$ nm depending on the velocity of the shock wave. Intensities are given to the initial pressure $P_1=1$ Torr.

The presented experimental data are show that Schumann-Runge bands contribution in non-equilibrium shock-heated air radiation does not exceed 20%. Moreover, this contribution increases with increasing velocity of the shock wave. In the equilibrium zone, the emission of Schumann-Runge bands in the air is more significant for speeds up to 6.5 km/s. For speeds of 7−10 km/s, the contribution to the equilibrium radiation of air from oxygen is due to the radiation from the attachment of electrons to O. These assumptions are valid under the condition of additively and independence of the contribution to the spectrum of shock-heated air from oxygen and nitrogen, that is not quite true.

5. Conclusion

The paper presents experimental data in shock-heated oxygen for shock speeds of 5.8−10 km/s. The contribution of oxygen to the radiation of air behind the shock wave front has been estimated. Observation of non-equilibrium radiation for speeds above 6 km/s is due to the rapid excitation of the state $B^3\Sigma_u^-$ and incomplete dissociation of oxygen for speeds up to 10 km/s. The obtained quantitative data will allow further comparison with computational models of radiation.

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