Experimental study of the evolution of NO radiation in the air at the velocities up to second cosmic

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Abstract. The results of a study of the dynamics of radiation of nitric oxide, which is formed behind the front of a shock wave in air, are given. Results are presented for shock wave velocities of 8–11.4 km/s. The shock wave velocity at which N+ radiation predominates in the range 210÷230 nm is determined experimentally.

1. Introduction
Assessment of the impact of heat and radiation fluxes to the surface lander in mixtures N2–O2 and CO2–N2 for the braking maneuver at present is of interest in connection with the design missions to Earth, Mars and Venus. When calculating the heat flux at the lander it is necessary to consider the radiation of the plasma of the shock layer. The magnitude of radiation fluxes increase with the size of the lander. The radiative processes have a significant influence on gas-dynamic flow if the size of the developed space vehicles over 3 meters [1]-[8]. Therefore it is necessary take into account the contribution of radiation processes significant in the development of thermal protection system of reentry vehicles. Testing computational models that describe radiation fluxes requires accurate experimental data in a wide range of speeds and pressures. One of the main sources of these data are the results of experiments made in shock tubes [2], [9]-[12].

The work continues to study the kinetics of formation and decomposition of NO behind the shock front, presented in [13], [14]. The results on the characteristics of radiation of nitric oxide with a high temporal resolution in the wavelength range 190-300 nm up to second cosmic velocity of the shock wave (SW) are presented.

2. Experimental Setup
The main elements of a double diaphragm shock tube (DDST) of the Institute of Mechanics of the Moscow State University and the registration system are described in [13]. The change in the conditions for the preparation of the driver gas in the high-pressure chamber made it possible to confidently obtain a second cosmic velocity at the initial pressure of the test gas of 0.25 Torr at the DDST facility.

The system of radiation registration has been changed figure 1. One channel is used that detects radiation in the spectral range of the spectrograph 190–670 nm (UV) Horiba CP140 1824. This channel registers on the CCD detector an integral distribution of the spectral radiance during the passage of the shock wave through the measuring cross-section. Instead of a channel registering spectral radiation on a CCD detector in the range of 500-1100 nm, a spectrograph Horiba 1061 with a Hamamatsu R446 photomultiplier was installed. Now the measurement scheme allows one to record...
the temporal evolution of radiation at three wavelengths in one experiment. A low-noise Hamamatsu R4220 photomultiplier is installed in the channel with a high spectral resolution. This made it possible to improve the signal-to-noise ratio.

Figure 1. Experimental setup. System of registration.

3. Results of Experiment
As was shown in [8], at shock wave velocities of less than 8 km/s, radiation in the spectral range 190±300 nm is basically a nonequilibrium emission of nitrogen oxide molecules. The main objective of the study was to study the evolution of the emission of an NO molecule in the UV spectral range for SW velocities of 8±1.2 km/s in air. The experiments were carried out for the initial pressure $P_1=0.25$ Torr. Figure 2 shows the temporal behavior of the normalized radiation intensities at a wavelength of 213±2 nm for different velocities of the shock wave ($V_{SW}$).

Figure 2. Experimental normalized profiles of the volumetric radiance of shock heated air on $\lambda=213\pm2$ nm for different $V_{SW}$ ($P_1=0.25$ Torr).
The absolute intensity of the maximum of the volume radiation was practically independent of the velocity of the shock wave and was of the order of 10 W/(cm$^3$·sr·μm).

As can be seen from figure 2, for velocities exceeding 10 km/s, the intensity of radiation from the equilibrium zone becomes more than 10% of the intensity of the nonequilibrium peak. At a speed of 11 km/s, these intensities become equal. However nonequilibrium radiation peak due to formation and decomposition of NO molecules behind the front of the shock wave is still pronounced. The contribution of radiation from the equilibrium zone to the spectral radiance becomes comparable with radiation from a nonequilibrium zone in the spectral range 190÷290 nm for velocities above 9 km/s. Such a behavior of the nonequilibrium and equilibrium radiations is characteristic only for the region of the spectrum where the NO molecules are emitted. This is clearly seen in figure 3 and figure 4, which show the temporal behavior of the normalized radiation intensities at a wavelength of 213 nm (NO radiation) and on other regions of the spectrum (N$_2^+$ and N$_2$ radiation).

Due to the fact that the duration of radiation in different spectral ranges is not the same (figure 3 and figure 4), the integral spectrum obtained on the CCD detector should be divided by the corresponding duration. Only then will the spectral density values of the brightness in the spectrum be correct. The duration of the radiation in the required spectral interval is defined as the area under the function of the normalized intensity versus time. In figure 2, 3 and figure 4, $\Delta\tau$ corresponds to these durations.

It should be noted that in the previous work [13], when processing the spectral distribution of the integral intensity, the time $\Delta\tau$ was equal to the duration of the entire luminous shock layer. This time is much longer than the $\Delta\tau$ times indicated in figure 2, 3 and 4. Therefore, the spectral brightness density obtained by processing the integrated intensity data from the CCD detector will be much larger.

![Figure 3](image-url)

**Figure 3.** Experimental normalized profiles of the volumetric radiance of shock heated air on $\lambda$:213 nm(NO); 391 nm(N$_2^+$); 336 nm(N$_2$(2+)). The velocity of the shock wave is $8\div8.33$ km/s; $P_1=0.25$ Torr.
Figure 4. Experimental normalized profiles of the volumetric radiance of shock heated air on $\lambda$; 213 nm(NO); 422 nm($N_2^+(1-)$). $P_1=0.25$ Torr.

Figure 5. Spectral distribution of integral on time emissivity of air heated by shock wave $P_1=0.25$ Torr. $V_{SW}=7.7 \div 11.36$ km/s.

When processing the spectra recorded by the CCD of the detector, the integration times $\Delta \tau$ were determined as described above (shown in figure 2 for the corresponding $V_{SW}$). It is seen that as the shock wave velocity increases, the saw tooth form of the spectrum characteristic of NO changes. In the wavelength range 210÷240 nm, a characteristic hump appears at the velocity above 10 km/s (figure 5).
This hump is due to the equilibrium radiation of the shock layer after the nonequilibrium peak of radiation due to the formation and decomposition of the NO molecule. The source of radiation is the N$^+$ ion, which is produced in the process of photodissociation of nitrogen atoms. In [15], the absorption spectrum of air under conditions of local thermodynamic equilibrium for 15000 K is given (in [15], figure 7). This figure shows that in the range of 46500 cm$^{-1}$, intense N$^+$ absorption peaks are observed in the spectrum.

Calculations of the concentrations of the components behind the shock front also show that the concentration of the N$^+$ ion becomes significant and practically constant only after the concentrations of the excited electronic states of the NO molecule have reached their maximum and significantly decreased [14].

4. Conclusion

In this article, studies of the nature of the nonequilibrium radiation of nitric oxide started in [13], [14] are continued. Modernization of the recording system made it possible in one experiment to obtain temporal radiation profiles in three different regions of the spectrum with a high resolution (<100 ns).

The measurements made showed that the nature of the radiation in different regions of the spectrum can differ substantially in shape and duration. This indicates various mechanisms for the decomposition and formation of molecules and atoms in the air behind the front of the shock wave.

A technique is proposed for processing the integrated spectra registered by CCD detectors in absolute units of spectral brightness.

The spectrum of the N$^+$ ion appearing in the range of 210÷240 nm in the equilibrium zone of the shock layer in the air at speeds above 10 km/s is identified.

In the future paper, the main attention will focus on the experimental study of the radiative contribution from the Schumann-Runge O$_2$ band in the spectral range 200÷300 nm for shock velocities of 5÷8 km/s in air.

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