# Precursor phenomena ahead of a re-entry vehicle into Earth atmosphere

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## 1.  Introduction

Thermochemical and radiative transfer processes called "Precursor phenomena" occur ahead of the shock layer generated around a space vehicle during the atmospheric entry flight. Most of the relevant works had investigated characteristics of post-shock flows to assess the heat flux and aerodynamic forces of a space vehicle accurately. Therefore, the influence of precursor phenomena on post-shock flows has been unclear. The authors investigated precursor phenomena ahead of a shock wave propagated in Ar, using a shock tube facility, clarifying the mechanism of photochemical reaction to generate precursor electrons ahead of the shock wave [1]. In the present study, as a next step, we target characteristics of precursor phenomena occurred in $N_2$. Radiation profiles correlated to the shock front are observed by the time-resolved spectroscopy. Theoretical analysis by a one-dimensional precursor model is also applied to clarify characteristics of precursor phenomena.

## 2.  Experimental setup and test conditions

In this study, a free piston-driven shock tube is used to generate a shock wave in $N_2$. Nominal shock velocity is 6.0±0.3 km/s and test gas pressure 100 Pa. Shock velocity was measured by the double-laser schlieren system. Time-resolved emission spectroscopy is conducted to obtain the temporal profiles of radiation intensity correlated to the shock front. The spectroscopic system is calibrated using a quartz tungsten halogen light (Newport, 63355) which is a NIST traceable light source to obtain absolute radiation intensity from the measured radiation intensity. The targeted species are $N_2$ (2+) (1,0), $N_2^+$(0,0), and N 3p 4S$^0$-3s$^4$P which are dominant emitters in $N_2$ plasma. The detail description of the shock tube and measurement system is found in refs. [2, 3].

## 3. One-dimensional precursor model

To analyze the behaviour of precursor electrons ahead of the shock wave, one-dimensional precursor model [1] is applied for $N_2$ in this study. In this model, precursor electrons are assumed to be produced by the photoionization represented as

$$N_2 + h\nu = N_2^+ + e^-  \qquad (1)$$

In this reaction, radiation emitted behind the shock wave is assumed to be absorbed ahead of the shock wave, producing electrons and excited $N_2^+$. The radiation is regarded as a black body radiation from the shock layer in this analysis because the radiation which can ionize $N_2$ is, in general, optically thick behind the shock wave. On the coordinate system fixed at the shock front, the mass conservation equation and the energy conservation equation are formulated and simplified by the order evaluation for each term in the present condition. Finally, the governing equation for electron density is given by

$$n_e = \frac{q_0}{V_{sh}} exp(\mu x) \qquad (2)$$

where $x$ is the coordinate aligned in the flow direction with its origin located at the shock front, $n_e$ is electron density, $V_{sh}$ is shock velocity, $q_0$ is total number of photons capable of ionizing nitrogen molecules, $\mu$ is absorption coefficient of photons.

The governing equation for electron temperature is given by

$$\frac{\partial T_e}{\partial x} = \mu(T_0 - T_e) - \frac{T_e \kappa_{ea} \nu_{ea}}{V_{sh}} \qquad (3)$$

where $T_e$ is the electron temperature, $T_0$ is the mean temperature of electrons produced in photoionization, $\kappa_{ea}$ is the energy transfer coefficient and $\nu_{ea}$ is the collision frequency of electrons against neutral species.

## 4. Results and Discussions

Figure 1 shows the measured temporal profiles of radiation intensity for $N_2$, $N_2^+$, and N, which are correlated to the shock front by laser schlieren signals. All the radiation intensities start to increase ahead of the shock front and reach a peak value immediately just behind the shock front, followed by the rapid decrease. The second increase of the radiation intensity can be seen after the rapid decrease due to the influence of the contact surface. From the

precursor radiation of $N_2$, electronic excitation of $N_2$ is considered to occur ahead of the shock front due to the absorption of radiation emitted from the shock layer. From the precursor radiation of N, photodissociation shown in Eq. (4) is found to occur ahead of the shock front.

$$N_2 + h\nu \rightarrow N + N \qquad (4)$$

The precursor radiation of $N_2^+$ is much more intense than those of $N_2$ and N, which is considered to be brought about by photoionization shown in Eq. (5).

$$N_2 + h\nu \rightarrow N_2^+ + e^- \qquad (5)$$
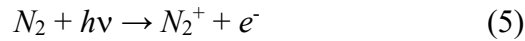
From the radiation measurements, photoionization is found to be dominant ahead of the shock front. In the present study, precursor phenomena ahead of shock wave have been analysed using a one-dimensional precursor model in which photoionization shown in Eq. (5) is assumed to be main photochemical reaction. Figure 2 shows the temporal profile of the electron temperature ahead of the shock front obtained from the analysis by the model for several equilibrium temperatures. The electron temperature is uniform and higher with increasing $T_{eq}$ ahead of the shock front. Figure 3 shows the temporal profile of the electron density ahead of the shock front obtained from the analysis by the model for several equilibrium temperatures. The electron density increases exponentially as approaching the shock front and becomes higher with the increase of $T_{eq}$.
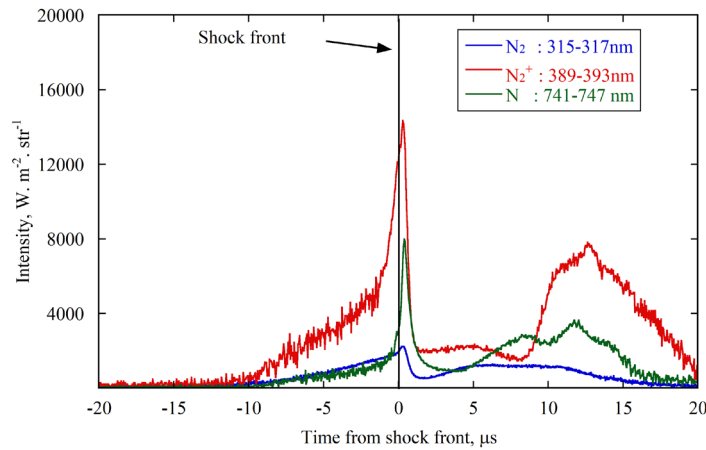


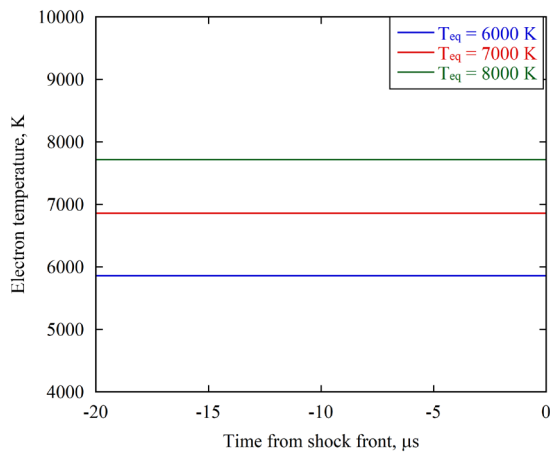Fig. 1 Temporal profile of radiation intensity for $N_2$, $N_2^+$ and N

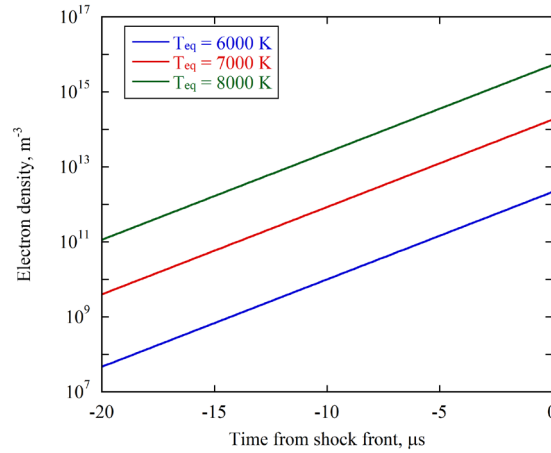Fig. 2 Electron temperature profile



Fig.3 Electron density profile

## 5.  Conclusions

In this study, precursor phenomena occurred in $N_2$ were investigated by radiation measurements and theoretical analysis. Temporal profiles of radiation intensity for $N_2$, $N_2^+$, and N were observed by the time-resolved emission spectroscopy. Radiation intensity of $N_2^+$ is found to be strong ahead of the shock front, showing that the photoionization of $N_2$ are significant. The one-dimensional precursor model considering photoionization is applied and the electron density and temperature are obtained ahead of the shock front, clarifying the behaviour of precursor electrons.

## 6.  Acknowledgement

## 7.  References

[1] Yamada et al., JFST, Vol. 9, No. 5, 2014, JFST0070.

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[3] Yamada et al., AIAA Scitech 2019, 2019, AIAA-2019-1350.