Anticorrelated temperature–density profiles in the quiet solar corona and coronal mass ejections: Approach based on the spine-type Hamiltonians

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ABSTRACT

Context. The mechanism of the solar corona heating remains one of key problems in astrophysics for a few decades; but none of the proposed mechanisms can give a definitive answer to this question. As a result, the novel scenarios are still suggested.

Aims. Here, we perform a critical consideration of the recently-proposed mechanism for the formation of the anticorrelated temperature and density profiles due to specific features of relaxation in the strongly non-equilibrium plasmas described by the so-called spine-type Hamiltonians

Methods. We employ the universal property of the above-mentioned systems to produce the long-lived anticorrelated temperature–density distributions and analyse their most important qualitative features that should be expected in the context of the coronal plasmas.

Results. As follows from our consideration, the anticorrelated profiles predicted by the spine-type Hamiltonians can be hardly relevant to explanation of the temperature distribution in the quiet solar corona. However, they might be interesting for the interpretation of the large-scale inhomogeneity of the powerful coronal mass ejections, possessing the filament-type structure.

Key words. Plasmas – Sun: corona – Sun: coronal mass ejections (CMEs)

1. Introduction

The mechanism of heating the solar corona, i.e., a sharp increase of temperature in its upper, very rarefied layers, remains one of key problems in astrophysics since the middle of the last century. Despite a lot of the proposed scenarios—based either on wave absorption or micro- and nanoflares—none of them can provide an ultimate resolution of the heating problem (e.g., reviews Walsh & Ireland 2003; Erdélyi & Ballai 2007, and references therein). As a result, the new original hypotheses continue to be suggested up to the present time.

One of them is an attempt to explain the coronal heating by the specific properties of the model plasmas described by the so-called spine-type Hamiltonians, whose mathematical theory is investigated for almost a century. As regards the equilibrium plasmas, one of the fields in which the spine-type Hamiltonians appeared was the statistical physics of strongly non-equilibrium systems for more than a decade. Unfortunately, the major part of their participants were specialists in theoretical and mathematical physics, unrelated immediately to the astrophysical or plasma-physics research. In the last years, a few papers on this subject went out of press (e.g., the above-cited works Casetti & Gupta 2014; Teles et al. 2015) in the journals on statistical and mathematical physics but, again, they remained almost unknown to the wide astronomical community.

Therefore, it is one of the aims of the present Letter to draw attention of astronomers and astrophysicists to the respective ideas. In Sec. 2 we give a brief overview of the corresponding mathematical formalism and in Sec. 3 apply it to the coronal plasmas.

It should be mentioned that possible application of the specific features in relaxation of such plasmas to the problem of solar corona heating was discussed at some conferences on the statistical physics of strongly non-equilibrium systems for more than a decade. Unfortunately, the major part of their participants were specialists in theoretical and mathematical physics, unrelated immediately to the astrophysical or plasma-physics research. In the last years, a few papers on this subject went out of press (e.g., the above-cited works Casetti & Gupta 2014; Teles et al. 2015) in the journals on statistical and mathematical physics but, again, they remained almost unknown to the wide astronomical community.

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1 There were also some earlier applications of the spin-type models to studying the strongly non-equilibrium processes in the continuous media, e.g., in our work (Dumin 2009), but they referred to the so-called ϕ⁴ nonlinear field model rather than to the plasma physics.

2 E.g., a series of conferences held in the Max Planck Institute for the Physics of Complex Systems (Dresden, Germany): “Fluctuation and Dissipation Phenomena in Driven Systems far from Equilibrium” (16–18.07.2007), “Many-Body Systems far from Equilibrium: Fluctuations, Slow Dynamics and Long-Range Interactions” (16–27.02.2009), “Large Fluctuations in Non-Equilibrium Systems” (04–15.07.2011), “Small Systems far from Equilibrium: Order, Correlations, and Fluctuations” (14–18.10.2013), “Stochastic Thermodynamics: Experiment and Theory” (10–14.09.2014).
2. Dynamics of the strongly non-equilibrium plasmas

2.1. Spin-type models

Let us present here a very brief review of the description of plasmas by the spine-type Hamiltonians and the main features of relaxation of their non-equilibrium states predicted by such models; more mathematical details can be found in the papers cited in Introduction. The main idea is—by using some approximations—to reduce a Hamiltonian for the system of charged particles to the Hamiltonian for a spin system. Next, since the theory of spine-type Hamiltonians is an extensive and well-developed branch of mathematical physics, involving a lot of nontrivial and universal findings, it will be possible to transfer the corresponding results to the plasma phenomena.

Let us consider the simplest one-dimensional system (which is a reasonable approximation for the strongly magnetized plasmas). For simplicity, we assume the periodic boundary conditions, i.e. the region under consideration is topologically equivalent to a circle. Then, from the mathematical point of view, positions of the charged particles can be conveniently characterized by the angles $\theta_i$, defined with respect to the center of the circle; see left panel in Fig. 1. Next, we approximate the Coulomb’s potential $U(\theta)$ by the lowest-order Fourier harmonic, namely, the cosine function with a period corresponding to the size of the system; see right panel in the same figure.

As a result, the ionic Hamiltonian takes the form:

$$\mathcal{H} = \frac{1}{2} \sum_{i=1}^{N} p_i^2 + \frac{J}{N} \sum_{i=1}^{N} \sum_{j=1}^{i-1} \left[1 - \cos(\theta_i - \theta_j)\right],$$

where $p_i$ are the momenta of ions (which, for simplicity, are assumed to be of a unitary mass), $N$ is their total number, and $J$ is the interaction parameter commonly introduced in the spine-type models, which can be expressed through the parameters of the Coulomb’s system. Since the entire plasma must be electrically neutral, the above-mentioned ionic system should be embedded into the uniform electron gas. This corresponds to the well-known OCP (one-component plasma) approximation.

Let us mention also that in the case of plasma (where particles of the same sign repel each other) the interaction parameter $J$ in formula (1) is negative. By terminology used in the condensed-matter physics, this is called the “antiferromagnetic” type of interaction. At positive $J$ (“ferromagnetic” interaction) the particles are attracted to each other, which is relevant to the gravitating systems.

Therefore, the original Coulomb’s system was reduced to the spin-type system (1), where the cosine-type interaction between the spins is a counterpart of the Coulomb's interaction between the charged particles. Both equilibrium and non-equilibrium properties of such Hamiltonians were investigated in very much detail in the physics of condensed matter. In the context of plasma physics, these Hamiltonians was studied in the papers by Casetti & Gupta (2014), Teles et al. (2015). As a result, the following most important features were found:

1. If plasma was originally created in a strongly non-equilibrium state (i.e., possessed considerable fluctuations both in the temperature and density), then its relaxation proceeds in two stages: Firstly, some quasi-equilibrium state is quickly formed. Then, at a much longer temporal scale, this state is transformed to the genuine thermodynamic equilibrium.

2. A universal property of the above-mentioned quasi-equilibrium state is an anti-correlation between the spatial inhomogeneities of temperature and density.

This peculiarities of the relaxation are schematically illustrated in Fig. 2.

Examples of the particular calculations are given in Fig. 3. Left panel corresponds to the case of “antiferromagnetic” (Coulomb’s) interparticle interaction with imposition of the permanent external field and non-Maxwellian initial velocity distribution. Right panel corresponds to the “ferromagnetic” (gravitational) type of interaction with a Maxwellian initial velocity distribution disturbed by a short sudden pulse of the external field. It is seen that, despite the very different simulation setups, the final results are qualitatively the same. So, formation of the anti-correlated profiles is a generic property of the systems described by the Hamiltonian (1).

An alternative explanation of the same phenomenon, also proposed by Teles et al. (2015), is based on the well-known effect of Landau damping (e.g., Lifshitz & Pitaevskii 1981; Somov 2012). Namely, a perturbation of the charged-particle system is equivalent to generation of the waves, which subsequently experience the Landau damping and, thereby, form a non-Maxwellian tail of the velocity distribution function. Then, the so-called effect of “velocity filtration” comes into play, when only the most energetic particles can reach the regions of reduced density, corresponding to the higher potential energy. As a result, the anti-correlated temperature and density profiles are again formed.

2.2. Pictorial interpretation

From our point of view, there is a much more pictorial and universal interpretation of the anticorrelated profiles, which is actually independent of the specific features of the spin-type Hamiltonians:

1. Existence of the first (fast) and second (slow) stages in the dynamics of strongly non-equilibrium plasmas immediately follows from the two very different time scales for the relaxation of pressure $\Delta p_r$, on the one hand, and for the density and temperature, $\Delta n_r$ and $\Delta T_r$, on the other hand. Really, the rate of relaxation of the pressure is about the speed of light, while the relaxation time of density and temperature is much longer.

Additional constant term was introduced into the sum in order to get an exact correspondence to the spin interaction. This term evidently does not affect the equations of motion.

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Employed in the original simulations, are used in all plots.

Fig. 2. Sketch of the two stages of relaxation in the strongly non-equilibrium plasmas predicted by the spine-type models. An empty space between the second and third plots implies a much longer duration of the second stage as compared to the first stage of the relaxation.

Fig. 3. Examples of the anticorrelated temperature (blue solid curves) and density (red dashed curves) computed for plasmas described by the spine-type Hamiltonians: (left panel) reprinted Fig. 2 with permission from [L. Casetti and S. Gupta, 2014, Eur. Phys. J. B 87, 91] © 2019 by the American Physical Society. The dimensionless units, employed in the original simulations, are used in all plots.

Fig. 4. Sketch of the various hypothetical profiles of the density $n(z)$ and temperature $T(z)$ that should be formed in various parts of the solar corona if they were caused by the spontaneous relaxation of the strongly non-equilibrium plasma states.

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\[ \langle \Delta n \Delta T \rangle = 0 \quad \rightarrow \quad \langle \Delta n \Delta T \rangle < 0 \quad \rightarrow \quad \langle (\Delta n)^2 \rangle \approx 0, \quad \langle (\Delta T)^2 \rangle \approx 0. \]

Plasmas can explain the observed temperature profile in the solar corona, where temperature sharply increases with decreasing density. In general, this idea is well in agreement with the modern paradigm that the corona is very irregular in the horizontal direction (e.g., Golub & Pasachoff 2010), and that the observed distribution of its parameters is just the average outcome of many nonstationary processes, occurring in the individual magnetic flux tubes, as conjectured by Aschwanden et al. (2007).

Unfortunately, a closer inspection of the “anticorrelation scenario” shows that it can hardly serve as a viable realization of this paradigm. There are two major obstacles already at the qualitative level (i.e., even before any quantitative estimates):

1. Emergence of the anticorrelated temperature and density distributions in the spin-type models assumes that both the temperature and density gradients are formed spontaneously in a self-consistent way. On the other hand, a strong density gradient in the solar corona evidently results from the gravitational attraction to the center of the Sun rather than from any plasma processes (corresponding to the Coulomb’s interaction). So, one of the major prerequisites for the scenario discussed in Sec. 2.1 is not satisfied in the quiet solar corona, as was already mentioned earlier in our paper (Dumin 2016).

2. Moreover, even if the anticorrelated temperature and density profiles would be self-consistently formed along the particular magnetic flux tubes, the corresponding gradients should be directed randomly, as illustrated in Fig. 4. So, the average distributions of the density and temperature with height would be either constant (if spatial resolution of observations is insufficient to resolve the individual flux tubes) or oscillating in the horizontal direction (if the resolution is sufficiently

3. Application to the coronal plasmas

It was suggested by Teles et al. (2015) that just the above-mentioned anticorrelation between the temperature and density developed during the relaxation of strongly non-equilibrium plasmas.
Fig. 5. Example of the coronal mass ejection with a complex filamentary structure, observed on 04 January 2002 by LASCO/C2 instrument onboard SOHO satellite; courtesy of SOHO/LASCO consortium (ESA & NASA).

4. Conclusions

1. A universal property of relaxation of the strongly non-equilibrium plasmas is a formation of the long-lived anti-correlated temperature and density profiles. This can be derived both from the mathematical formalism of the spin-type Hamiltonians as well as from the more pictorial arguments presented in Sec. 2.2.

2. Unfortunately, as follows from the simple qualitative arguments, this mechanism is hardly applicable to explanation of the average temperature profile in the quiet solar corona.

3. However, the corresponding processes may be important for other solar phenomena, e.g., formation of the large-scale inhomogeneity in the powerful CMEs.

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5 The coronogram was taken from the SOHO LASCO CME Catalog https://cdaw.gsfc.nasa.gov/CME_list/