MEASUREMENTS AND ANALYSIS OF UV-RADIATION INTENSITY OF PLASMA STRUCTURE ALONG ORBITAL RE-ENTRY TRAJECTORY OF SPACE VEHICLE “SOYUZ-TM” BASED ON OBSERVATION DATA OBTAINED ON BOARD ISS

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Results of experimental and theoretical investigation are presented of UV radiation intensity from plasma structure during the re-entry of descending space vehicle “Soyuz-TM” in the Earth atmosphere.

Radiation in UV range from re-entry space vehicles moving in the Earth atmosphere has been experimentally investigated at velocities 3.5 [1] and 5 km/s [2]. Theoretical analysis of radiation for conditions of these experiments has been made in [3] and [4]. In the latter paper shock tube experiments have also been used.

The measurements of UV radiation from plasma structure over re-entry vehicle (RV) “Soyuz-TM” described in this work have been carried out 24.10.04 onboard International Space Station (ISS) in night conditions with the use of high sensitive radiometric UV-camera “Fialka-MV-Kosmos”. The comparison of theoretical predictions and experimental results is made on radiant intensity from plasma structure over the space vehicle in the range of spectrum 230–370 nm.

Experiment description

During realization of the “Relaxation” Space Experiments Series onboard ISS experimental investigation has been carried out in night conditions of radiant intensity in UV range of spectrum 230-370 nm from plasma structure over space vehicle “Soyuz-TM” in the Earth atmosphere. For the measurements of absolute intensity along the vehicle re-entry trajectory the high sensitive optical system “Fialka-MV-Kosmos” installed on the ISS was used. The system is analogous to the one installed onboard “Mir” orbital station [5], but one order of magnitude more sensitive. The measurements were made using high sensitive solar-blind UV-camera with MCP image intensifier with threshold sensitivity $\sim 1.7 \cdot 10^{-17}$ W/cm^2, a field of view – 10.5 degrees and a pixel instant field of view – $2 \cdot 10^{-4}$ radians.

The RV “Soyuz-TM” is a blunt segment-cone body – a combination of a spherical 30^{o}-degree segment with a sphere radius $R = 2.32$ m, and a reversed cone with a half

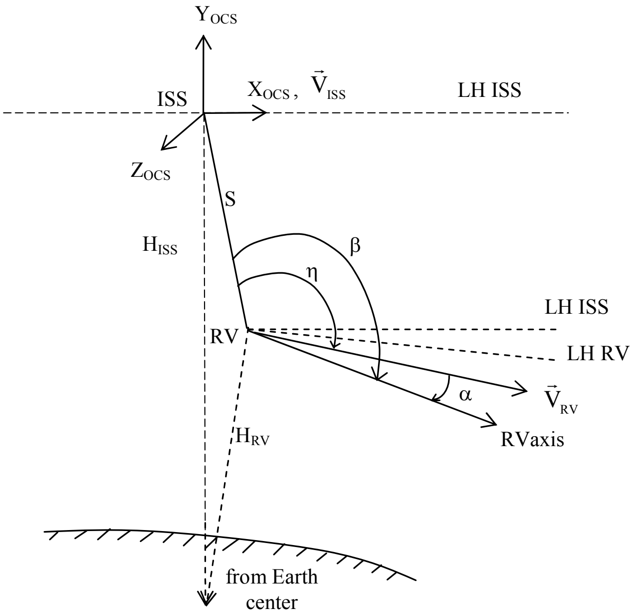

Fig. 1

angle 7°. A tangent line of the segment and the cone is rounded with a radius r/R=1/50.

The absolute calibration of apparatus sensitivity was made on base of star radiation measurements used as a calibrating source. A temporal dependence of radiant intensity was obtained beginning from the height ~ 99 km and down to 25-30 km. Space vehicle velocity along the trajectory is listed in Table 1. An angle of attack of the space vehicle in the considered range of altitudes was approximately

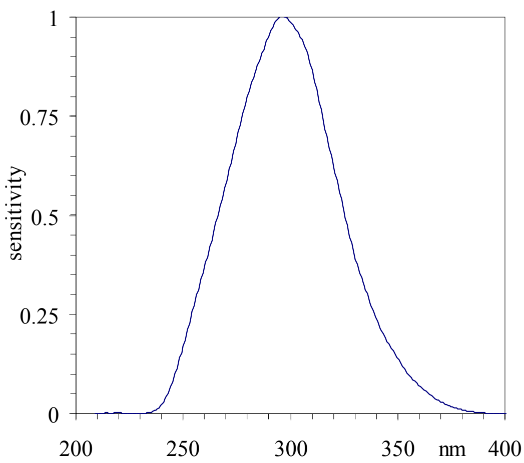

Fig. 2

constant and equal to 22°. Changes of some other parameters along the trajectory are presented in Table 2. Designations correspond to a scheme shown in Fig.1. Here LH RV and LH ISS – local horizons in RV and ISS positions, H_{RV} и H_{ISS} – altitudes of RV and ISS, S – ISS – RV distance, β – observation angle (between S and RV axis) , η – angle between $\vec{V}_{RV}$ and S, α – angle of attack (between $\vec{V}_{RV}$ and RV axis), $(XYZ)_{OCS}$ – orbital coordinate system at ISS position. Also in Table 2 results of measurements of absolute radiant intensity I_{exp} (W/sr) are presented in sensitivity range of UV-camera, shown in Fig.2.

Numerical method

Radiation measurements from plasma structure over space vehicle “Soyuz-TM” descending in the Earth atmosphere have been carried out in the near ultraviolet. The main contribution in this range of spectrum is made by the radiation of a high temperature shock layer on the forward side of the space vehicle.

The shock layer on the side surface and the wake behind the vehicle practically do not radiate in the ultraviolet because of comparatively low values of temperature which take place there. For the same reasons in calculations of UV radiation one can omit from consideration the boundary layer. Therefore computations have been made only for the forward side and a small part of the side surface of the vehicle (0.15 *R*), in order to obtain supersonic flow on the exit boundary of the computational domain and thus eliminate upwind influence of the rest flow.

For numerical simulation three dimensional Euler equations have been e used supplied with mass conservation equations for individual chemical species. The equations are cast in arbitrary curvilinear coordinates in the conservative form. Calculations are made using an implicit iterative LU-SGS (Lower-Upper Symmetric Gauss Seidel) scheme [6].

More details on the numerical method used can be found in [7].

In computations a thermo-chemical model of nonequilibrium radiating air is used [8, 9] which has been tested, in particular, by comparison with flight measurements on electron number density in the shock layer over experimental RAM-C vehicle. Briefly, the model is as follows. Air is supposed to consists of 9 chemical species: N_2, O_2, NO, N, O, N_2^+, O_2^+, NO^+ and e^-. Rotational temperature, vibrational temperatures of molecular ions N_2^+, O_2^+, NO^+ and the temperature of free electrons are assumed equal to translational temperature. Generally for neutral molecules N_2, O_2 and NO conservation equations of vibrational energy are solved (vibrationally nonequilibrium model with different vibrational temperatures). But preliminary calculations have shown that at the considered conditions vibrational temperatures of molecules N_2, O_2 и NO are very slightly differ from translational temperature. Therefore the temperatures of their vibrational excitation are also assumed equal to translational temperature.

Table 1

H, km	V_∞, m/s	$Re_{\infty,Rb}$	P_∞, atm	T_∞, K
80.5	7604	$2.61 \cdot 10^4$	$1.00 \cdot 10^{-5}$	184.9
70.1	7510	$1.06 \cdot 10^5$	$5.67 \cdot 10^{-5}$	218.7
60.7	7109	$3.00 \cdot 10^5$	$2.17 \cdot 10^{-4}$	251.0
52.6	6116	$6.17 \cdot 10^5$	$6.07 \cdot 10^{-4}$	274.0
45.6	4537	$1.09 \cdot 10^6$	$1.43 \cdot 10^{-3}$	272.3

Intensity of UV radiation has been calculated in the following molecular bands; N_2 (2+), N_2^+ (1-), O_2 (SR) and NO (β,γ,δ,ε). Populations of electronic excited levels of molecules are determined by solution of a conservation equation for each level with account of the processes of convection, collisional formation and disappearance and finite radiative life time [9]. Calculations of electronic level populations have also been made in the approximation of thermodynamic equilibrium with local translational temperature. In computations of radiation spectroscopic data on molecular constants and probabilities of vibrational and electronic transitions taken from [10, 11] are used. Spectral distribution of radiation intensity is determined using the "just overlapping" approximate model [10]. An approach of thin optical layer is assumed in calculations of radiation from the whole shock layer.

Calculations have been carried out on a grid 50×30×40 (in longitudinal, transverse and circumferential directions respectively). The bow shock wave is fitted supposing that the Rankine-Hugoniot jump conditions take place across it. On the vehicle surface nonpermeable condition (velocity normal to the wall $V_n = 0$) is used. Along the symmetry axis conditions of evenness and oddness of flow parameters are employed. On the exit boundary an extrapolation of first or second order of accuracy is used.

Results and discussion

Calculations have been made for a part of the entry trajectory of the space vehicle "Soyuz-TM" into the Earth atmosphere in the altitude range 80.5 – 42.6 km when the processes of dissociation, ionization and excitation of internal degrees of freedom have a type transitional from a strongly nonequilibrium to a nearly equilibrium state. At lower altitudes these processes are in equilibrium, at higher altitudes they are very slow (frozen). Trajectory parameters and characteristics of the Earth atmosphere are presented in Table 1.

In Fig.3*a* isolines of temperature are shown with a step of $\Delta T = 500$ K in the shock layer on the forward side and on a part of the side as well as near the surface of the space vehicle "Soyuz-TM" for a trajectory point with a higher altitude (H = 70.1 km). It is seen that temperature in the shock layer on the forward side abruptly decreases from shock wave to the vehicle surface which is the consequence of the processes of dissociation and ionization.

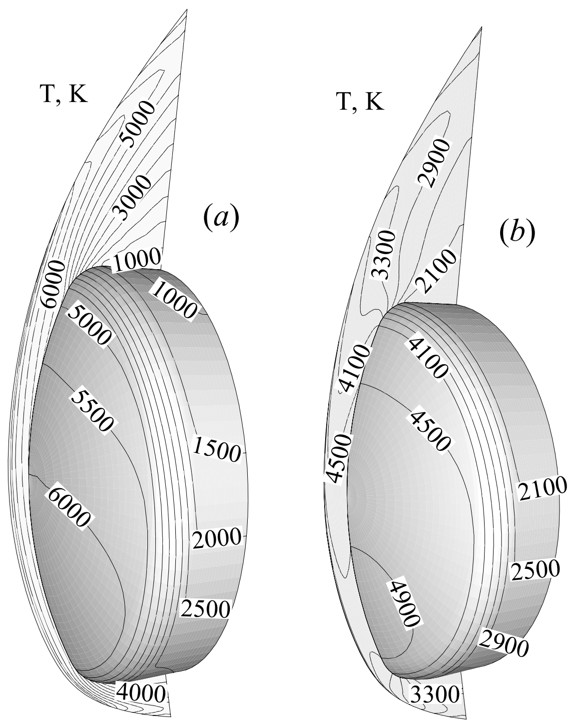

Fig. 3

For example along the stagnation line temperature diminishes approximately from 21000 to 6200 K, the main temperature decrease being occurred just after the shock wave – by more than 10000 K on the distance of 0.1 of the shock detachment thickness.

On the contrary, in the longitudinal direction temperature gradients in the shock layer are considerably less. For example, on the vehicle surface temperature changes from 6200 to 5000 K. Near the corner edge where the flow turns temperature diminishes, particularly on the leeside (about 5 times – from 5000 to 1000 K). On the forward side due to a large angle of attack temperature decreases not so abruptly – approximately by a factor of 1.5.

An analogous picture of temperature isolines with a step of $\Delta T = 400$ K for a lower altitude (H = 45.6 km) is presented in Fig.3b. The values of temperature in the shock layer in this case are notably less as a result of velocity diminishing from 7.5 to 4.5 km/s. In contrast to the case of an altitude of 70.1 km, temperature in the main part of the shock layer on the forward side is almost constant normal to the vehicle surface except in the nearest vicinity of the shock wave. This implies that the processes of dissociation, which are strongly nonequilibrium and result in temperature decreasing across the shock layer at higher altitudes, are in equilibrium at lower altitudes. Temperature decreasing at the turning point near the corner edge on the forward side is

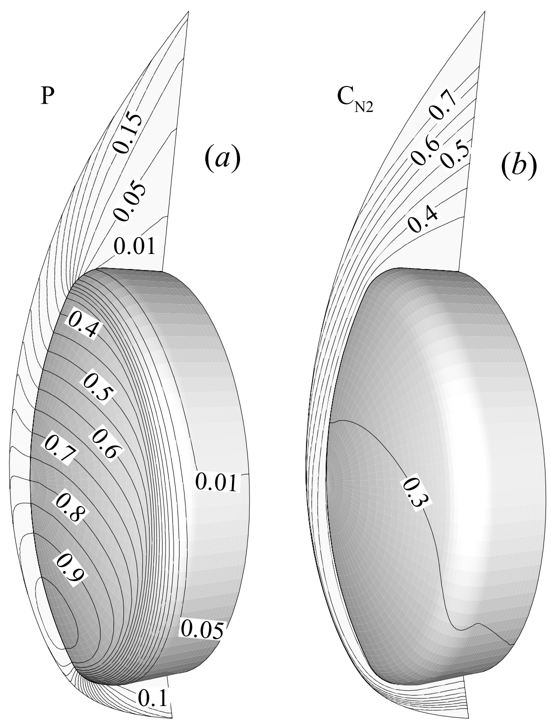

Fig. 4

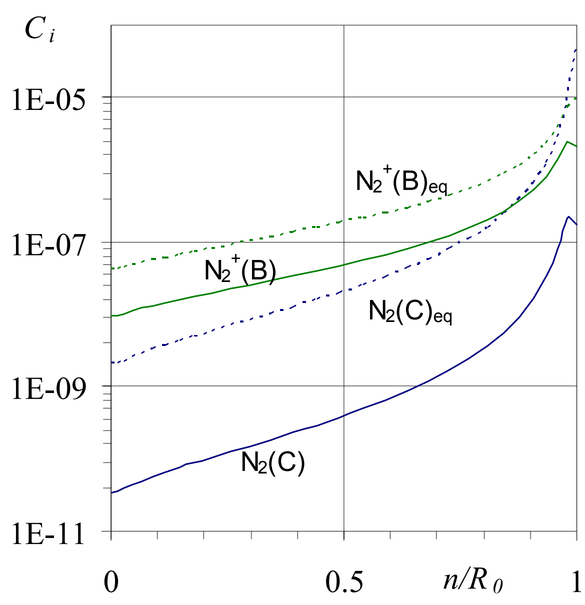

Fig. 5

about 1.5 times, i.e. approximately the same as for an altitude of 70.1 km. Diminishing of T near the corner edge on the leeside is about 2 times which is considerable less than at 70.1 km where it is equal to about 5 times. This discrepancy is probably caused by the less level of dissociation at the lower altitude.

Isolines of pressure $P/\rho_\infty U_{2\infty}$ and mass concentrations of molecules N2 at an altitude of 70.1 km are shown in Fig.4. It is seen that on the forward side from the stagnation point to the corner edge pressure decreases approximately two times – from 0.95 to 0.4. The change of pressure across the shock layer along almost the whole of forward side is several percents. Only close to the corner edge on the leeside it reaches 20 – 30%. At the turning point near the corner edge pressure decreases down to 0.1 and 0.01 on the forward and lee side respectively. In the range of considered conditions the distribution of pressure in the shock layer depends very slightly on altitude (especially on the forward surface).

In Fig.5 the distributions of mass concentrations of excited electronic levels N2(C3Πu), second positive band system, and N2+(B2Σu+), first negative band system, across the shock layer along the stagnation line at an altitude of H=70.1 km. Solid and dotted curves correspond to calculations in nonequilibrium and locally equilibrium approaches. It is seen that at the considered conditions the nonequilibrium populations of the above electronic levels significantly lower than the populations determined using the local equilibrium approach. The difference is about one and two orders of magnitude for N2+(B2Σu+) and N2(C3Πu) levels respectively.

The spectral radiant intensity *I*λ, W/mkm·sr, from the whole of the shock layer on the forward side of the space vehicle "Soyuz-TM" at an altitude of 70.1 km in nonequilibrium and locally equilibrium approaches is presented in Fig.6*a* and 6*b*.

In the case of nonequilibrium the main contribution in the considered range of spectrum is made by the following molecular band systems: NO(γ), N2(2+) and N2+(1-).

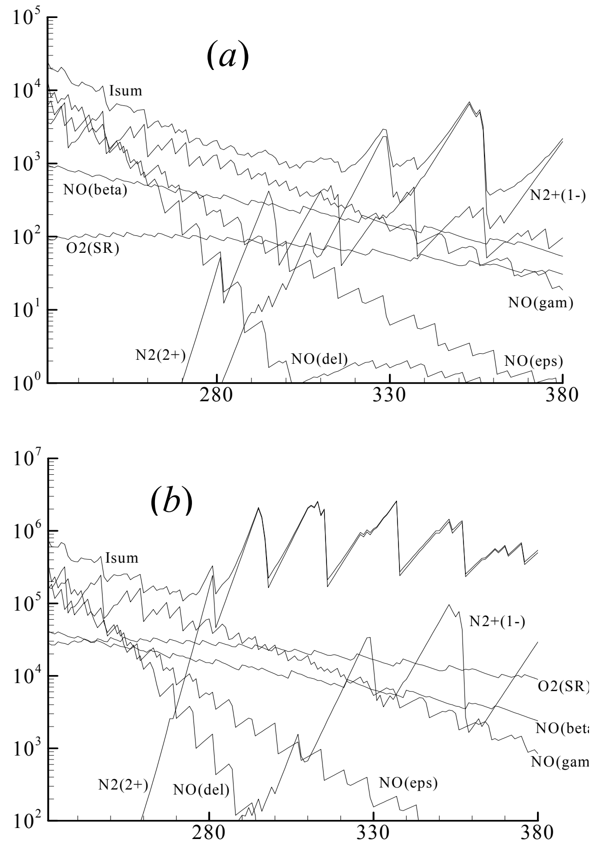

Fig. 6

In the range 230-300 nm the band systems NO(β) and O2(SR) are also significant. In the case of local equilibrium approach the relative contribution of band systems is retained on the whole except the band system N2+(1-) the contribution of which is negligible. But the absolute values of radiant intensity are about three orders of magnitude higher than for nonequilibrium approach.

Table 2

H, km	S, km	η°	I_{eq},W/sr	I_{non-eq},W/sr	I_{exp},W/sr
70.1	405	129	$1.9{\cdot}10^4$	117	113
60.7	390	129	$2.1{\cdot}10^4$	143	115
52.6	390	103	$2.3{\cdot}10^4$	182	93
45.6	390	103	$1.3{\cdot}10^4$	81	68

In Table 2 numerical results of radiation in nonequilibrium and equilibrium approaches are listed with correction for spectral sensitivity of UV camera shown in Fig 2. Also there are given the flight radiation measurements. It is seen that taking into account the processes populating and depopulating excited electronic levels of molecules are very important at the considered conditions – the difference between theoretical radiant intensity obtained in non-equilibrium and equilibrium approaches are about two orders of magnitude. From analysis of the presented data also follows that satisfactory agreement takes place between numerical results obtained in nonequilibrium approach and experimental data if one takes into account that measurement accuracy is about 30%.

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