A. S. Gadun and V. N. Karpinskiĭ. *Problems of the structuration of the sun and stars.* All layers and formations on the sun and stars inherently have a complicated system of structures. Instability in the core is characteristic of the "structureless" Standard Solar Model (SSM). The instability should evolve through the appearance of nonuniformities and motions.[1] The nonstationariness of the solar neutrino flux in July 1991 was recorded by both independent neutrino experiments SAGE and GALLEX and constituted 300 SNU with a background value of 75 SNU and 132 SNU for SSM.[2] The reality of fine-structural nonuniformities in the radioactive core and the base of the convective zone was discussed in Refs. 3 and 4. Significant density nonuniformities inside the sun could possibly be observed with the help of accurate measurements of the shape of the surface of the gravitational potential near the sun. The main regular structures of the solar photosphere—supergranulation, mesogranulation, and granulation (Fig. 1)—form above the convective zone.

Studies of the fine structure of the sun are based on optical observations with high spatial resolution of fractions of an arc second (less than 500 km on the sun's surface). Photographs obtained at the Soviet Stratospheric Solar Observatory 20 years ago remain unsurpassed as a source of new information. A great deal of valuable data was obtained, using the PAMIR telescope, from 1978 to 1988 during the Pamir expedition of the Main Astronomical Observatory of the USSR Academy of Sciences. The

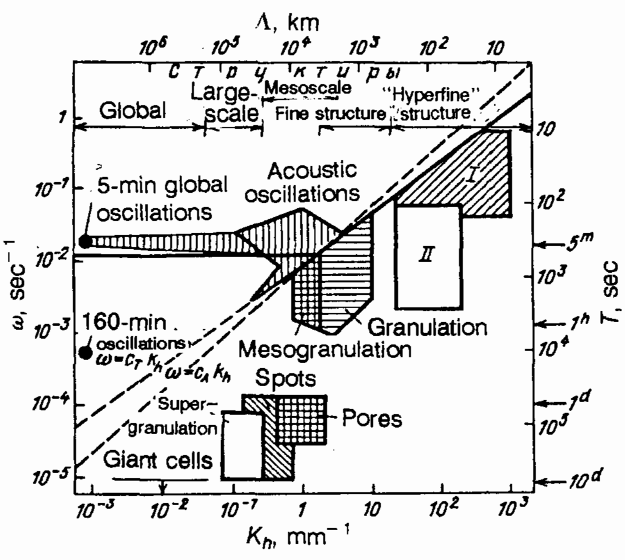

FIG. 1. System of structures of the solar photosphere. k_h—horizontal wave number, ω—frequency. *I*—microturbulence, *II*—"point" granules, filagrees, "point" magnetic flux tubes.

measurements of the contours of the spectral lines to within 0.1% and the spectral line bisectors, which characterize the line asymmetry and contain the main information, have made it possible to study unresolved fine structure not only on the sun but also on stars.[5]

The theory was of little value and the theoretical predictions were wrong. Three-dimensional numerical modeling of structures with the help of conservation equations written in the most general form first became possible at the beginning of the 1980s.[6,7] The results of such modeling can be compared directly to observational data. The physicality and closeness of the models to reality come with limitations. These limitations are associated with the impossibility of modeling with an adequate degree of detail a large volume as well as the selective radiant energy transfer in a nonuniform medium. There arises here an arbitrariness in the boundary conditions and subgrid turbulent viscosity. Numerical models have become an important research tool.

We now consider the key observational facts:[8]

1. The rms magnitude of the brightness nonuniformities is 22% of the average brightness for the center of the solar disk. Our estimate was significantly greater than previous estimates.

2. The magnitude of the brightness nonuniformities decreases monotonically and slowly to 6% from the center to the edge of the solar disk. Fine structure was first observed at the very edge of the solar disk and even "beyond the edge" of the point of inflection of the photometric profile of the edge.

3. Motions with velocities of the order of 1 km/sec are characteristic of the entire thickness of the photosphere. High correlation of the Doppler line shifts is observed for spectral lines formed at altitudes ranging from 50 to 250 km above the apparent surface of the solar disk. Here the structure of the velocities is uniform in the vertical direction and consists of vertical cylindrical columns. Higher up this structure breaks down rapidly in a thin layer several tens of kilometers thick, as if the vertical flows encounter some barrier.

4. Brightness nonuniformities in the continuous spectrum are markedly different from those in spectral lines. Maps constructed for a vertical section of the photosphere have shown that the brightness structures are strongly nonuniform in the vertical direction already at altitudes of 70 km, and they are substantially three-dimensional, complicated, and diverse. The boundaries of light and dark formations are strongly inclined with respect to the vertical (by angles greater than 80°).

The character of the brightness structures differs qualitatively from that of the velocity structures. The predominant rising of hot matter and sinking of cold matter are characteristic only of the lowest layers of the photosphere. Typically, the bright elements of the structure—granules—rotate in the vertical plane.

5. The photospheric brightness field is well represented by a collection of two-dimensional simply connected bright granules and dark porules of brightness impulses, starting at a definite brightness level, the "starting" level, nad lying above and below it. The starting level lies 4 to 10% below the average brightness level of the photosphere surface, and part of the radiant flux is associated with the fine structure. The structure of the photospheric brightness field is well organized and differs from both a "purely random" Gaussian field and the usually adopted cellular structure of "unipolar" bright formations (granules), separated by an unbounded network of narrow dark intervals.

6. Over a time shorter than the average lifetime of granules of 5 min the number of granules on an area of $4 \cdot 10^8$ km^2, containing about 300 granules, changes coherently by a factor of 1.5. The total area occupied by the granules changes in antiphase, and the average area of the granules changes by a factor of 2.[10] A reliable change in the mathematical expectation of the number of granules is accompanied by a decrease of their random fluctuations. This is characteristic for autowaves in stochastic nonlinear ensembles. The spread in the observational data could reflect the observed nonstationariness. Similar oscillations of radio emission, which are probably associated with the change in the structure of the lower chromosphere, have been recorded.[11]

7. P. Brandt, A. M. Title, G. Sharmer, *et al.* employed a different approach.[12] They associate to the scalar brightness field a vector field of the velocities of the brightness fronts. From this field they extract different spatiotemporal components, estimate the divergence, circulation, and vorticity, and follow the streamlines by the method of test particles "cork pattern". An impressive computer film and morphodynamic model have been constructed from the observational data.[13] The brightness field inherently contains stable large-scale "currents," "sink" lines and points, and vortex structures.[14] Our data do not confirm the conclusion that "exploding granules" play a determining role. We note that identification of the motions of the brightness fronts with real horizontal motions of matter in the photosphere is incompetent. The obtained results are, however, very important, in spite of their phenomenological nature. They indicate that the apparent "random" pattern of the evolution of granules is governed by strict laws.

The results of numerical modeling agree qualitatively with the observations. The rms brightness nonuniformities give a large spread of 10-30% for both the observational and model estimates. A number of characteristics cannot be reliably compared due to the smallness of the area being modeled.

In summarizing the results, we arrive at the following picture of the structures (Fig. 2).

In the lower photosphere (h=0–50 km) the velocity structures are identical to the temperature structures. It is only here that the concept of "granule" for designating an element of the three-dimensional structure makes sense. Convection plays a significant role here.

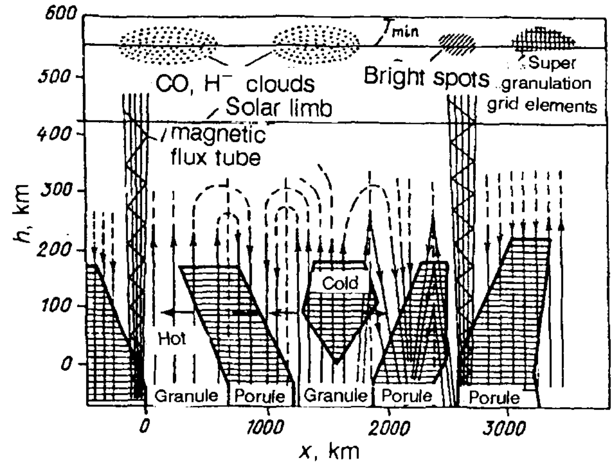

FIG. 2. Fine structure of the solar photosphere (vertical section).

The columnar structure of the velocities, which is now no longer correlated with the complicated vertically nonuniform temperature structures, remains in the middle photosphere (h=50–250 km). A singular cellular structure also does not exist. Matter flows out through the stationary boundary of a granule, as a structural formation, and this process is accompanied by intense cooling of the matter (by 5–10 K/km). This is the convectively stable region of penetrating convection. The hot rising flows cool rapidly, while the sinking flows, conversely, are heated due to compression. Cooled matter can also rise.

At an altitude of 250 km the columnar structure of the velocities breaks down rapidly. Granulation-scale convective motions do not reach directly the top of the photosphere. But they can engender secondary motions and waves.[15] Density nonuniformities associated with magnetic flux tubes (F. Kneer, 1991) or deviations from hydrostatic equilibrium can be seen at an altitude of 350 km above the disk edge. Here and higher up nonuniformities can have a nonconvective nature (CO and H^- clouds), and they can generate nonthermal energy which heats up the chromosphere and corona.[16,17]

What is the nature of the fine structure of the atmospheres of other stars and how does it change as the sun evolves? In order to answer these questions extensive highly accurate measurements of the spectral line contours were performed for bright stars and the shapes of the spectral line bisectors were estimated.[18,19] The character of the structures depends primarily on the effective temperature of the star. The top boundary of the photospheres of solar-type stars lies at the level of the radiating layer $\tau_R = 1$, and the photospheric structures are an epiphenomenon of convection. In the hotter atmosphere of Procyon granulation is of a more contrasting "open" character; hot rising convective fluxes spread into the upper photosphere up to $\tau_R = 10^{-3}$; only the shape of the bisector changes qualitatively. For colder stars granulation is "stamped out," and the top convection boundary lies below the radiating layer. For stars of early spectral classes the bisector is inverted, and the nature and morphology of the granulation are qualitatively different from that of the sun.

CONCLUSIONS

1. The small-scale nonuniformities form an organized dissipative structure. They are associated with generation, transfer, and release of nonthermal energy, i.e., with fundamental processes occurring on the sun and stars.

2. A reliable and quite complete system of observational facts has been constructed. These facts must be generalized in dynamical models at different levels—physical and phenomenological. Theories must be developed for the structures and new key observational problems must be formulated. The following are of special interest: vortex "polar" structures; nonuniformity and nonstationariness of the "quiet" atmosphere of the sun; the character of the interaction of structures of different levels—from "hyperfine" to gigantic—and their nonhierarchical nature; collective processes in the fine structure; and, the determining role of the fine structure in large-scale global phenomena.

3. New methods of adaptive polarimetry make possible direct studies of the fine structure of magnetic fields taking into account their unresolved "hyperfine" structure.

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Translated by M. E. Alferieff