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GENERAL CONCEPTS REGARDING THE ROLE OF PLASMA PROCESSES IN SPACE: THE EMERGENCE OF THE TERM “PLASMA ASTROPHYSICS”

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It is well established that the cosmos is predominantly composed of plasma. Only a very small fraction of matter in the Universe exists in a solid state, and an even smaller portion — in liquid form. Of course, not every gas is plasma, yet under cosmic conditions even regions consisting of neutral hydrogen or the atmospheres of cool stars — where the number of ionized atoms may be fewer than one per thousand neutral atoms — still exhibit plasma behavior.

The term “plasma” was introduced by the American chemist Irving Langmuir in 1923 to describe the behavior of matter in gas-discharge tubes. However, astrophysicists had been studying plasma long before the concept itself was formally defined. Indeed, one of the crucial milestones in astrophysics was the development of the theory of stellar atmospheres by the British astrophysicist and mathematician Edward Milne in 1921. His work was based on analyzing the dependence of ionization levels in gas on temperature (the Saha equation), which made it possible to explain the fundamental features of stellar spectra. The discovery of distinct regions of ionized and non-ionized hydrogen in interstellar space by the Danish astronomer and astrophysicist Bengt Strömgren in 1939 also had profound implications for the physics of the interstellar medium and stellar evolution theory. These are only two examples among many [1].

Yet, despite recognizing that most matter in the Universe exists in the plasma state, astrophysicists, until relatively recently, considered only one dimension of its physics.



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GESCHICHTE, ARCHÄOLOGIE UND KULTUROLOGIE

The central problem of astrophysics is the analysis of the spectra of celestial objects, in the broadest sense of the term. Indeed, if we exclude the interplanetary medium—currently being actively explored through space probes—as well as planets, which in the near future (and already at present in the case of the Moon, Venus, and Mars) will be studied through direct measurements on their surfaces (and in their atmospheres), all other astrophysical objects—stars, nebulae, galaxies, quasars, pulsars, and so forth—can be studied only through the analysis and interpretation of their radiation spectra. These spectra include optical and radio ranges, as well as X-ray, ultraviolet, and infrared emissions. A certain (relatively small) amount of information is also carried by corpuscular radiation, such as cosmic rays and neutrinos.

Thus, the central task of astrophysics is the interpretation of spectra. However, accomplishing this requires, first, an understanding of the theoretical mechanisms of radiation, and second, the ability to determine the physical states of the systems that emit electromagnetic waves. For a long time in astrophysics—especially during the period when observational astronomy existed almost exclusively within the optical domain—only radiation emitted by atoms was considered. It was during this period that the term “astrophysics with consideration of atomic theory” emerged.

The relationship between astrophysics and atomic physics was mutually beneficial: not only did astrophysics rely extensively on theoretical and experimental results from atomic physics, but it also contributed significantly to the understanding of atomic processes—for example, in the study of metastable states and forbidden transitions. At that time, the role of plasma physics in astrophysics was extremely limited; it was applied merely to estimate ionization levels of atoms and to determine the concentration of free electrons.

By the late 1940s and early 1950s, radio astronomy began to develop rapidly. For the interpretation of the radio spectra of celestial bodies, atomic physics could no longer provide much insight—its use was limited mainly to the analysis of a few observable radio lines (hydrogen, hydroxyl, water, formaldehyde). Braking radiation mechanisms came to the forefront: electrons accelerated or decelerated while passing near ions generate radiation, which in astrophysics is often referred to as free-free radiation as well as cyclotron radiation in the case of non-relativistic electrons and synchrotron radiation for relativistic ones. At this stage, the role of plasma physics became more significant: the state of the plasma determines the conditions for generating radiation through these mechanisms and the conditions under which radio waves propagate.

However, radio astronomy did not limit itself to braking radiation mechanisms. The study of sporadic solar radio emission and, especially, the discovery in the 1960s of the most powerful radio sources—radio galaxies, quasars, and pulsars—required physics to “invent” highly efficient emission mechanisms capable of rapidly converting other forms of energy into electromagnetic waves. Furthermore, it

became clear that the acceleration of relativistic particles under cosmic conditions is not a rare anomaly, but rather a regular and widespread process. At this stage, astrophysics demanded much more from plasma physics: the deepest plasma properties had to be incorporated into the analysis of the spectra of celestial objects.

In essence, plasma differs from an ordinary gas not only by the fact that it consists of ions and electrons rather than solely neutral atoms. The crucial point is that, due to the long-range nature of Coulomb forces and the mobility of light electrons, plasma is dominated by collective processes—that is, oscillations and waves. While in a neutral gas one can consider only acoustic waves, which are practically unrelated to electromagnetic radiation, or very low-frequency Alfvén waves, plasma contains many distinct types of waves with diverse spectra that are, in one way or another, coupled to electromagnetic fields and therefore to electromagnetic emission. A particularly important case is that of so-called collisionless plasma, in which the electron mean free path is much greater than the characteristic spatial scales of collective processes. It is precisely under such conditions that the oscillatory and wave properties of plasma manifest themselves fully. Considering that the spectra of many cosmic objects—especially in the radio domain—are formed in collisionless plasma, it becomes evident that plasma phenomena must play a major role in interpreting such spectra. Thus, one may speak of the emergence of “astrophysics based on plasma theory”. Here, the relationship between astrophysics and plasma physics can be expected to be mutually beneficial: astrophysics will not only employ experimental and theoretical results obtained from studies of terrestrial plasma but will also generate new findings of relevance to plasma physics as a whole. Moreover, whereas atomic physics gained comparatively little from astrophysics in relation to what it provided to it, plasma physics stands to gain far more. Astrophysics has posed new problems for plasma physics, offering concrete applications for topics previously considered abstract or purely theoretical.

Based on these considerations and recognizing the needs of science, in 1972 Samuel Kaplan and Vadim Tsytovich introduced the term “plasma astrophysics” in their book of the same name, defining it as a branch of physics and astrophysics that addresses a distinct range of fundamental problems [2; 3].

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