Light versus sound

A quasi-steady optical discharge in a supersonic air flow generated by a wind tunnel was obtained for the first time in the world at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk). Interaction of the thermal wake from the discharge with the shock wave generated by the model was found to reduce the shock wave strength. This effect can be applied in aviation for decreasing the sonic boom intensity.

The permanently increasing pace of today's life and business globalization, which require high-speed transportation, stimulate research aimed at the development of civil supersonic airplanes. The development of supersonic passenger aircraft of the second generation has been pursued in Russia and abroad for the last four decades. Specialists unanimously believe that the main obstacle on this way is the environmental restriction on the *sonic boom* (SB) level.

When an aircraft flies in the atmosphere with a velocity greater than the sound speed, the disturbed flow region is bounded by the bow *shock wave* (SW) emanating from the nose part of the aircraft and the tail SW formed in the rear part of the aircraft. The area in the vicinity of the aircraft (the so-called *near zone*) contains intermediate shock waves and also *expansion and compression waves* generated by individual elements of the aircraft structure. As the disturbances generated by each point of the aircraft surface propagate with a velocity close to the sound speed (which is smaller than the aircraft velocity), the SW shape is close to conical.

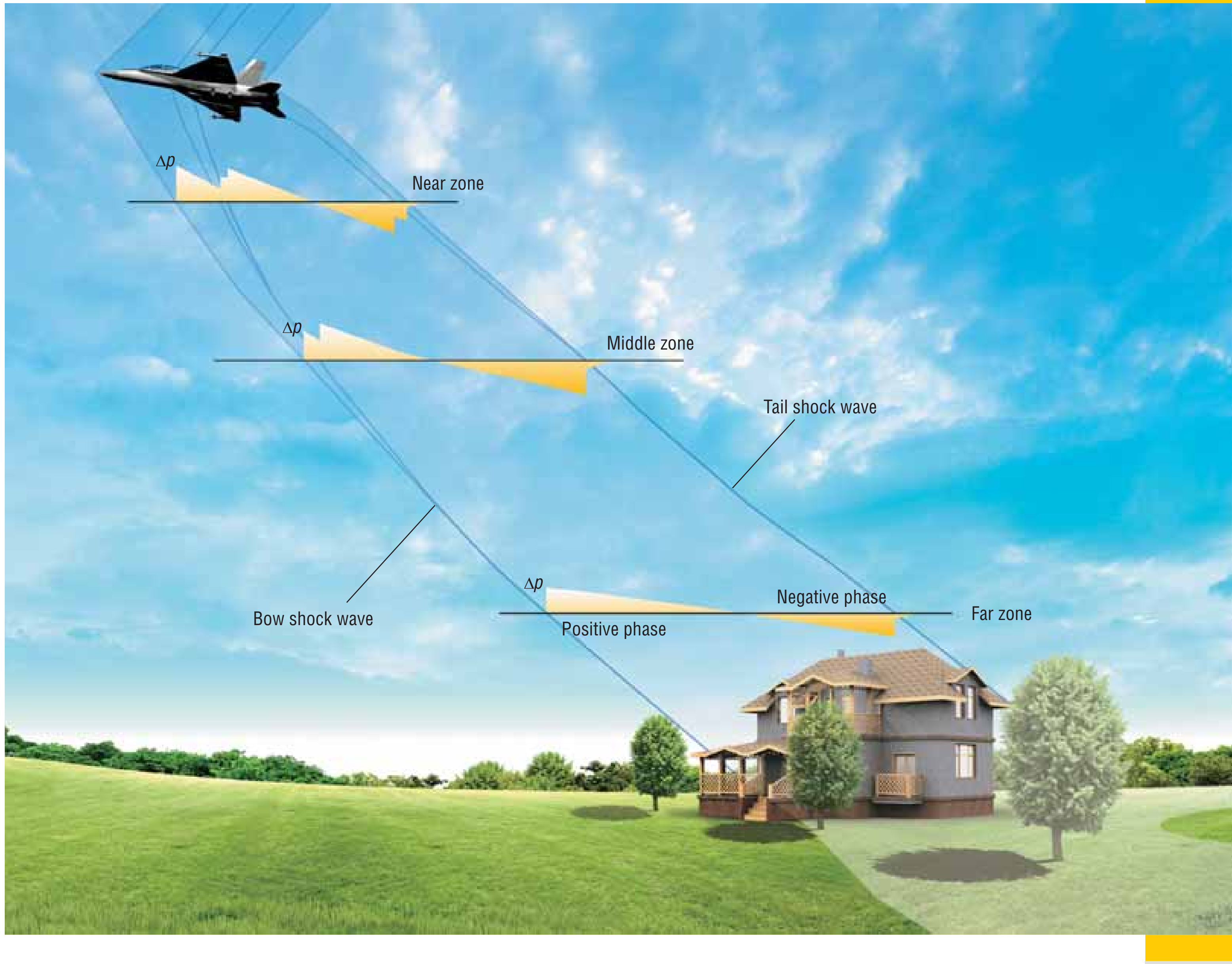
The pressure, temperature, and density of air behind the bow SW increase in a jumplike manner owing to superposition of disturbances. The flow at a greater distance from the aircraft (the so-called *far zone*) is transformed by nonlinear effects (dependence of the propagation velocity of disturbances on their amplitude) in such a way that distribution of the excess pressure (with respect to the atmospheric value) acquires an N-shaped signature. A person on the Earth's surface observes this *N-shaped wave* as one or two (depending on the aircraft size and flight altitude) remote explosions. This phenomenon induced by drastic drops of pressure on the shock wave is called the sonic boom.

The admissible excess pressure on the SW had to be limited because of the adverse effect (both psychological and physiological) of the sonic boom on human beings and animals and its destructive influence on buildings. A specific value of this restriction was periodically revised, as new information on the SB effect on the environment was gained. In view of the prediction for 2012 (15 Pa), we can state that in the last 40 years environmental requirements have become more severe almost by an order of magnitude.

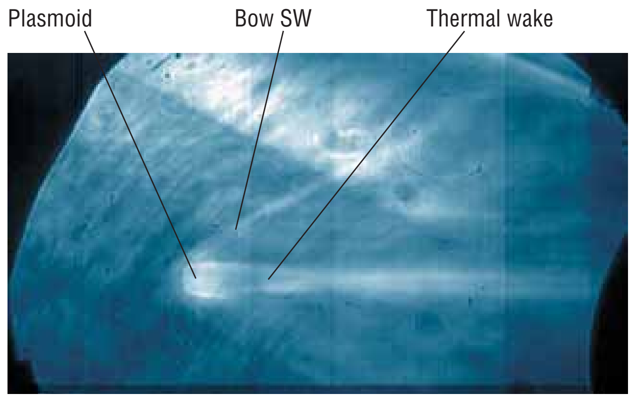
According to Whitham's classical theory used for design of supersonic aircraft, the pressure drop on the bow SW is determined by the distribution of the volume and lift force along the aircraft. This pressure drop decreases with increasing flight altitude and aircraft length and with decreasing aircraft weight. With a fixed payload and flight range, conditions that assist in SB reduction do not allow the same aerodynamic efficiency and, hence, cost efficiency of the aircraft to be ensured. For flying vehicles with a weight over 100 tons, it seems problematic to satisfy the currently imposed environmental requirements even with reduced cost efficiency.

Taking into account the limited capabilities of conventional methods, the scientists at the Institute of Theoretical and Applied Mechanics (ITAM) of the Siberian Branch of the Russian Academy of Sciences initiated the study of SB reduction by means of an active impact on the disturbed flow: with the help of mass or energy supply near the aircraft surface or, vice versa, with the help of energy removal. In particular, a unique method of controlling the parameters of the intermediate SW by coolant injection into the region of SW formation was developed in 2007. This made it possible to reduce the pressure drop on the bow SW by 40% almost without increasing the aircraft drag.

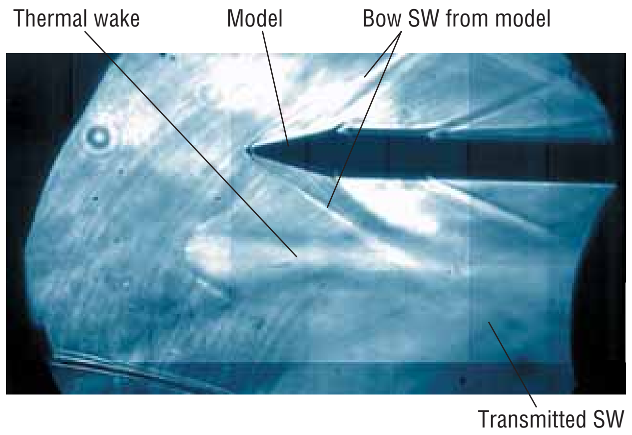
The current research at ITAM involves the possibility of SB attenuation due to interaction between the disturbed flow and the layer of heated air. Preliminary numerical simulations predict that the shock wave passing through a low-density gas layer with a high sound speed (provided by



When an aircraft flies with a supersonic velocity, the disturbed flow region is bounded by the bow shock wave and the tail shock wave. First, the pressure of air behind the bow SW increases in a jumplike manner owing to superposition of disturbances (positive phase of the SB signature). Further downstream, the pressure decreases below the atmospheric value under the action of flow expansion around the vehicle (negative phase of the SB signature). At large distances from the aircraft (far zone), the flow is transformed so that the pressure distribution acquires an N-shaped form.
The plots show the excess pressure Δp (with respect to the atmospheric value) as a function of the coordinate counted in the downstream direction in typical zones



Schlieren picture of the flow structure formed owing to interaction between a supersonic air flow (with a Mach number M = 2) and a plasmoid generated by laser radiation.
The CO_2-laser developed at ITAM operated in a pulsed-periodic regime and ensured a peak power up to 150 kW. A shock wave is formed ahead of the optical breakdown region, as in the case ahead of a blunted solid. The heated air wake is seen behind the plasmoid; the transverse size of this wake is nonmonotonic in the downstream direction



Schlieren picture of the flow structure formed owing to interaction between the optical breakdown region and the disturbed flow generated by a cone-cylinder model. The SW generated by the model and passed through the thermal layer is observed. The flow structure behind the incident SW is noticeably different. The flow behind the shock wave entering the thermal layer is re-oriented in the free-stream direction

heating) can be substantially attenuated at a certain ratio of temperatures in the layer and in the flow.

Experiments on the effect of the thermal layer on the SW generated by model objects were performed in a small-scale aerodynamic facility, which ensured a supersonic air flow with a transverse size of 100 mm. The thermal layer was formed by radiation of a gas CO_2-laser developed at ITAM. The mean power of this laser reached 4.5 kW. In view of the fast development of laser and microwave engineering, these devices can be considered as the most promising onboard sources of energy. The radiation energy can be fed to a supersonic air flow in the region of the *optical breakdown*. This term is usually used to indicate the transition of the gaseous substance into the plasma state under the action of an electromagnetic field with optical frequency. For this effect to be realized, the laser radiation intensity should be of the order of 10^9—10^{10} W/cm^2 during the time interval of 0.3—1 μs. Such extreme values of parameters can be ensured at the moment only in the regime of repeated (with a frequency of 80—100 kHz) pulses of focused radiation. In this case, plasma blobs (*plasmoids*) with a temperature of 20,000—30,000 degrees arise in the air flow. A thermal wake is formed behind the plasmoid.

In the first experiments, the researchers' attention was focused on studying the specific features of the flow structure formed owing to interaction of the plasmoid with the air flow whose velocity was twice higher than the sound speed.

The next milestone in activities was the analysis of interaction between the optical breakdown (discharge) region and the disturbed flow generated by a conical model. The instants when the SW disappeared after passing through the thermal layer were registered in the interaction region on the background of an unsteady flow. The observations were performed with a shadowgraph and a CCD camera.

The clearly observed changes in the flow structure evidence attenuation of the bow SW generated by the model. Note, in addition, that the shock wave from the plasmoid is estimated to be much less intense than the shock wave from the model even at small distances.

Now the primary effort is aimed at quantifying the effect of the thermal wake generated by the plasmoid on the SW parameters. For this purpose, direct measurements of the pressure distribution in the air flow are planned.

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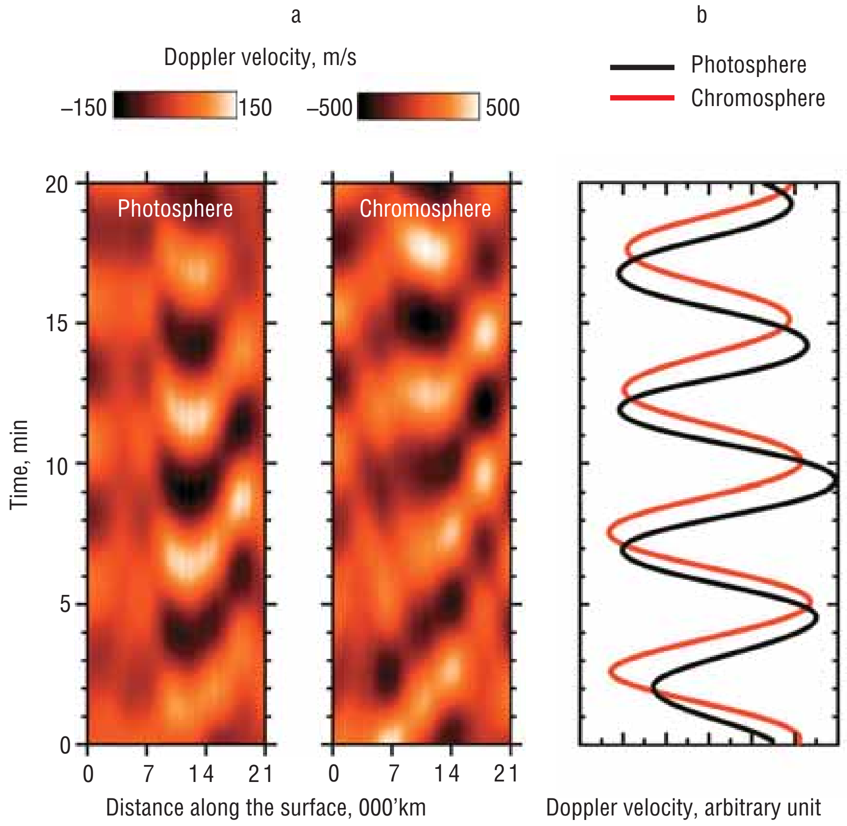
Waves in the solar coronal holes

A group of scientists from the Institute of Solar-Terrestrial Physics SB RAS (Irkutsk) have revealed propagating plasma waves at the base of solar coronal holes. Several Russian scientific teams along with their colleagues from abroad have joined their efforts to show that photospheric waves penetrate the solar corona because of the waves' parametric resonance with the oscillation modes of corona's magnetic structures. The result was recognized as the most important in 2008 in the Sun section of the RAS Astronomic Council.

Heating of the *solar corona*, the most outer cover of our lamp of the day, is a long-standing problem of astrophysics. The same can be said about the majority of star atmospheres. It has been firmly established that the Sun's surface visible to the eye (*photosphere*) has the temperature of about 5,800 K, while the upper *chromosphere* (the layer situated 2,000 to 3,000 km higher) is heated to 20,000 K, and the temperature of some areas of the corona reaches 4,000,000 degrees. How does the relatively "cool" photosphere heat the upper layers of the solar atmosphere? The second law of thermodynamics rules out the possibility of direct heat transfer from the photosphere to the hotter corona, which means that the energy must be transported in a different way.



a) Spatial-temporal diagrams of Doppler velocity in the Sun's photosphere and chromosphere illustrate the process of plasma waves' distribution in the coronal holes base. The color scale gives an idea of the amplitude of oscillations; dark areas show motion from the observer, and light areas indicate motion toward the observer.

b) The lag of oscillations in the chromosphere have helped to determine the velocity of wave propagation from the photosphere to the chromosphere

At present, two possible mechanisms are considered that claim to be energy “suppliers” to the corona. They can act both independently and together. The first one is the magnetic fields that penetrate the solar atmosphere to great heights and are able to accumulate and release significant energy. The second one is *plasma waves* generated by convective motions in sub-photospheric layers and other dynamic processes. Depending on the prevailing restoring force (the force that seeks to restore plasma equilibrium), the waves can be acoustic (waves of elasticity), gravity, or magnetic. Often these forces act simultaneously, and then we deal with the real centaur-waves: magnetoacoustic, acoustic-gravity, etc.

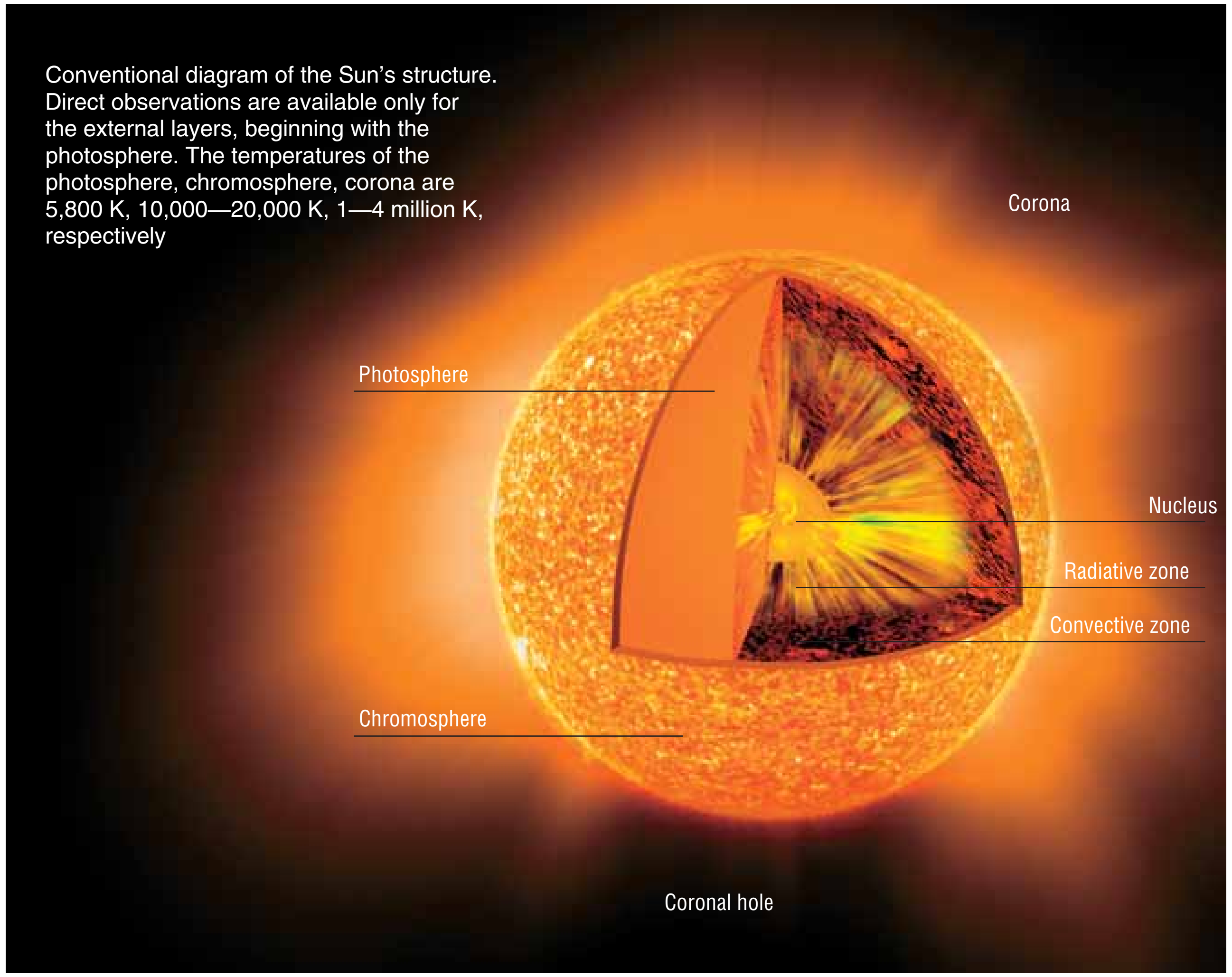
To study the oscillatory-wave processes on the Sun, we need large solar telescopes equipped with high-sensitive spectropolarimeters. According to the *Doppler effect*, the motions of radiative plasma bunches from an observer and to the observer respectively increase or decrease the length of the spectral line wave, shifting it from the initial position (the higher the speed, the greater the shift). The equipment available at the Institute of Solar-Terrestrial Physics in Irkutsk is able to register variations constituting less than one ten-millionth of the radiation wave’s length. Making synchronous measurements on several specially chosen spectral lines it is possible to obtain high-altitudinal cuts of Doppler velocity within the range of photosphere-chromosphere heights (which are about 2,000 km) for the solar atmosphere objects featuring various configuration of magnetic field. The largest and most interesting among these objects are the *coronal holes* (CH).

The coronal holes owe their name to the fact that in X-ray and extreme ultraviolet ranges they look like dark depressions in the bright corona. Astronomers connect them to the large-scale magnetic structures with an open configuration of magnetic field, i.e., the one when magnetic field lines in the photosphere are perpendicular to the surface and preserve this direction when exiting into the inner corona. By the way, the *solar wind* – a flow of charged particles from the Sun – which plays such an important role for the Earth, comes out of the CHs.

To study certain oscillation modes in detail, we used the frequency filtering methods, which allowed us to single out the components we were interested in from the noise-type mixture of quasi-stationary motions and various oscillations, and then to restore their initial spatial-temporal distribution with the help of reverse transformation. This operation has turned out to be especially useful for revealing propagating waves. We have discovered and recorded convincing manifestations of waves propagating upward in the immediate base of the coronal holes.

The presence of wave motions of this kind is indicated by the repetitive inclined stripes on the spatial-temporal diagrams of Doppler velocity. Distances between the stripes along the time axis correspond to the period of oscillations, and the angle between a stripe and the time axis is related to the horizontal projection of propagation velocity (the bigger the angle, the higher the velocity). The propagation velocity of a wave from the photosphere into the chromosphere was determined by the average time lag of Doppler velocity signals. As a result, we learned that dominating were the waves with a 5-minute period (*fundamental photospheric mode*), although we often observed oscillations with a 10- to 15-minute period. The measured phase velocity made up 40—45 km/s for equatorial CH and 70—80 km/s for polar CH.

Joint efforts of several scientific teams from the Institute of Applied Physics RAS, Institute of Solar-Terrestrial Physics SB RAS, Central (Pulkovo) Astronomic Observatory RAS, Nizhniy Novgorod State University, and Helsinki University of Technology, which involved radio data, have showed that penetration of photospheric waves into the Sun’s corona is possible as a result of *parametric resonance* of these waves with the oscillating modes of the corona’s magnetic structures. Though, as it often happens, we have ended up in having more new questions than answers to the questions asked earlier.



Conventional diagram of the Sun’s structure. Direct observations are available only for the external layers, beginning with the photosphere. The temperatures of the photosphere, chromosphere, corona are 5,800 K, 10,000—20,000 K, 1—4 million K, respectively

In the future, we should learn what part of energy of plasma waves is spent on the heating of the corona, and what part is taken away with the solar wind. In this case, coronal holes might play the role of an energetic valve that regulates the degree of corona heating. We believe that the joint grant of the Russian Foundation for Basic Research and Royal Astronomical Society of Great Britain received in 2008 will help to move further in the solution of this problem thanks to the joint efforts of Russian experimenters and British theorists.

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