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Scientific legacy of S.B. Pikel'ner and today's astronomy

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The scientific heritage of S.B. Pikel'ner has been considered systematically over 35 years after his death. We mark which of his results preserve their primary significance, which suffered noticeable specifications and development and which of them gave rise to new directions of astrophysical investigations.

Keywords: Personalia

1 Introduction

Solomon Borisovich Pikel'ner died at the age of 54, at the zenith of his scientific creative power. This is not a usual phrase from the obituary but the exact diagnosis. Actually, only in 1975, the last, incomplete year of his life, he published papers on field annihilation and particle acceleration in solar flares (jointly with V.N. Tsytovich), and on the influence of fluctuations of interstellar medium density on measurements of the velocity of supernova remnants (jointly with K.V. Bychkov), the popular article in the Russian journal "Priroda" (Nature) about solar flares, "moustaches" and spiculae. A month before his death, he gave a substantial lecture titled "Scientific Discovery and its Perception" (Pikel'ner, 1984) at the Methodological Seminar in SAI. And all this was combined with regular lectures and countless consultations for students, graduate students, candidates for Ph.D. and for Soviet Doctors of science, intensive work at the editorial office of the Soviet "Astronomical Journal", where he contributed significantly to the image of the leading Soviet astronomical journal. Half a dozen of S.P's scientific papers and four fundamental collective monographs to which he contributed substantially were published after his death.

We publish this article on the occasion of 90th birthday of a distinguished Soviet scientist S.B. Pikel'ner, whose ideas played a substantial role in the development of many branches of astrophysics. A whole generation of Soviet astrophysicists was trained on the base of his ideas. Many of his pioneering works still keep being developed in spite of the 35 years elapse since his untimely death.

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Solomon Borisovich Pikel'ner (February 7, 1921 – November 19, 1975)

S.P.'s untimely death was a tremendous blow to the Soviet astrophysics. Obituaries dedicated to him appeared in almost all the Soviet and many outside-USSR astronomical journals.

More than 35 years have passed since that sad day, November 19, 1975; it is more than Solomon Borisovich lived in science. Practically all his contemporaries, his friends, colleagues and opponents have passed away; rows of his pupils are thinning out. But astrophysics is an intensively developing science: new experimental facts and theoretical concepts keep appearing, and young researchers join the science. And they should know, on the shoulders of what giants, according to Newton, they are coming to stand.

S.P's interests covered practically all the fields of astrophysics, from Jupiter red spot and Earth night sky luminescence up to galactic nuclear activity, except perhaps the problems of radiative energy transfer and stellar interior structure. When he was asked why he avoided such "up-to-date" subjects as neutron stars and black holes, S.P. answered that he preferred to deal with problems that are still lacking their full physical explanation but already have a substantial observational basis.

S.B. Pikel'ner was among the first to appreciate all the importance of magnetohydrodynamics and plasma physics for penetrating into the nature of the cosmic object. Through his works on many phenomena in the interstellar medium, galaxies and solar atmosphere gained a new apprehension which has changed the face of contemporary astrophysics. In this transformation of theoretical astrophysics into a science of physical conceptions of processes in plasma S.B. Pikel'ner's contribution is invaluable.

We will consider the place of basic scientific results of S.P. in contemporary science, pointing out which of them preserve initial value even now, over the decades, which of his results underwent noticeable specifications and development and which

of his results opened new trends in research. We have divided his basic works into three extensive groups related to three large subjects: "solar physics", "physics and evolution of stars" and "physics and cosmogony of the interstellar medium and galactic structures".

2 Solar physics

Results of solar observations, carried out up to the 60s of XXth century, allowed S.P. to create the first consistent picture of development of physical phenomena on the Sun. This picture helped significantly to orientate in new observational data, to find places for the new discovered phenomena and to give them reasonable physical interpretation.

2.1 Dissipation and thermal radio emission of the solar corona

The first Pikel'ner's (1950a) work which brought wide acclaim was his consideration of dissipation of particles from the solar corona. He constructed the correct model of evaporating corona, but in the late 1950s it was displaced by the dynamic model, developed independently by E.A. Ponomarev (1957) and E. Parker (1958); after a number of publications by latter one and introduction by him the term "solar wind" his gas dynamic theory became widely accepted.

I.S. Shklovsky and S.B. Pikel'ner (1951) developed the theory of thermal radio emission of the solar corona. They estimated a full flux from the chromosphere and corona for the wavelength range from 1 cm to 2 m, and predicted enhancement of decimetric emission on the solar limb was certainly confirmed.

2.2 Magnetohydrodynamical phenomena on the Sun

One of the most interesting works by Pikel'ner (1962) was his explanation of existence of the chromospheric network. The main S.P.'s merit is that he offered the motion transmission mechanism from supergranulation cells situated in depth to external layers, associating it with peculiar plasma raking up mechanism. A result of the idea expressed by S.P. was that the magnetic field properly becomes stronger to the borders of supergranulation cells. Simon and Leighton (1964) confirmed this prediction by direct observations of field amplification on the borders of the chromospheric network.

At present a convection theory in the presence of a magnetic field develops intensively due to the new computational capabilities. However, the mechanism proposed by S.P. revealed itself obviously in this modeling first within the framework of two-dimensional and then three-dimensional magnetoconvection theory. At the present time the local helioseismology allows studies of the motions in deep solar layers. In this direction one of very new results is a determination of chromospheric network depth which S.P. estimated rather arbitrarily, but successfully as it follows from helioseismology. Under a solar spot at the depth from 10000 to 20000 km a region was found which is hotter than the surrounding plasma. S.P. assumed the possible existence of such a structure but his work of 1975 remained incomplete. The investigation

carried out in 1966 by S.P. jointly with Livshits and Obridko (Livshits *et al.*, 1966) about a sinking of the corona above spots, in spite of active debates at that time, appeared to be correct and went into everyday use.

Until today S.P.'s (1969a) results concerning the fine structure of the middle chromosphere remain actual; the heterogeneous nature of the chromosphere and physical conditions in small loops-filaments of the middle chromosphere or fibrils – were confirmed by subsequent 30-year observations.

S.P. started a large study on the clarification of the structure of the coronal layers of active regions and on the propagation of magnetohydrodynamic waves there. Despite a considerable amount of new observations of the active regions in different spectral ranges and the study of differential emission measure dependence on the temperature, the general conception about coronal condensation, proposed by S.P. in 1961, has not been changed essentially.

The role of plasma evaporation from the chromosphere into the coronal part of arches is considered the same way. Investigation by van den Oord and Zuccarello (1996) only specified an energy balance in coronal loops and gave a natural explanation of the well-known similarity law, derived from the analysis of the first Sun's images in the soft X-ray range.

The problem of oscillation propagation in the outer solar atmosphere was considerably developed. Its investigation was started in the paper on the wave interaction in the chromosphere (Pikel'ner and Livshits, 1964). Theoretical analysis of linear and non-linear propagation of waves in the outer solar atmosphere has been widely developed during last 30 years. This analysis connected propagation of waves with various magnetohydrodynamic instabilities which can originate in bunches of force lines, filled with hot plasma. Oscillations of coronal loops were discovered with the TRACE satellite, and the mentioned theoretical ideas allowed giving their interpretation. Thus, a new possibility appeared for diagnostics of physical conditions in fine coronal structures.

The interest to the S.P.'s work on prominences arose repeatedly in recent years. Within the framework of his "siphon" model of the quiet prominence (Pikel'ner, 1971) it turned out to be possible to understand a row of conformities discovered in observations in the extreme ultraviolet and X-ray regions both in quiet prominence and in their fine structures. In modern films, for example, from satellite TRACE, siphon motions in coronal loops are frequently visible, and the transformation process of hot plasma into the cold one, calculated by S.P., can be observed directly.

So, S.P.'s contribution to the study of active solar regions (plages) consists of the consideration of problems relating simultaneously to all the layers: to photospheric faculae, flocculus and coronal condensation. In recent years a number of refined observations were carried out, however the general understanding of a picture of stationary phenomena remains at the level of ideas advanced by him.

The investigation by N.D. Kostjuk and S.B. Pikel'ner (1974) became a classic one. It was the first research of a gas-dynamic response of the chromosphere to impulsive heating. Afterwards this work was continued: a numerical modeling for the case of strong heating particle streams, which appear in powerful solar and stellar flares (Livshits *et al.*, 1981), and besides numerical computations the exhaustive analytical consideration of this problem was carried out (Fisher *et al.*, 1985). In some periods a number of works on this problem exceeded a hundred per year.

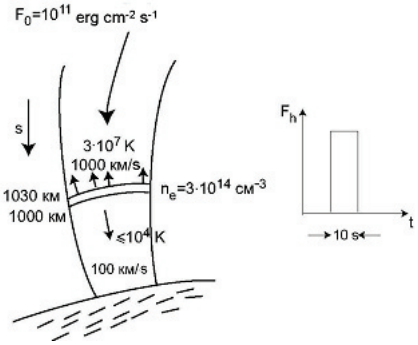


Figure 1 Scheme of gas-dynamics response of the chromosphere to impulse heating. Values of the accelerated electron beam energy F_0 and the duration of the beam exposure on the chromosphere (10 sec) are given. The volume occupied with dense cold gas is moving downward while hop plasma flows upward from its upper boundary. The quantity s is the Lagrangian coordinate.

The results of the study of chromosphere response to impulsive heating were confirmed with different observations. An outflow of hot plasma from bright points was directly discovered; properties of a source of optical line emission in fact coincided with theoretically predicted ones; momentum balance of gas propagating up and down from the high pressure region which occurs at the beginning of the process was checked (Bentley *et al.*, 1997). These results are directly confirmed from the RHESSI data (Liu *et al.*, 2006). Now the exact computations of this task have been already started on the base of the equation system of radiative gas dynamics for the solar (Abbett *et al.*, 1999) and stellar (Allred *et al.*, 2006) flares.

Within the framework of conception, developed by Pikel'ner and Kostjuk, the gas-dynamical model of impulsive flares on red dwarf stars (Fig. 1) has been developed since 1981 (Katsova *et al.*, 1997). This model allows evaluating the most exactly radiant areas of continuous optical sources of stellar flares; at present observational results and their interpretation, based on new analogous computations, enable us to conclude that majority of flares on red dwarf stars are similar to compact flares on the Sun (Katsova *et al.*, 2002).

2.3 Field annihilation and plasma physics

After the appearance of works on magnetic field reconnection as a possible energy source in solar flares Pikel'ner began to deal systematically with problems of plasma astrophysics. Three directions of his research can be marked here.

Pikel'ner (1969a) developed the theory of origination of small-scale ejections of so-called chromospheric spicules, and the theory of appearance of the bright emission sources at different levels of the outer atmosphere. In the case of bright points acceleration up to speeds of about 500 km/s and heating of small amounts of plasma are produced directly by the magnetic field and by forces related to it, but not by electron beams. In the 1990s this approach turned out to be rather attractive for the analysis of phenomena of not high power, in particular, for X-ray jets (Shimojo *et al.*, 1996).

A flare is a powerful process of rapid energy release. In the middle of the 1960s, S.I. Syrovatsky began to develop actively a conception on dynamic dissipation of the magnetic field related to acceleration of all the particles in current sheets to relativistic energies. S.B. Pikel'ner formulated a few serious restrictions of qualitative character on the flare theory. The most essential of them is a necessity to have a mechanism for effective gas removing from the sheet with a sufficient high speed, and this problem remains open.

Nowadays irrefutable evidences were obtained that at the definite (post-eruptive) flare stage the development of reconnection of magnetic field lines actually takes place. The direct observations of this process are started at the satellite YOHKOH and today there are already more than 10 cases, registered at the satellite RHESSI (Sui *et al.*, 2004). These observations show that after reconnection in the current sheet positioned at the coronal heights, some loops are compressed towards the photosphere under the action of magnetic forces (shrinkage effect), and other loops are thrown outside to the external corona and interplanetary space.

In studies of 1974–1975 it was underlined that in plasma when exceeding the electronic temperature above the ionic one the ionic-sound instability appears which originates at the lowest threshold for the most important current instabilities. In recent years problems of direct magnetic field energy transformation into energy of large-scale ion motions related to tiring-instability development came into a question more frequently. Besides, from data obtained at a few nearby spacecrafts it follows that development of processes in collisionless shock waves takes place in a different way than previously presented. It requires the revision of those concepts on conditions in current sheets of solar flares and on structure of collisionless shock waves in cosmic plasma, which were developed in books by Kaplan, Pikel'ner and Tsytovich (1974, 1977).

The first picture of solar MHD events was proposed by S.B. Pikel'ner in the review of 1966 (Pikel'ner, 1966). And now it is impossible to imagine the contemporary state of solar physics without studies developed by S.B. Pikel'ner.

3 Physics and evolution of stars

Pikel'ner's research into stellar physics was very largely the extension of his investigation of the Sun.

3.1 Stellar coronae

Pikel'ner (1950b) immediately applied the above described model of the stationary solar corona dissipation to stars of different types. Although the dynamical model of stellar wind soon prevailed, in the framework of the stationary coronae evaporation model there were considerations about the temperature-stabilizing ("thermostat") effect of this process, namely about the connection of corona temperature with proton escape velocity in the stellar gravitational field. And these considerations resulted in a simple correlation for the estimation of expected temperature of stellar corona on the stellar surface gravitational potential. The conclusion based on this correlation about the expected low coronal temperatures of late giants and expected high temperatures

of hot supergiants has become widely used for estimations of expected radiation of these stars in different wavelength ranges.

3.2 Solar-type activity of stars

3.2.1 Solar-type activity of red dwarf stars

On the basis of analysis of photometric, spectral and radio observations, R.E. Gershberg and S.B. Pikel'ner (1972) concluded that processes on red dwarf stars and the solar activity are physically identical and that the activity of young T Tauri type stars evolves into that of the red dwarfs. Together with the idea of strong magnetic fields being responsible for such stellar activity presented shortly afterward by D. Mullan (1975), these two works formed the basis of an important conceptual branch of solar-stellar physics: the activity of the main sequence solar-type stars. In subsequent years this line of investigations was intensively developed, substantially due to supplementing the research in optics with that in ultraviolet, X-ray and radio range.

Investigations of emission spectra of the flare stars during "quiet" states made the analysis of stellar chromospheres and coronae possible and led to the construction of models of these structures qualitatively similar to the respective solar atmospheric structures. The long series of spectral observations of active stars allowed revealing the stellar activity cycles analogous to the 11-year solar cycle. The X-ray observations found stellar corona on hundreds of active dwarf stars and registered dozens of X-ray flares on them.

The high time-spectral-and-spatial resolution observational data on active processes on the solar surface served as a base for the models of transient flares, dark spots, active regions, coronal loops and other local stellar structures. On the other hand, very young and very old G dwarfs allowed figuring out objectively the evolution of solar activity during the past and forthcoming billions of years (Fig. 2). Characteristics of solar activity follow the general dependence of respective characteristics of stars of the axial rotation period. So, now it is clear that the braking in stellar rotation is the main factor of activity evolution. Therefore the cause of essential distinction between single and binary stars in the duration of the activity phase becomes clear: the rotation of the single stars is decelerated for approximately a billion years due to the transfer of the angular momentum by the magnetized stellar wind, while in the case of the components of binary systems fast rotation and hence high activity level are kept for many billions of years at the expense of transferring of the orbital momentum onto the axial rotation.

A summary of investigations on the solar-type activity of the main-sequence stars is given in the monograph Gershberg (2005) and in papers by Katsova and Livshits (2006) and by Katsova *et al.* (2007).

3.2.2 Solar-type activity on accretion discs

S.B. Pikel'ner's idea of the magnetic reconnection mechanism applicability not only to the Sun and other stars with the activity of magnetic nature, but it also found a wide application to X-ray sources of both the stellar and galactic nature.

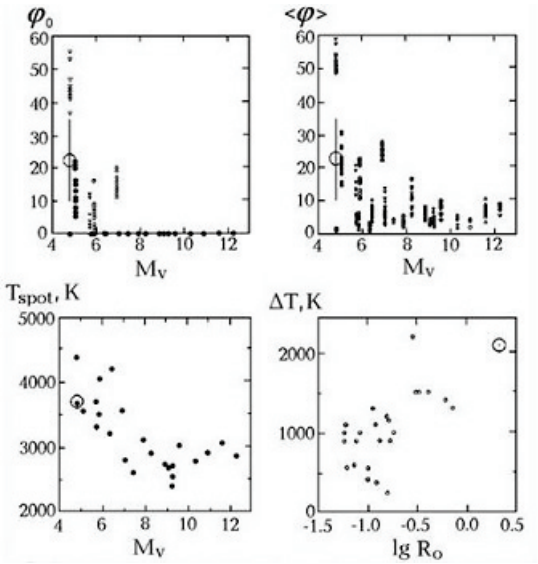


Figure 2 Dependences of some global parameters of certain stars from the surface spottedness characteristics. Upper left box shows the lower boundary of spot latitude φ_o from the star absolute magnitude M_v; upper right box gives dependence of the spot average latitude $<\varphi>$ from M_v; left down, spot temperature ΔT_{spot} from M_v; and right dawn, temperature difference T between photosphere and the spot as function of Rossby number R_o (the star spin period / convective vortex turnover time-span ratio); the solar characteristics are marked by the symbol of the Sun (Alekseev, 2001).



Figure 3 Magnetic structure of the inner parts of the accretion disk around black hole, with a moderate accretion rate, the luminosity remaining far below the Eddington limit (Bochkarev, 1985b).

The important role of great solar-like flares on accretion discs around black holes was first proposed by V.F. Shvartsman and L.A. Pustil'nik (see Pustil'nik and Shvartsman 1974). Previously, V.F. Shvartsman (1970, 1971) showed that flickering inside accretion discs is a result of solar-like flares due to reconnection of magnetic field force lines in magnetic arches above the disc surface and concluded that within the innermost parts of the disc closest to the black hole, the magnetic field pressure becomes commensurable with gas pressure and the disc breaks into separate fragments

connected by magnetic arcs. Their entangling by differential rotation leads to reconnections producing X-ray flares of millisecond or shorter duration.

N.G. Bochkarev described this model in his popular books about magnetic fields in space (Belov and Bochkarev, 1983; Bochkarev, 1985b), and gave a picture (Fig. 3) illustrating the model by L.A. Pustil'nik and V.F. Shvartsman. Currently this is the conventional model explaining the rapid non-periodic flare X-ray variability of astronomical objects containing black holes.

4 Physics and cosmogony of interstellar medium and galactic structures

4.1 Emission and reflecting diffuse nebulae

G.A. Shajn, V.F. Gase and S.B. Pikel'ner (1954) carried out photometric research of several dozen nebulae of different types and drew out a correlation between the nebula type and the spectral type of an exciting star. Within the framework of the Stromgren zone conception, a simple correlation exists between emission nebula size, gas density and hot star ionizing factor. Using different models of hot star photosphere, R.E. Gershberg and V.I. Pronik (1959) and V.I. Pronik (1960) calculated the numerical factors for the exiting stars of the spectral types from O5 to B2.5 and showed that, according to the observational data by Shajn *et al.* (1954), HII regions are not to be found around late B stars, whereas the obtained factors well represent the size of HII regions around O5–O8 stars.

S.B. Pikel'ner (1953) analyzed helium ionization in the emission nebulae near the hot stars and developed the helium zone theory analogous to the Stromgren theory for hydrogen. Due to the existence of two stages of helium ionization, this theory turned out to be richer than that for the hydrogen zones.

Research on excitation of planetary nebulae including temperature distinction at Lyman hydrogen and helium continua was considered by V.I. Pronik (1964). He represented energy distribution in stellar spectra within the ranges 912–504 Å, 504–228 Å and shorter as frequency power functions and proposed a parameter determination algorithm for these functions out of observational data. Later V.V. Golovaty and coauthors (Golovatyi *et al.* 1993, Holovatyy and Havrilova 2005) constructed a thorough self-consistent photo-ionization model of gaseous nebula that allows determining, on the basis of spectral observations, the nebula chemical composition and energy distribution within the ionizing range of a stellar spectrum in the form proposed by V.I. Pronik. Presently the construction of photo-ionizing models for HII regions and restoration of spectral energy distribution within the range 100–912 Å, visible neither from the Earth nor from the Solar system vicinity, is an independent direction of astrophysical research based on detailed computer models of the nebulae.

In early 1950s there were some attempts in astrophysics to introduce the first dynamic conception of the interstellar medium: the locally-isotropic Kolmogorov turbulence.

S.B. Pikel'ner (1954a) developed a turbulence research method based on fluctuations of surface brightness of nebulae. S.P. and G.A. Shajn (1954) applied it to the study of Orion nebula. Having performed the nebula photometry, they built surface brightness statistic functions and found that within two-three hundredths of parsec

observations do not contradict to the isotropic turbulence models. Later B.P. Artamonov and R.E. Gershberg (1962) and B.P. Artamonov (1964) got similar results for the diffuse nebulae NGC 6618 and NGC 2237-9, respectively. However, a later analogous analysis of the Orion nebula image in H_α, obtained in the prime focus of the 2.6 m Shajn reflector with better resolution showed the statistic function of surface brightness fluctuations to be closer to the function of accidental brightness distribution than to the turbulence model (Gershberg, 1964).

As a development of Pikel'ner's work on nebulae small-scale inhomogeneities one should mention the elaboration by A.F. Kholtygin (Kholtygin and Feklistova 1992; Kholtygin, 2005) of a formalism that allows determining from the observed ratios of forbidden spectral lines of heavy elements, not only the temperature and electron density but also the mean-squared scattering of the proper parameters.

4.2 Fine filament structures – remnants of supernovae' flares

Using the nebular spectrograph, S.B. Pikel'ner (1954b) obtained spectra of the fine-filament nebula in Cygnus. To explain such structures, he developed the theory of luminescence of the shock waves in the interstellar medium. The numerical methods, in spite of their active developing over the last 50 years, yielded no substantial changes in our understanding of the essence of physical processes revealed in that pioneer work by S.P.

Computing shock wave luminescence, S.P. took into account the fact that energy in a wave is first transmitted to the heavy particles. Therefore in shock wave early profiles the ion temperature is the highest. Solving a system of hydrogen and helium ionization and energy balance equations, S.P. determined physical conditions – temperatures T_i and T_e and hydrogen and helium ionization degree – along the axis $n_H t$ (Fig. 4). For those conditions he calculated the expected radiation intensities in observed hydrogen lines H_α and H_β and forbidden lines of OII, OIII, NII and SII.

Having found out the shock wave front structure, Pikel'ner (1954b) associated the filamentary structure of supernova flare remnants with the crossing of shock waves refracted on interstellar medium inhomogeneities. In such a case the second shock wave is formed in the cooling but still ionized gas exited by the first shock wave.

S.P's model allows deriving from one skillfully selected essential parameter – wave speed – a number of observable magnitudes: relative intensities of five emission lines, filamentary structure and absolute luminosity.

Later Pikel'ner (1961) suggested another filament forming mechanism in supernova shells: cosmic rays squeeze out the magnetic field as individual loops, and the matter rolling down into them takes the shape of fine filaments.

As early as in 1959 S.P. studied the structure of the shock wave in partially ionized gas in the presence of the magnetic field. He was a pioneer in his study of collisionless shock wave physics (Pikel'ner, 1959).

By the middle 1970s it became clear that the gas temperature in the nebulae – supernova flare remnants – derived from X-ray observations was higher than that corresponding to the high-speed filaments observed by T.A. Lozinskaya (1970, 1973) and identified with the front of the shock wave produced by the supernova. K.V. Bychkov and S.B. Pikel'ner (1975) explained that discrepancy by assuming that the shock front does not coincide with the observed filaments but outruns them. Although

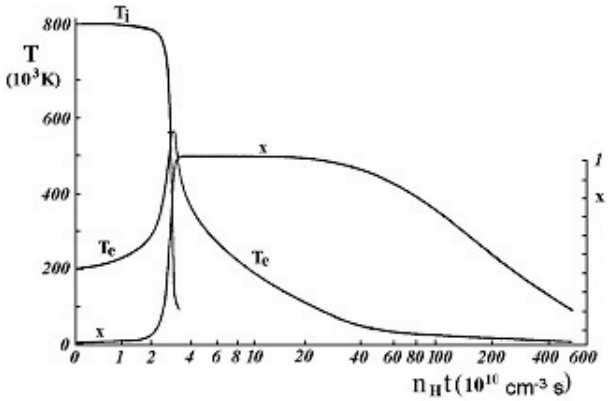


Figure 4 Calculated profile of a shock wave propagating through interstellar gas with the initial velocity of 144 km/s: T_i and T_e are ion and electron temperature, respectively, x is degree of hydrogen ionization, n_H, full hydrogen density behind the shock front (Pikel'ner, 1954b).

small-scale gas conglomerations get driven by the approaching strong shock wave from the supernova, their speed is lower than that of the shock front. Consequently, direct determination of the shock-wave-heated gas temperature is not possible.

Thus, investigating the fine-filament nebulae S.B. Pikel'ner (1954b) first considered shock waves in the astrophysical medium where low density of matter and radiation lead to considerable deviations from the local thermodynamic equilibrium. That research gave a start to an important new branch of cosmic gas dynamics. In particular, S.P.'s work on two-temperature gas in shock waves was about 20 years ahead of time. Later the idea of two-temperature conditions found a wide application in the modeling of the inner parts of the accretion discs around black holes.

4.3 The Crab nebula

In 1950s the Crab nebula – a remnant of the supernova explosion in 1054 – took a special position in astronomy: after I.S. Shklovsky had identified continuous radiation of its amorphous mass with synchrotron radiation of relativistic electrons in the magnetic field, this object became the "central engine" of that time forming radio astronomy and all-wavelength astrophysics. And S.B. Pikel'ner actively participated in this process.

G.A. Shajn, S.B. Pikel'ner and R.N. Ikhsanov (1955) estimated the degree of radiation polarization of the Crab nebula in its different regions and discovered that its value varies over the nebula. That fact, confidently confirmed by S.B. Pikel'ner's (1956) subsequent observations with a more advanced technique, served as an important argument in support of the Shklovsky's model.

The known age of the Crab nebula turned out to be considerably greater than the electron decay lag in the optical range. Therefore S.B. Pikel'ner (1956) abandoned the statistical particle acceleration mechanism, formerly developed with his participation (Ginsburg *et al.*, 1955), and proposed the hypothesis of continuous ejection

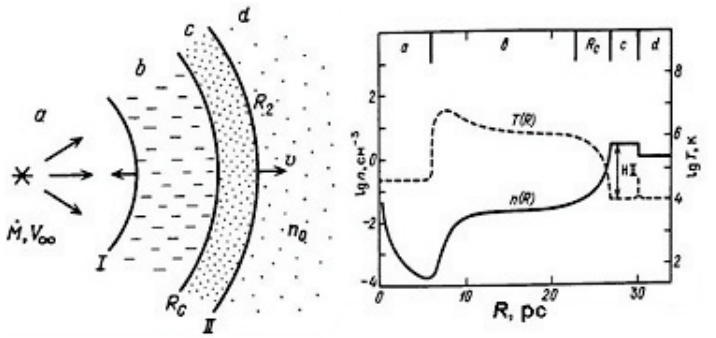


Figure 5 Structure of a stellar wind formed nebula considered by S.B. Pikel'ner (Pikel'ner and Shcheglov, 1968; Pikel'ner, 1968). Left: a scheme of two layer shock wave: a – free propagating wind; b – hot decelerated wind; c – a shell of compressed interstellar gas; d – not-disturbed gas; I and II – shock wave fronts in the wind and interstellar gas, respectively; R_c – discontinuity surface. Right: T and concentration n distribution along the nebula radius.

of relativistic electrons from the nebula nucleus. In the course of this work, S.P. developed a method for nebula magnetic field intensity estimation through the break frequency of the synchrotron emission spectrum of a source with the known age. The S.P.'s idea about continuous electron acceleration in that nebula was confirmed 12 years later, when a pulsar was discovered in its core. The proposed method for radio source magnetic field determination by the radio spectrum break frequency found wide application in radio astronomy for age and magnetic field estimations.

4.4 Nebulae and their structures formed by the stellar wind

In 1963 R.E. Gershberg and P.V. Shcheglov (1964) carried out interferometric observations of several bright diffuse nebulae and in some of them discovered motions with a velocity of up to 40–50 km/s; the subsequent engineering improvements doubled the range of detected velocities. These results were interpreted by S.B. Pikel'ner and P.V. Shcheglov (1968) and by S.B. Pikel'ner (1968) as an effect of interaction of the stellar wind from the hot stars which excites the nebula with the nebula matter. A double-layer model of expanding envelope was brought forward: the extended inner layer contains hot gas of the hindered stellar wind and the geometrically thin outer layer consists of the raked up interstellar gas (Fig. 5).

The outer layer is responsible for the observed optical radiation, while the soft X-ray radiation was predicted to come from the inner one. .. Lozinskaya (1970, 1973) applied the Pikel'ner's model to the analysis of optical and radio observations of the annular nebula around the Wolf – Rayet star (see, also Lozinskaya, 1986), and S.B. Pikel'ner (1969b, 1973b) improved to some extent the primary model. This S.P.'s cycle of works (1968–73) had the greatest world resonance. Just 3 journal pages long, Pikel'ner's (1968) paper proved to be the most quoted of all his original scientific publications.

The conception of the shock stellar wind – interstellar medium interaction was applied to phenomena of very different scales.

4.4.1 Structures from a fraction to a dozen of parsec sizes

Within the framework of the improved model of the stellar wind S.B. Pikel'ner and R.L. Sorochenko (1973) explained the considerable density fluctuations in the Orion nebula, and S.B. Pikel'ner (1973b) explained the formation of radial filaments in the planetary nebulae with previously excited heterogeneities compression by a shock front produced by the stellar wind (Fig. 6).

S.P.'s conception of the stellar wind – surrounding medium interaction found a wide application in the study of planetary, cometary and bipolar nebulae, bowshocks, "elephant trunks" in diffuse regions of ionized hydrogen, cosmic masers in star formation regions, formation of small and frequently moving outside clots in the previously heterogeneous medium, pressed on by the stellar wind.

S.B. Pikel'ner (Pikel'ner and Shcheglov 1968; Pikel'ner, 1968) predicted that nebulae formed by the stellar wind should be the sources of soft X-ray radiation. In the middle 1980s Bochkarev (1985) carried out detailed computations of X-ray radiation from these nebulae. Bochkarev and Lozinskaya (1985) analyzed all the known nebulae of this type and showed that the soft X-ray from the nebulae attempted to be observed in that range to that date, could not be registered due to the interstellar absorption. The most perspective one seemed to be the nebula NGC 6888. N.G. Bochkarev (1988) using the Einstein observatory archive, discovered and studied the soft X-ray radiation of that nebula. Thus, 20 years after S.P.'s prediction this new class of X-ray sources was discovered.

4.4.2 Structures of hundred parsec sizes

Investigations of the stellar wind and interstellar medium interaction were further stimulated by the discovery in 1970s of the large-scale (100–300 pc) envelope-like structures in the interstellar medium (Sivan, 1974) that contained very rarefied and

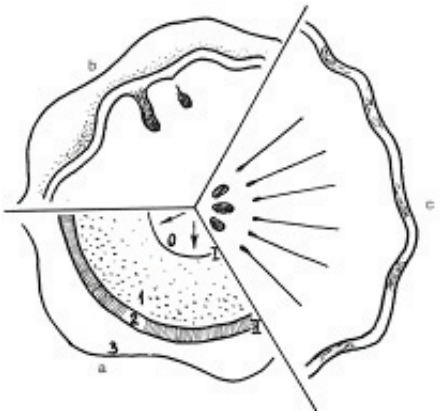


Figure 6 Formation of inhomogeneities in planetary nebulae. Sector *a* shows the structure of undisturbed nebula formed by stellar wind; sector *b* shows the front deformation at the already existing inhomogeneities; *c*, the shock front has propagated on along the interstellar gas; one or several layers of compactions are formed (Pikel'ner, 1973 a, b).

hot coronal gas, filling up tens of percent of the volume of the galactic gas discs. Physical processes which governing their structure, evolution and radiation turned out to be the same as those described by S.P. in his foregoing works.

The study of such huge envelopes has now become a large direction of research, because superbubbles determine to a large extent the large-scale structure (Bochkarev, 1984ab) and evolution of the Galaxy as well as of other spiral and irregular galaxies. According to the ideas widely accepted recently, these envelopes played an important role in the early Universe at the epoch of formation of the first objects with the red shift $z = 5$–20.

The large work by N.G. Bochkarev and T.G. Sitnik (1985) on structure and origin of Cygnus superbubble and the representation by N.G. Bochkarev (1984b, 1987a,b) of the Local interstellar medium as a superbubble of about 350 pc in diameter were produced in development of S.P.'s works on interaction of the stellar wind and interstellar medium. This model was brought forward simultaneously and independently from the work by D.P. Cox and R.J. Reynolds (1987). It allowed an explanation of the origin of the soft (<0.5 keV) X-ray sky background. The study served as a base for the monograph "Local interstellar medium" by N.G. Bochkarev (1990). The detailed study of the Local Superbubble is to a great extent important because all the extragalactic objects and background radiation heterogeneities are observed through it.

Superbubbles were found to break through gaseous discs of galaxies and carry matter away into galactic halo creating the so-called galactic fountains and "flues", and, besides produce the galactic wind enriching the intergalactic gas in galaxy clusters with heavy elements. Description of these processes has already been included in student manuals (e.g., Bochkarev, 1992).

4.4.3 Microstructure of the interstellar medium

S.B. Pikel'ner and V.N. Tsytovich (1968, 1969) showed the subcosmic rays necessary to explain the HI clouds temperature to be accelerated by plasma turbulence originating at old supernova remnant shock fronts. It turns out that these thin sheets of plasma are responsible for radio pulsar scintillations discovered in 1968.

S.B. Pikel'ner and V.N. Tsytovich's conclusion about the radio source scintillations originating on these thin sheets theoretically justified the thin phase screen model used as a base for the scintillations investigation, and scintillations proper turned out to be a useful probe for the interstellar plasma turbulence.

Later it was found out that scintillations originate, as a rule, on the superbubble borders, but due to the same turbulence excitation process. That is, S.P. and V.Ts's work bore the test of time.

Investigations of scintillations of radio sources are being carried out. In 2006 the IAU Colloquium on that problem was held at Pushchino. V.I. Shishov (2001) from that Observatory showed the heterogeneities' spectrum to be Kolmogorov's one in a range of scales covering more than 6 orders of magnitude: from $<10^9$ cm up to $>10^{15}$ cm.

4.5 Interstellar gas, magnetic fields and cosmic rays

4.5.1 The gaseous halo of the Galaxy

On the basis of the observed isotropy and energy spectrum monotony of the cosmic rays S.B. Pikel'ner (1953b) brought forward the conception of the galactic corona. It has changed radically our view about the interstellar medium of the Galaxy. The idea of such a corona gave rise to a vivid discussion, but over 4 years after this publication the data on the existence of gaseous coronae around other galaxies were accumulated. Pikel'ner and Shklovsky (1957, 1959) worked out a detailed picture of the galactic halo.

Soon after the discovery of pulsars the characteristic half-thickness of the interstellar gas electron components was shown to be close to 1 kpc and the plasma density at such distances from the galactic plain $n_e \sim 0.01$ cm^{-3}, was in complete agreement with the result obtained earlier by S.P. and I.S.

S.B. Pikel'ner (1961) explained the approximate equality of cosmic ray and magnetic field energy density in the Galaxy disc used in the model of the galactic corona with a valve mechanism anticipating in a sense the Rayleigh–Taylor–Parker instability brought forward by E. Parker several years later.

In 1980s the gaseous halo existence was observationally confirmed through the detection of UV interstellar absorption lines of high-ionized ions in stellar spectra: in Magellan Clouds gas with $n_e \sim 0.001$ cm^{-3} was found at distances of up to 5 kpc from the galactic plane.

This extensive observational data gave way to a number of theoretical works which showed that the gas in halo of the Galaxy and other spiral galaxies is in a non-stationary state (as well as assumed by S.P.) and also made it possible to draw a dynamic picture rich in details: infrared cirrus, galactic fountains, high-speed and high-latitude clouds, galactic winds, so-called "flues" by Heiles *et al.* (1996) and so on.

The gas comes from the galactic plane through the "flues", i.e., breaks in a layer of the interstellar matter located in the galactic plane opened by a combined effort of the stellar winds from stars of OB-associations and/or explosions of supernovae creating superbubbles. Walls of "flues" are observed in the line of hydrogen 21 cm, and along the "flues" the rarefied hot gas together with the embedded magnetic fields floats up into the galactic halo.

4.5.2 Interstellar gas heating mechanism and two-phase model of the interstellar medium

In 1967, it became clear that the temperature of HI clouds is 50–100 , i.e. much higher than the previously assumed 15–20 K. On the basis of the analysis of the Faraday rotation of polarization planes of radio sources S.P. showed the gas to be heated by particles of high energy, and they ionize hydrogen and helium simultaneously with the medium heating. In 1968 observations of pulsars confirmed that statement. The heating-ionizing radiation could be cosmic soft rays and/or X-ray photons.

S.B. Pikel'ner (1967) calculated a cooling function for the temperature below 10000 K (Fig. 7). It corresponds to non-monotonous pressure – temperature dependence. Those results, obtained as a development of the research on thermal instability helped

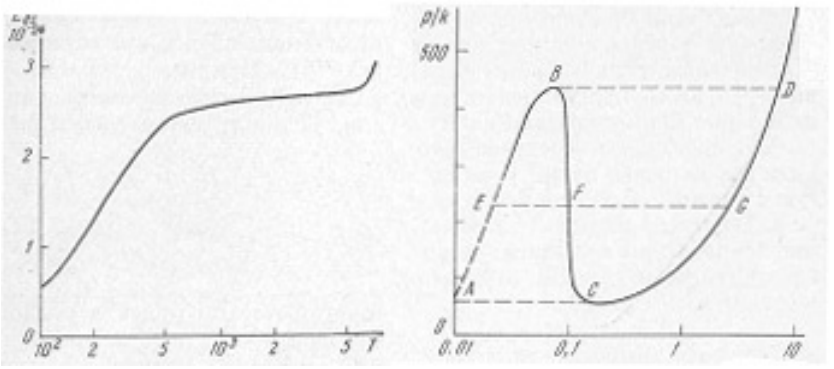


Figure 7 Left: Interstellar gas cooling rate dependence from temperature T (Pikel'ner, 1967). Right: stationary pressure dependence from density ρ (Zeldovich and Pikel'ner, 1969).

to tell apart two interstellar medium phases: the dense cold clouds and the rarefied hot inter-cloud medium or hot HI gas.

Pikel'ner's (1967) paper resulted in the beginning of his 1968–69 collaboration with V.N. Tsytovich and Ya.B. Zeldovich. Discussions on sources, flow and spectrum of the sub-cosmic rays not penetrating into the Solar system continue up to the present.

This work by Pikel'ner changed the classical view of interstellar medium structure making all its basic parameters – density, temperature, degree of ionization and so on to be reconsidered. According to ADS NASA, it proved to be one of S.P.'s papers most quoted outside the USSR/Russia.

S.P.'s pupil N.G. Bochkarev soon carried out further investigations of the problem. The papers by Bochkarev (1972) and Beysekova and Bochkarev (1973) presented numerical results of interstellar cloud and inter-cloud medium physical parameter computations. Moreover, Bochkarev (1972) considered the hypothetical pulsar surrounding ionization zones of a characteristic size of about 100 pc, that might be formed by fast protons from supernovae flares and exist for tens of millions of years. Over the last years similar objects enjoy a continuously growing interest.

N.G. Bochkarev (1973, 1979) carried out a detailed analysis of hard electromagnetic radiation impact on the atomic interstellar gas that resulted in a physical scheme for photoionization models. He was the first to study the now widely known properties of the soft X-ray radiation effects on stationary and non-stationary low-density cosmic plasma in all the temperature ranges up to the level at which the birth of electron-positron pairs becomes important. Thermally stable phases were investigated for different temperatures. It was shown that the X-ray radiation with low-frequency spectrum break in the region of a few hundreds eV produces an abnormal gas ionization: hydrogen and helium may still remain partially neutral while elements of the II and III rows of the Mendeleev chemical element table display the whole range of coexisting ions from II–III up to IV–VII stages of ionization.

Interstellar medium division into two phases with the temperatures $\sim$100 K and $\sim$10000 K is a universal property of the rarefied cosmic atomic plasma occurring under different conditions of heating and determined by the energy level system of hydrogen and the most abundant heavy elements.

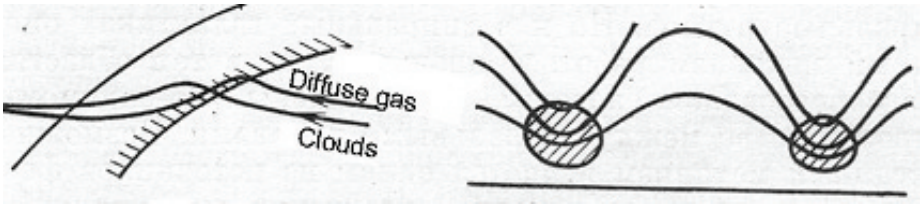


Figure 8 Large-scale structure of galaxies. Left: trajectories of motion of diffuse gas and clouds inside galaxy spiral arm. Hatching marks the spiral shock wave. Right: Rayleigh–Taylor–Parker instability in the gravitational filed of the galaxy. Gas concentrations in magnetic pits are shown. The lines mark the magnetic field, the horizontal line is the galactic plane.

4.6 Galactic structures

For a long time S.B. Pikel'ner was interested in the nature of galactic spiral arms. In 1965 he published 3 papers based on the assumption of the basic role of the magnetic fields in the structure formation. But as soon as the theory of spiral waves had been brought forward, S.P. adopted it. Pikel'ner (1970ab) showed that since the gas is, unlike stars, as a dissipative system, approaching in the course of rotation the inner edge of an arm, it creates a spiral shock wave. Behind the shock front the heated gas promptly emits its energy, contracts, and the thermal instability transfers it into a dense cold phase, thus creating the conditions favourable for the star formation. The new-born massive bright stars together with HII zones around them created the observable luminous spiral pattern.

On the basis of this new, deeper understanding of the galaxy and interstellar medium behavior, S.B. Pikel'ner (1972, 1976) advanced the theory of stellar cluster formation in dense gas-dust complexes. The amount of matter accumulated in the form of large gas-dust clots at the bottom of "magnetic pits" formed through Rayleigh–Taylor–Parker instability is sufficient to screen its interior from heating and ionizing ultraviolet and sub-cosmic rays. As a result the gas must become as cooled and dense to make possible the process of its intensive fragmentation due to gravitational instability. Hence, both massive and small stars may be formed. This scheme explains both the spotty appearance of the galaxy spirals and the typical distances between star formation region centers of about 1–2 kpc (Fig. 8).

Pikel'ner's 1967–70 works traced a triune picture of the structure of the interstellar medium in spiral galaxies:

1) Formation of clouds by thermal instability in gas heated by subcosmic rays;

2) Spiral shock wave as a trigger of star formation;

3) The spiral pattern spottedness explanation as a result of Rayleigh–Taylor–Parker instability in the magnetized galactic gaseous disc containing cosmic rays.

S.P. completed the main features of this picture for 1969 Yalta conference on cosmic gas dynamics, where it was most highly appreciated by the world leading specialists – see Habing (1970). This picture bore the test of time and presently, enriched with "updatings" and specifications, can be found in textbooks.

In 1975, a few months before his death, S.B. Pikel'ner created a qualitative scenario of globular cluster origination out of fragmentation of protogalaxies and evolution of the globular clusters. His pupil V.G. Surdin successfully followed this line of research.

Thus, S.B. Pikel'ner laid the foundation for the quantitative theory of star formation from the diffuse medium that is the most important process in contemporary astrophysics; he connected the abstract theoretical scheme of gravitational condensation with observational data.

A week before his sudden death, S.P. proposed to one of us (N.B.) to work together with him on the problem of molecular hydrogen origination in the early Universe in the epoch prior to the first massive object formation. When he was asked about the ionization sources necessary for the molecule formation, besides the already known at that time process of "tempering", when in expanding matter of the Universe not all the electrons have enough time to recombine, S.P. answered with confidence that in his opinion at those stages of cosmological evolution magnetic fields and cosmic rays had already existed. Unfortunately that idea, too much ahead of time, was not realized then. It was vividly discussed only in the last 2–3 years in the context of discovery at $z \sim 8$ of quasars and galaxies with heavy elements, dust and etc. Presently there is a real boom in this field and S.P.'s idea is being worked on "later and independently".

5 Pikel'ner's publications

Over 30 years of his scientific activity S.B. Pikel'ner published about 140 papers and 8 monographs. Their range is not limited by the three considered above main directions, his studies covered fields from cosmology (variation of the Hubble constant, intergalactic gas and magnetic field – see, e.g. Pikel'ner 1963, 1974), elementary particles (quarks, e.g., Zeldovich *et al.*, 1965), to magnetic storms on the Earth, etc.

It was S.B. Pikel'ner's usual practice to take into account in his papers and monographs the new approaches to the nature of processes in space brought forward by all the scientific community. For English-speaking astrophysicists, his most well known monograph is Kaplan and Pikel'ner (1970).

According to NASA's ADS on November 16, 2006, there are 817 references to S.B. Pikel'ner's papers in 723 papers. Unfortunately, this base is very incomplete up to the mid 1970s, it involves only about 60% of his earlier scientific works. From 1974 the histogram of references to S.B. Pikel'ner's papers can be approximated by an exponent with the decrement equal to 20.8 years (see Fig. 9).

In conclusion, we would like to emphasize one basic crucial idea.

In S.P.'s time as well as now, there were a number of scientists, experts in their fields, making progress in understanding and penetrating the problems under investigation. Certainly, S.P. was one of them. He carried out a lot of brilliant works and research in which he suggested and developed many ideas that keep on being important up to now. Among them are coronal outflow, the Kostjuk–Pikel'ner model of the chromospheric response to the flare heating, general structure of the solar chromosphere and corona in quiet regions and above sunspots. He was among the first to recognize the importance of electrodynamic processes for astrophysics, considered wave interaction in cosmic plasma, and made important progress in understanding physics and structure of the interstellar medium, star formation processes, the Galaxy structure.

Up to the present, hundreds of papers have been published on each of these topics and, during at least 10–20 years S.P's. priority was emphasized and his contributions

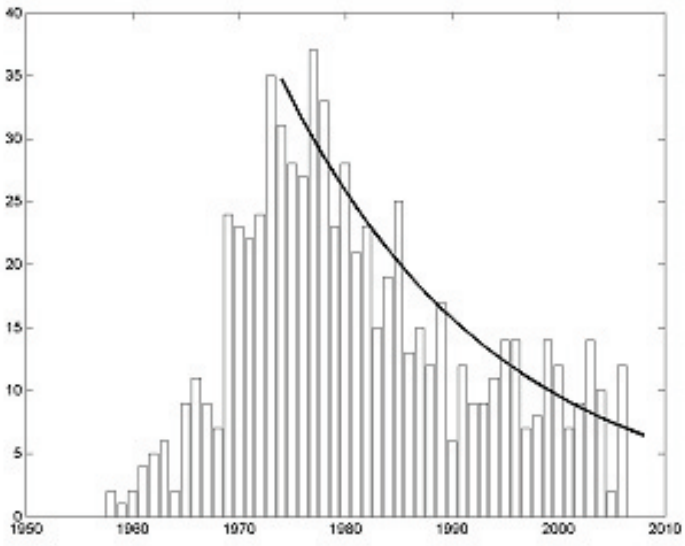


Figure 9 Histogram of references on papers by S.B. Pikel'ner.

were turned to. However, unlike most scientists, S.P. also brought forward, developed and distributed a widely spread general outlook on a large number of astrophysical problems. It is the main, many-years-surviving remnant and legacy of all of the scientific publications of S.P. that his general results continue to help astrophysicists all over the world to find their way in the ocean of new data. *It seems that up to now no other similar person has appeared and may not appear in the future due to fast increase of new data and concepts.*

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