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Making the physics of interstellar matter: a tribute to Nikolai G. Bochkarev

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Nikolai G. Bochkarev, DSc (Physics and Mathematics), Professor, Sternberg Astronomical Institute, Moscow University, past away on December 24, 2022. From the mid 1980s until 1992 he was an informal leader among the "interstellar community" in the Soviet Union. Further on after disintegration of the USSR he was recognized in this position by astronomers of the former Soviet Union. Since 1999 and until his last days Nikolai G. Bochkarev was heading up the working group "Physics of the ISM" of the Scientific Astronomical Council at the Russian Academy of Sciences.

His professional interests covered a wide scientific area in astronomy from physical processes in interstellar matter, physics and observational properties of active galactic nuclei and X-ray binaries to astrobiology and exolife. In this article I briefly outline just a few topics of interstellar matter physics he developed in the initial period of his career: physical processes governing thermal and ionization state of the ISM, ionization structure and dynamics of extended galactic halos, morphology and physics of the Local interstellar medium.

Keywords: Interstellar medium, interstellar plasma, stellar wind bubbles, circumgalactic medium

1 Introduction

Nikolai Bochkarev made a considerable contribution in different branches of astrophysics from physics of the interstellar medium (ISM) to life in the Universe. His most recent activity was primarily concentrated on physics of X-ray binaries and active galactic nuclei. In this brief essay I would like to review his work at the beginning of his career.

In 1971 Nikolai Bochkarev joined a PhD programme in Moscow State University under the supervision of Prof. S.B. Pikelner. His PhD project was devoted to study physical conditions in the interstellar medium heated by X-rays and cosmic rays (CR). The beginning of his work encompasses the period when everything related to inter-

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stellar space became a physical science.

In this essay I will concentrate mainly on three topics of primary significance for physics of the ISM, namely: the thermal state of the ISM, physical kinetic of the extended halo gas, and physical state of the Local ISM. Nikolai Bochkarev obtained fundamentally important results in the studies of these topics.

The two interrelated branches of astrophysics "Physics of the Interstellar Medium" and also "Cosmic Gas Dynamics" originated in the twentieth century – from the beginning of the 1950s to the end of the 1960s. In a very short time many physicists and mathematicians experienced in physical kinetics and aerodynamics in laboratory and terrestrial conditions realized that diffuse space media included many interesting and unsolved physical and dynamical problems. In 1953 the International Union of Theoretical and Applied Mechanics and the International Astronomical Union organized the joint symposium "Gas Dynamics of Cosmic Clouds" supported by UNESCO and the symposium proceedings was published in 1955, edited by G.I. Taylor (Taylor, 1955). Among others, fundamentally important issues related to generation of magnetic field in cosmic plasma (Batchelor, 1955; Biermann, 1955), and sub- and supersonic turbulence in compressible interstellar medium (Lighthill, 1955; von Hoerner, 1955) were posed explicitly for the first time.

In the preliminary communications of the symposium H.C. van de Hulst suggested a list of the key problems which could be approached from physical ground (van de Hulst, 1955). Among others he emphasized the questions of *i)* why interstellar gas exists, *ii)* why the young hot stars preset there, *iii)* how they interconnect with each other. As a possible solution van de Hulst refers to the idea by L. Spitzer and J. Oort that stars increase pressure in edges of Strömgren spheres and can give rise to gas compression and to violent motions of clouds. In these brief notes by van de Hulst an initial step to the currently and commonly exploited understanding of stellar feedbacks can be recognized.

Sometime later another IAU symposium on cosmic gas dynamics was organized (Burgers, 1958). In the summary J.H. Burgers & R.N. Thomas emphasized the principal difference between physical states of gaseous systems in terrestrial and laboratory conditions from one side and in astronomical environments from the other. When the cosmic gaseous media are understood in a broad sense, including stellar interior, stellar atmospheres and coronae their gas densities cover more than 20 orders of magnitude from ~ 0.1 cm^{-3} in diffuse interstellar gas to $\gtrsim 10^{24}$ cm^{-3} in stellar interior. Such a wide spread of densities is associated with differences in gas temperature from $\lesssim 10$ to $\gtrsim 10^8$ K, respectively. This circumstance in itself suggests an unbelievable spread of gas pressure. Such an extremely wide range of physical parameters looked promising in new physical effects and attractive for study.

Another important intrinsic property of the ISM was recognized during this breakthrough period. This concerns a principal difference of thermodynamic state of the ISM and laboratory gaseous and plasma media. As a precursor of this concept the idea of a two-phase gas state first proposed by H. Zanstra was emphasized by van de Hulst in his brief report in (van de Hulst, 1955). H. Zanstra developed the model of a possible spontaneous breaking of a tenuous uniform gas illuminated by a hot star on to two phases: a dense and diffuse phase which coexisted side by side under pressure equilibrium (Zanstra, 1955). This can be treated as a precursor of the new concept of a two-phase equilibrium equation of state of the interstellar medium developed by a

cycle of publications a decade later (Pikel'ner, 1968; Spitzer & Tomasko, 1968; Field et al., 1969; Goldsmith et al., 1969; Spitzer & Scott, 1969; Werner et al., 1970).

The first steps of the scientific career of N. Bochkarev began in this environment.

2 Thermal state of the interstellar gas

One of the key issues with the new concept of the interstellar medium as an open system concerns the equation of state (EoS) of the gas under such conditions. It is obvious that the EoS cannot be merely the ideal gas equation $PV = Nk_BT$, even though formally the interstellar gas seems to satisfy the ideal gas conditions. However the energy input from cosmic rays, X-ray and ultraviolet photons that pervade the interstellar gas, makes it an open and strongly thermodynamically non-equilibrium system.

Each volume of the ISM contains not only the gas, but also non-thermal energy sources that ionize and heat it. In these conditions the gas temperature is not an independent thermodynamic variable, but is determined by the energy input from non-thermal sources (NTS). The heating efficiency is proportional to the energy flux from the NTS and gas density $H = \Gamma(\mathbf{x}, \Phi)n$, with Γ being the energy input from NTS per one ISM particle, n is the ISM gas density, Φ characterizes the NTS and the efficiencies of their interactions with the ISM gas. In the simplest case of an optically thin and dilute ISM medium, the energy gained by gas is partly transferred into low-energy photons due to mutual collisions between the gas particles, and eventually leaves the system. The corresponding energy loss rate is $L = \Lambda(T, \mathbf{x})n^2$, with T, the gas temperature, $\mathbf{x}$ is a vector characterizing the ionization state and the chemical abundance pattern. This results in the energy balance equation (Pikel'ner, 1968; Spitzer & Tomasko, 1968; Field et al., 1969; Goldsmith et al., 1969; Spitzer & Scott, 1969; Werner et al., 1970)

$$\Lambda(T, \mathbf{x})n = \Gamma, \tag{1}$$

which provides the gas temperature T as a functional of its density, chemical composition, fractional ionization and the sources of energy $T = T(\mathbf{x}, n, \Phi)$. The gas temperature in this framework is determined as the one that compensate the energy input from NTS at a given density. In a very simplistic form of a constant heating Γ, and a fixed fractional ionization the "classical" cooling function $\Lambda(T, \mathbf{x})$ is characterized by three different branches: the two stable ones at $T \sim 10^2$ K and $T \sim 10^4$ K where the radiative cooling is determined by collisional excitations of the fine-structure and low energy levels of atoms and ions (like CI, OI, CII etc.) and of the 2p state of atomic hydrogen with the energy $E = 10.2$ eV, and also the unstable state in the range between $\sim 10^2$ K and 10^4 K. On the stable branches $\partial \ln T / \partial \ln n \simeq 0$, while in the unstable one $\partial \ln T / \partial \ln n < -1$. Correspondingly, it results in an anomalous (negative) compressibility of the interstellar gas within $\sim 10^2$–10^4 K: $\rho^{-1}\partial\rho/\partial p < 0$. This property ensures a possibility for the interstellar gas to break into two stable phases with $T \sim 10^2$ and T^4 K, when hydrodynamic perturbations bring the gas to the critical unstable state where $\rho^{-1}\partial\rho/\partial p < 0$. This explains one of the fundamental queries raised at the IUTAM/IAU symposium in 1953 (Taylor, 1955).

In a series of studies it has become clear that the precise range of conditions at which such a transition from a homogeneous to cloudy medium takes place and

the resulting cloud parameters, are very sensitive to the interplay of all processes that govern heating and cooling of the interstellar gas (Pikel'ner, 1968; Spitzer & Tomasko, 1968; Field et al., 1969; Goldsmith et al., 1969; Spitzer & Scott, 1969; Syunyaev, 1970; Werner et al., 1970). A detailed study of the kinetics of all involved processes was the main objective of the PhD thesis of Nikolai Bochkarev. He described the obtained results in a series of papers (Bochkarev, 1973b,a; Beisekova & Bochkarev, 1973; Bochkarev, 1979).

2.1 Heating

One of the main issues connected with the correct description of thermodynamics of the ISM relates to the gain of energy from NTS and transfer of it to the gas. It concerns mainly the details of redistribution of gained energy between δ-electrons and the field electrons through a series of cascades. Previous studies were mostly restricted by order of magnitude estimates and approximate considerations. The description in (Bochkarev, 1973b,a, 1979) concentrated on the three mechanisms: *i)* the primary heating from low-energy cosmic rays via acceleration of the free electrons in field plasma, *ii)* the heating by δ-electrons from ionization by low-energy cosmic rays and X-rays, and *iii)* the heating and ionization by secondary high-energy photons produced by recombinations and excitations of HeI and HeII.

In general, the transfer of energy from an electron accelerated by a CR or X-ray particle is a heavily branching cascade, with the energy distribution function (EDF) ranging from the initially gained energy to thermal energy of field ISM electrons. In his paper (Bochkarev, 1973b,a) N. Bochkarev performed for the first time a very scrutinized and detailed statistical description of the EDF of the superthermal electrons in the process of their deceleration to heat the ambient gas.

The description is based on a self-consistent approach that involves the ionization, heating and cooling processes simultaneously assuming the gas to be in a steady-state equilibrium. The set of governing equations in a generalized form includes the ionization equilibrium

$$[\zeta_{i_z,j} + \beta_{i_z}(T)]n_{i_z} = \alpha_{i_z}(T)n_{i_{z+1}}n_e, \tag{2}$$

with

$$n_e = \sum_{i,i_z} i_z n_{i_z}, \tag{3}$$

and the energy balance

$$H(n,T,\mathbf{z}) = L(n,T,\mathbf{z}), \tag{4}$$

with

$$H(n,T,\mathbf{z}) = \sum_{i,j} \Gamma_j(T,\mathbf{z})n_i, \tag{5}$$

being the total energy input from all non-thermal sources j, acting on species i with their ions, and the partial heating rates

$$\Gamma_j(T, \mathbf{z}) = \sum_{i_z, i} \zeta_{i,j} \langle E_h \rangle_{i,j}, \tag{6}$$

with $\langle E_h \rangle_{i,j}$ being an average energy transfered in heat in a particular process, and the integral cooling rate

$$L(n, T, \mathbf{z}) = \sum_{a, i_z} \Lambda(T, \mathbf{z}) n_a n_{i_z}, \tag{7}$$

with $a = e,\ p,$ HI are the projectile particles, i_z, the target cooling agents, the subscript i_z denotes the specie i in ionization state z, ζ denotes ionization rate by a NTS, $\beta(T)$ describes a thermal collisional ionization rate, α_{i_z} describes the radiative recombination rate of the z-th ionization state of the i-th specie, vector $\mathbf{z}$ denotes the ionization state,

$$\zeta_{i,j} = 4\pi \int_E \nu_j(E, n, \mathbf{z}) \Psi_j(E) \sigma_{i,j}(E) dE, \tag{8}$$

is the ionization rate of the specie i by an NTS j, j counts cosmic ray particles, X-ray and UV photons, and high energy photons from radiative recombinations and excitations of HeI and HeII, ν_j is the number of secondary electrons produced by each δ-electron.

The self-consistency in the system (2–4) as described in (Bochkarev, 1973a) is provided by a simultaneous solution of the ionization and thermal balance with all auxiliary functions in Eqs (5)–(8). The essential element of the calculations was a statistical Monte-Carlo modeling of energy transfer through the cascade tree (Bochkarev, 1973a).

2.2 Cooling

The cooling rates in this modeling have been taken from literature of that period (Hjellming, 1966; Seaton, 1958; Goldsmith et al., 1969; Penston, 1970). As a result, N. Bochkarev presented a comprehensive compilation of fractional cooling functions of the dominant cooling species under the thermal steady-state condition in the temperature range 10^4–6×10^6 K. In the lower temperature range 10–10^4 K, the total cooling function has been calculated for fractional ionization supported by a combined action of the low-energy cosmic rays and X-ray background emission. At higher temperatures the cooling function and ionization states of the dominant species have been described self-consistently for the first time.

The model of the total cooling function presented in his paper (Bochkarev, 1979) (see also Fig. 90 in the book by Kaplan & Pikel'ner, 1979) covers the temperature range from 10 to 10^{12} K, and currently can also be used as the reference for understanding and estimates of thermal properties of the ISM. As already mentioned, N. Bochkarev in his PhD work in 1974 (published later in (Bochkarev, 1979), see also Fig. 89 in the book (Kaplan & Pikel'ner, 1979)) presented one of the first full scale calculations of the ionization state of dominant species under collisional ionization equilibrium, nearly 20 years before the well known description by (Sutherland & Dopita, 1993).

3 Galactic halo

The existence of an extended galactic halo has been predicted in pioneer papers by I.S. Shklovsky (Shklovskii, 1952), S.B. Pikelner (Pikel'ner, 1953a,b, 1957), and L. Spitzer (Spitzer, 1956), based on different theoretical and observational arguments. The primarily theoretical challenge of this model was connected with the energy sources capable of supporting the halo gas at a proper temperature as stressed in (Spitzer, 1956; Pikel'ner, 1957). A possible solution of this problem has been suggested by R.A. Sunyaev in (Sunyaev, 1969; Syunyaev, 1970), that the background X-ray photons are the energy source for heating the halo gas. The optical thickness of the ISM disk layer in the M31 galaxy to the photons of energy $E \sim 100$ eV seems to support this hypothesis (Sunyaev, 1969).

These arguments have been further developed by N.G. Bochkarev and R.A. Sunyaev in their fundamental consideration in (Bochkarev & Siuniaev, 1977). In the self-consistent approach elaborated in (Bochkarev, 1973b,a) the presented analysis allowed making critically important predictions for the physical state and observational manifestations of the gas at galactic peripheries. Among these are: spacial variations of the atomic hydrogen column density $N_{\rm HI}(r)$ far from the galaxy centers, their sensitivity to the flux of the backround far UV and X-ray radiation, $\lambda = 912$ Å, to 10 Å, with assumingly a flat spectrum, the radial distribution of the total hydrogen $n_{\rm H}(r) = n_{\rm HI}(r) + n_{\rm HII}(r)$ and its column density $N_{\rm H} = N_{\rm HI} + N_{\rm HII}$. Even such a simplified model provided an efficient tool for evaluation of the gas content in other galaxies, and constrained the ionizing UV and X-ray background.

This method was later applied to determine the parameters of the background ionizing radiation and parameters of the absorbing gas in various galaxies. In a set of galaxies a sharp edge of the transition between the HI and HII phases has been observed with the column density $N_{{\rm HI},e} \sim 2 \times 10^{19}$ cm^{-2} at the edge, and a well pronounced correlation between the $N_{{\rm HI},e}$ and its sharpness (Corbelli et al., 1989; van Gorkom, 1991; Corbelli & Salpeter, 1993a,b; Maloney, 1993) – the higher the intensity the sharper the transition, according to the prediction in (Bochkarev & Siuniaev, 1977).

Later studies of the HI–HII edge in galactic haloes and their interrelation to the ionizing background radiation methodologically are tightly connected with the ideas pronounced first by N.G. Bochkarev and R.A. Sunyaev (Bochkarev & Siuniaev, 1977). This relates also to galaxies at higher redshifts $z \gtrsim 2$–6 (Fardal et al., 1998; Weymann et al., 2001; Faucher-Giguère et al., 2008, 2009; Adams et al., 2011).

During the recent decade the presence of gas in extended galactic halos and circumgalactic matter (CGM) attracted great attention with reference to additional sources of gas for feeding star formation in the disks, and support of mass and energy exchange between galaxies and their environments. Observational manifestations of such halos are found in extended galactic disks filled with dust (Xilouris et al., 2006; Muller et al., 2008; Heithausen, 2012; Baes & Viaene, 2016; Al Najm et al., 2016), in cold cloudy HI component (Wolfe et al., 2013; Welsh & Lallement, 2013; Taylor et al., 2014; Lehner et al., 2015; Lockman, 2017; Bland-Hawthorn et al., 2017), and H-α emission (Ramya et al., 2011; Abramova & Zasov, 2012; Saburova et al., 2021).

A particular interest of the effects related to the interaction of the ionizing extragalactic background and galactic halos is connected with measurements of the galax-

ies' rotation curves in HI. This line of study has been initiated by (Bland-Hawthorn et al., 1997), and further developed in (Kravtsov & Manwadkar, 2022; Eibensteiner et al., 2023). One of the most challenging issues in such measurements is connected with the self-shielding effects, and minimization of contaminations and the respective uncertainties from them requires a full scale consideration based on the approach described in (Bochkarev & Siuniaev, 1977).

4 The local interstellar medium

The first indication of the existence of a loop-like structure presumably located in the nearby interstellar environment has been reported in (Hanbury Brown et al., 1960) and described as Loop I. This structure was later confirmed in more extended surveys focused in particular on radio loops and other similar structures (Berkhuijsen, 1971; Haslam et al., 1982). The Loop I is a circle-like structure with a diameter of $\sim 100^\circ$ extending from $l \simeq 30^\circ$ and $b \simeq 10^\circ$ north. Overall, these two surveys have revealed three more loops: Loops II and III in the southern part ($b < 0^\circ$) and Loop IV in the northern part $b > 0^\circ$) of the Milky Way.

The origin of the loops is still in dispute in spite of the long background to their study. The most intriguing question remains – whether Loop I directed toward the Galactic centre (GC) nearly between $-30^\circ < l < +30^\circ$ is a nearby structure as suggested by H. Weaver (Weaver, 1979), or does it lie around the GC following the study of Y. Sofue & T. Handa (Sofue & Handa, 1984)? The concept of the local interstellar medium (LISM) as a giant bubble outlined by the Loop I and produced under the action of the stellar wind and a subsequent supernova explosion from the Sco-Cen OB-association was pronounced in (Weaver, 1979; Cleary et al., 1979). Five years later this term was "legitimated" in the IAU Colloquium "*Local Interstellar Medium*" (Bruhweiler, 1984; Bruhweiler et al., 1984; York & Frisch, 1984). Within the Colloquium, Loop I and Sco–Oph bubble have been treated as a single giant structure as demonstrated in these talks (Cowie, 1984; Paresce, 1984a,b) (see, e.g., Fig. 3 in (York & Frisch, 1984)), which is consistent with EUV data.

A comprehensive overview of this concept with a detailed analysis of its physical properties and morphology was given by N. Bochkarev in his review (Bochkarev, 1987). This analysis allowed him to build a model of the overall configuration and dynamical state of the LISM. The most important elements of it can be summarized as: *i)* the Sun is embedded in a hollow filled with warm and low-density gas adjacent to the HI cloud towards the Galactic center, *ii)* this in turn neighbors the outer region of the shell of the hot bubble around the Sco–Cen association, *iii)* the edge where the hollow and the adjacent HI cloud overlap with the hot bubble manifests through the X-ray emission, apparently seen as the North Polar Spur, *iv)* when the hot bubble contacts denser HI clouds, it forms warm and dense interface coronae around the clouds, that can influence the bubble expansion. A more generic consequence from this is that the LISM can represent a "microcosm" of the three-phase ISM dominated by supernovae explosions as described in McKee1977 and observed in the "boiling" galaxy NGC 253 (Sofue et al., 1994).

This model stimulated additional studies in this direction by other authors. The LISM soon became one of the topical directions in physics of ISM as can be seen from

a summary of one of the workshops on the origin and evolution of the Local bubble in (Breitschwerdt et al., 1996). The conclusion in (Bochkarev, 1987) about the LISM consisting of hot bubbles spread through out the Milky Way received further development. Different aspects of the interaction of the hot coronal gas with interstellar clouds and observational characteristics of the conductive interfaces similar to those manifested in the LISM are studied in (Borkowski et al., 1990; Ji et al., 2019).

A later study of the LISM making use of the pulsar scintillations confirmed the general features of our nearby vicinity predicted in (Bochkarev, 1987). In this regard one can mention here several papers (Bochkarev & Ryabov, 1997; Bhat et al., 1998; Bhat & Gupta, 2002).

The first numerical model of the LISM reproducing the general concept proposed by N. Bochkarev was performed in (Breitschwerdt et al., 2000; Breitschwerdt, 2001; Berghöfer & Breitschwerdt, 2002; Shelton, 2003). More recent observations deliver new facts and details of the overall picture of the LISM, however leaving the conceptual elements stable (Fuchs et al., 2006; Wolleben, 2007; Frisch et al., 2011).

After the discovery of the Fermi-Bubbles by Fermi-LAT (Su et al., 2010), the common opinion has turned to the Galactic center as the preferential location of the sources responsible for Loop I (North Polar Spur) structure. The reason was not only related to the similarity of the morphologies of the Fermi-Bubbles and Loop I. Among the difficulties of the local origin of Loop I are: *i)* an order of magnitude higher HI column density than expected in the local scenario (Egger & Aschenbach, 1995), *ii)* a relatively high latitude of the Loop I center $b \simeq 24^\circ$, suggests the correspondingly high vertical position of the SN explosions that presumably have driven the bubble $z_{SN} \simeq 70$ pc in which case the bubble would expand predominantly above the Galactic plane (see discussion in (Shchekinov, 2018)), *iii)* the amount of expected SN explosions within the recent 3–5 Myr as required in the scenario is a factor of 10 lower than needed (Donaldson et al., 2017), *iv)* the ROSAT pattern of X-ray absorptions towards the Aquila rift and the terminus of the North Polar Spur puts a lower limit to its boundary $\simeq 642$ pc (Lallement et al., 2016) and $\simeq 1.1$ kpc (Sofue, 2015), respectively.

However, more recently a detailed numerical study of transport of ^{60}Fe and several other isotopes to the Solar system to link it to the observed on Earth restore the paradigm of the LISM in the new observational background (Schulreich et al., 2017; Fujimoto et al., 2020; Chaikin et al., 2022; Schulreich et al., 2023; Wang et al., 2023). The two structures observed towards the Galactic center – Loop I in the local vicinity of the Sun and Fermi-Bubbles in the Galactic center – can be reconciled assuming the superposition of their images due to projection effects as mentioned in (Shchekinov, 2018).

5 Conclusions

The above three issues – ionization equilibrium and thermodynamics of the ISM, extended gaseous galactic halos, and the Local ISM – still remain fundamentally important for understanding the physics of galaxies and their evolution as complex self-organizing systems. Nikolai G. Bochkarev was among those who sculpted the basis of modern understanding of these objects the puzzling diversity of which is determined by a continuous interplay between the stars and the interstellar medium.

References

Abramova O. V., Zasov A. V., 2012, Astronomy Letters, 38, 755
Adams J. J., Uson J. M., Hill G. J., MacQueen P. J., 2011, Astrophys. J., 728, 107
Al Najm M. N., Polikarpova O. L., Shchekinov Y. A., 2016, Astronomy Reports, 60, 389
Baes M., Viaene S., 2016, Astron. and Astrophys., 587, A86
Batchelor G. K., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, Turbulence and Magnetic Fields. p. 117
Beisekova G. K., Bochkarev N. G., 1973, Sov. Astron., 17, 272
Berghöfer T. W., Breitschwerdt D., 2002, Astron. and Astrophys., 390, 299
Berkhuijsen E. M., 1971, Astron. and Astrophys., 14, 359
Bhat N. D. R., Gupta Y., 2002, Astrophys. J., 567, 342
Bhat N. D. R., Gupta Y., Rao A. P., 1998, Astrophys. J., 500, 262
Biermann L., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, Remarks Concerning Interstellar Magnetic Fields. p. 137
Bland-Hawthorn J., Freeman K. C., Quinn P. J., 1997, Astrophys. J., 490, 143
Bland-Hawthorn J., Maloney P. R., Stephens A., Zovaro A., Popping A., 2017, Astrophys. J., 849, 51
Bochkarev N. G., 1973a, Soobshcheniya Gosudarstvennogo Astronomicheskogo Instituta, 183, 3
Bochkarev N. G., 1973b, Sov. Astron., 16, 619
Bochkarev N. G., 1979, Issledovaniia Geomagnetizmu Aeronomii i Fizike Solntsa, 48, 195
Bochkarev N. G., 1987, Astrophys. and Space Sci., 138, 229
Bochkarev N. G., Ryabov M. I., 1997, Astronomical and Astrophysical Transactions, 13, 261
Bochkarev N. G., Siuniaev R. A., 1977, Sov. Astron., 21, 542
Borkowski K. J., Balbus S. A., Fristrom C. C., 1990, Astrophys. J., 355, 501
Breitschwerdt D., 2001, Astrophys. and Space Sci., 276, 163
Breitschwerdt D., Egger R., Freyberg M. J., Frisch P. C., Vallerga J. V., 1996, Space Sci. Rev., 78, 183
Breitschwerdt D., Freyberg M. J., Egger R., 2000, Astron. and Astrophys., 361, 303
Bruhweiler F. C., 1984, in NASA Conference Publication Vol. 2345 of NASA Conference Publication, Absorption Line Studies and the Distribution of Neutral Gas in the Local Interstellar Medium. p. 39
Bruhweiler F. C., Oegerle W., Weiler E., Stencel R. E., Kondo Y., 1984, in NASA Conference Publication Vol. 2345 of NASA Conference Publication, Observations of Local Interstellar MG i and MG II. p. 64
Burgers J. M., ed. 1958, Cosmical Gas Dynamics, proceedings from IAU Symposium no. 8. Vol. 8
Chaikin E., Kaurov A. A., Fields B. D., Correa C. A., 2022, Monthly Notices Royal Astron. Soc., 512, 712
Cleary M. N., Heiles C., Haslam C. G. T., 1979, Astron. and Astrophys. Suppl., 36, 95
Corbelli E., Salpeter E. E., 1993a, Astrophys. J., 419, 94
Corbelli E., Salpeter E. E., 1993b, Astrophys. J., 419, 104

Corbelli E., Schneider S. E., Salpeter E. E., 1989, Astron. J., 97, 390
Cowie L. L., 1984, in NASA Conference Publication Vol. 2345 of NASA Conference Publication, Modelling the Local ISM as a Supernova Remnant in a Multiphase Gas. p. 287
Donaldson J. K., Weinberger A. J., Gagné J., Boss A. P., Keiser S. A., 2017, Astrophys. J., 850, 11
Egger R. J., Aschenbach B., 1995, Astron. and Astrophys., 294, L25
Eibensteiner C., Bigiel F., Leroy A. K., Koch E. W., Rosolowsky E., Schinnerer E., Sardone A., Meidt S., de Blok W. J. G., Thilker D., Pisano D. J., Ott J., Barnes A., Querejeta M., Emsellem E., Puschnig J., Utomo D., Bešlić I., den Brok J., Faridani S., Glover S. C. O., Grasha K., Hassani H., Henshaw J. D., Jiménez-Donaire M. J., Kerp J., Dale D. A., Kruijssen J. M. D., Laudage S., Sanchez-Blazquez P., Smith R., Stuber S., Pessa I., 2023, Astron. and Astrophys., 675, A37
Fardal M. A., Giroux M. L., Shull J. M., 1998, Astron. J., 115, 2206
Faucher-Giguère C.-A., Lidz A., Hernquist L., Zaldarriaga M., 2008, Astrophys. J., 682, L9
Faucher-Giguère C.-A., Lidz A., Zaldarriaga M., Hernquist L., 2009, Astrophys. J., 703, 1416
Field G. B., Goldsmith D. W., Habing H. J., 1969, Astrophys. J., 155, L149
Frisch P. C., Redfield S., Slavin J. D., 2011, Annual Rev. Astron. Astrophys., 49, 237
Fuchs B., Breitschwerdt D., de Avillez M. A., Dettbarn C., Flynn C., 2006, Monthly Notices Royal Astron. Soc., 373, 993
Fujimoto Y., Krumholz M. R., Inutsuka S.-i., Boss A. P., Nittler L. R., 2020, Monthly Notices Royal Astron. Soc., 498, 5532
Goldsmith D. W., Habing H. J., Field G. B., 1969, Astrophys. J., 158, 173
Hanbury Brown R., Davies R. D., Hazard C., 1960, The Observatory, 80, 191
Haslam C. G. T., Salter C. J., Stoffel H., Wilson W. E., 1982, Astron. and Astrophys. Suppl., 47, 1
Heithausen A., 2012, Astron. and Astrophys., 543, A21
Hjellming R. M., 1966, Astrophys. J., 143, 420
Ji S., Oh S. P., Masterson P., 2019, Monthly Notices Royal Astron. Soc., 487, 737
Kaplan S. A., Pikel'ner S. B., 1979, Physics of the interstellar medium.. Nauka, Moscow
Kravtsov A., Manwadkar V., 2022, Monthly Notices Royal Astron. Soc., 514, 2667
Lallement R., Snowden S., Kuntz K. D., Dame T. M., Koutroumpa D., Grenier I., Casandjian J. M., 2016, Astron. and Astrophys., 595, A131
Lehner N., Howk J. C., Wakker B. P., 2015, Astrophys. J., 804, 79
Lighthill M. J., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, The Effect of Compressibility on Turbulence. p. 121
Lockman F. J., 2017, in Gil de Paz A., Knapen J. H., Lee J. C., eds, Formation and Evolution of Galaxy Outskirts Vol. 321, Neutral Gas Outside the Disks of Local Group Galaxies. pp 223–225
Maloney P., 1993, Astrophys. J., 414, 41
Muller S., Wu S. Y., Hsieh B. C., González R. A., Loinard L., Yee H. K. C., Gladders M. D., 2008, Astrophys. J., 680, 975
Paresce F., 1984a, in NASA Conference Publication Vol. 2345 of NASA Conference Publication, Absorption and Emission of EUV Radiation by the Local ISM. p. 169

Paresce F., 1984b, Astron. J., 89, 1022
Penston M. V., 1970, Astrophys. J., 162, 771
Pikel'ner S., 1953a, Izvestiya Ordena Trudovogo Krasnogo Znameni Krymskoj Astrofizicheskoj Observatorii, 10, 74
Pikel'ner S., 1953b, Akademiia Nauk SSSR Doklady, 88, 229
Pikel'ner S. B., 1957, Sov. Astron., 1, 773
Pikel'ner S. B., 1968, Sov. Astron., 11, 737
Ramya S., Prabhu T. P., Das M., 2011, Monthly Notices Royal Astron. Soc., 418, 789
Saburova A. S., Chilingarian I. V., Kasparova A. V., Sil'chenko O. K., Grishin K. A., Katkov I. Y., Uklein R. I., 2021, Monthly Notices Royal Astron. Soc., 503, 830
Schulreich M. M., Breitschwerdt D., Feige J., Dettbarn C., 2017, Astron. and Astrophys., 604, A81
Schulreich M. M., Feige J., Breitschwerdt D., 2023, Astron. and Astrophys., 680, A39
Seaton M. J., 1958, Reviews of Modern Physics, 30, 979
Shchekinov Y., 2018, Galaxies, 6, 62
Shelton R. L., 2003, Astrophys. J., 589, 261
Shklovskii I. S., 1952, Astron. Zh., 29, 418
Sofue Y., 2015, Monthly Notices Royal Astron. Soc., 447, 3824
Sofue Y., Handa T., 1984, Nature, 310, 568
Sofue Y., Wakamatsu K.-I., Malin D. F., 1994, Astron. J., 108, 2102
Spitzer Lyman J., 1956, Astrophys. J., 124, 20
Spitzer Lyman J., Scott E. H., 1969, Astrophys. J., 158, 161
Spitzer Lyman J., Tomasko M. G., 1968, Astrophys. J., 152, 971
Su M., Slatyer T. R., Finkbeiner D. P., 2010, Astrophys. J., 724, 1044
Sunyaev R. A., 1969, Astrophys. Lett., 3, 33
Sutherland R. S., Dopita M. A., 1993, Astrophys. J. Suppl., 88, 253
Syunyaev R. A., 1970, Sov. Astron., 13, 729
Taylor G. I., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, Opening Address. p. 1
Taylor R., Minchin R. F., Herbst H., Davies J. I., Rodriguez R., Vazquez C., 2014, Monthly Notices Royal Astron. Soc., 443, 2634
van de Hulst H. C., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, A Survey of Problems and Suggested Solutions. p. 42
van Gorkom J., 1991, in Haschick A. D., Ho P. T. P., eds, Atoms, Ions and Molecules: New Results in Spectral Line Astrophysics Vol. 16 of Astronomical Society of the Pacific Conference Series, An HI' View of the Universe. p. 1
von Hoerner S., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, Contribution to the Turbulence Theory of Galaxies. p. 172
Wang X., Clark A. M., Ellis J., Ertel A. F., Fields B. D., Fry B. J., Liu Z., Miller J. A., Surman R., 2023, Astrophys. J., 948, 113
Weaver H., 1979, in Burton W. B., ed., The Large-Scale Characteristics of the Galaxy Vol. 84, Large Supernova Remnants as Common Features of the Disk. p. 295
Welsh B. Y., Lallement R., 2013, Publ. Astron. Soc. Pacific, 125, 1455
Werner M. W., Silk J., Rees M. J., 1970, Astrophys. J., 161, 965
Weymann R. J., Vogel S. N., Veilleux S., Epps H. W., 2001, Astrophys. J., 561, 559
Wolfe S. A., Pisano D. J., Lockman F. J., McGaugh S. S., Shaya E. J., 2013, Nature, 497, 224
Wolleben M., 2007, Astrophys. J., 664, 349

Xilouris E., Alton P., Alikakos J., Xilouris K., Boumis P., Goudis C., 2006, Astrophys. J., 651, L107
York D. G., Frisch P. C., 1984, in NASA Conference Publication Vol. 2345 of NASA Conference Publication, Synthesis of Data on Local Interstellar Medium. p. 51
Zanstra H., 1955, in Gas Dynamics of Cosmic Clouds Vol. 2, On the Formation of Condensations in a Gaseous Nebula. p. 70