Effect of external magnetic field and friction force on the dynamic properties of the particles in the Yukawa liquids

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Strongly coupled plasmas are the class of physical systems, where a pair-interaction potential energy dominates the average kinetic energy of the particles [1]. To describe the properties of such systems, the "one-component plasma" (OCP) model is often used. The important thing is the choice of the interaction potential of the particles. The polarizable form of the interaction potential is the Yukawa potential: $\phi(r) = \frac{Q^2}{4\pi\varepsilon_0}\frac{\exp(-r/\lambda_\mathrm{D})}{r}$, where Q is the charge of the particles and λ_D is the screening (Debye) length due to the electrons and ions. This Yukawa potential is widely used as the interaction potential of the micron-sized dust particles in dusty plasmas [2, 3].

The aim of this work is to study the simultaneous effect of the magnetic field and the friction on the cage correlation functions and on the velocity autocorrelation functions (VACFs) and Fourier transform of VACF in a wide region of parameters. Our studies are based on Langevin dynamics (LD) simulation into which a proper description of the movement of the particles under the influence of an external magnetic field is incorporated [4]. Our numerical integration scheme of the particles' equations of motion follows the approach of Ref. [5], which takes into account the external magnetic field in the expansion of positions and velocities in the Taylor series. In Ref. [6], we introduced the friction force into the Velocity Verlet scheme, which is used in the present simulations.

Let the particles move in a two-dimensional (2D) Yukawa system in the (x,y) plane, and the homogeneous magnetic field is directed perpendicularly to the layer of the particles, that is $\mathbf{B} = (0,0,B)$. The equation of motion of the i - th particle ($i = 1..N, N$ is a number of the particles in a simulation cell) is:

$$m\ddot{\mathbf{r}}_i(t) = \sum_{i\neq j}\mathbf{F}_{ij}(r_{ij}) + Q[\mathbf{v}_i\times\mathbf{B}] - \nu\, m\mathbf{v}_i(t) + \mathbf{F}_\mathrm{Br}, \tag{1}$$

where the first term on the right hand side gives the sum of inter-particle interaction forces for two particles separated by a distance r_{ij}, the second is the Lorentz force. The friction force (ν is the friction coefficient of the dust particles in the background gaseous environment) is represented by the third term, while the fourth term takes into account an additional randomly fluctuating "Brownian" force due to the random kicks of the gas atoms on the dust particles. Time scales are normalized by plasma frequency $\omega_\mathrm{p} = \sqrt{nQ^2/2\varepsilon_0 ma}$. Here m is the particle mass, $a = (1/\pi n)^{-1/2}$ is the 2D Wigner–Seitz radius for a number density n.

The ratio of the inter-particle potential energy to the thermal energy is expressed by the coupling parameter $\Gamma = \frac{Q^2}{4\pi\varepsilon_0 a k_B T}$, where T is temperature. The screening parameter is $\kappa = a/\lambda_D$.

The strength of the magnetic field is written as: $\beta = \Omega/\omega_p$, where $\Omega = QB/m$ is the cyclotron frequency of the dust particles. The strength of the friction is defined by the dimensionless parameter $\theta = \nu/\omega_p$. So, the system is fully characterized by four parameters: Γ, κ, β and θ. We use a square simulation cell with $N = 1024$ and apply periodic boundary conditions. The integration of the equations of motion is executed according to the modified Velocity Verlet Scheme.

The localization of the particles characterized by the cage correlation function was investigated via the method of Ref. [7, 8], which allows the tracking of the changes in the surroundings of individual particles. The cage correlation function $C^c_{\rm cage}(t)$ is obtained by averaging the function $\Theta(c - N_i^{\rm out})$ over particles and initial times, that is,

$$C^c_{\rm cage}(t) = \langle \Theta(c - N_i^{\rm out}(0,t)) \rangle, \tag{2}$$

where Θ is the Heaviside function, $N_i^{\rm out}$ the number of particles that have left the original cage of particle i at time t. We compute the cage correlation functions for $c = 3$, and take the definition of the "caging time" when $t_{\rm cage}$ is defined as $C^3_{\rm cage}(t_{\rm cage}) = 0.1$.

The VACFs [9, 10] is defined as: $A_{\rm vv}(t) = \langle \mathbf{v(t)} \cdot \mathbf{v(0)} \rangle$, while its normalized value (giving $\bar{A}_{\rm vv}(0) = 1$) is expressed as:

$$\bar{A}_{\rm vv}(t) = \frac{\langle \mathrm{v}(\mathbf{t}) \cdot \mathrm{v}(\mathbf{0}) \rangle}{\langle \mathrm{v}(\mathbf{0}) \cdot \mathrm{v}(\mathbf{0}) \rangle}. \tag{3}$$

The velocity autocorrelation in the frequency domain is given by the Fourier transform of $A_{\rm vv}$:

$$A_{\rm vv}(\omega) = \int_0^\infty A_{\rm vv}(t) e^{i\omega t} dt, \tag{4}$$

and is calculated by replacing the upper limit of the integration with a time t_{max}, for which $A_{\rm vv} \cong 0$ at $t > t_{max}$. The results of our simulations obtained for the cage correlation function and VACFs under the conditions of the simultaneous presence of the external magnetic field and the friction imposed by the background gaseous environment.

The results of our simulations obtained for the cage correlation functions and caging time under the conditions of the simultaneous presence of the external magnetic field and the friction imposed by the background gaseous environment are presented in Figure 1. As a general observation, we can note that the cage correlation functions decay to the 0.1 value on the time

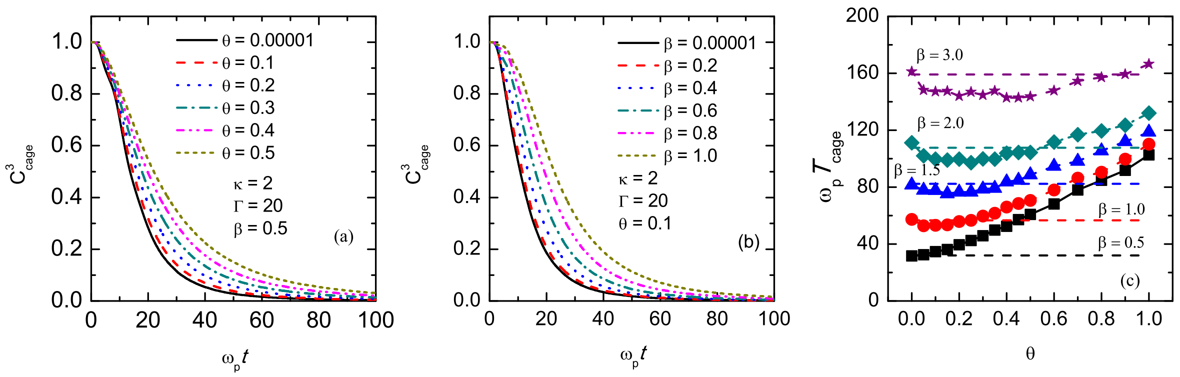

Figure 1: Cage correlation functions and dependence of the caging time on the friction parameter θ at given values of β, in the highly magnetized domain.

scale of 2–5 plasma oscillations for the conditions of Figure 1, panel (a) and (b). Such a long decay is characteristic for strongly-coupled plasmas. At small values of the magnetic field, the caging time increases monotonically with increasing friction see Figure 1(c). At $\beta > 0$ however, this dependence is non-monotonic. The effect, that the caging time first decreases as a function of friction coefficient becomes more pronounced at higher magnetic fields. Thus, the interplay of the magnetic field and the friction is non-trivial. Both mechanisms, when acting alone, are known to increase the caging time. The magnetic field results in this by forcing the particles to move on circular trajectories. When the Larmor radius is smaller than the inter-particle separation, diffusive motion across the field lines is significantly hindered, and the caging time is enlarged. The effect of friction on the caging time is similar but results from a different physical mechanism.

The results of the investigation the simultaneous effect of friction as well as a homogeneous external magnetic field on the Fourier transform of VACF of the dust particles were presented in Figure 2. The results of the normalized VACFs obtained for different values of system parameters, but in this paper we present the results of the Fourier transform of VACF. The increase

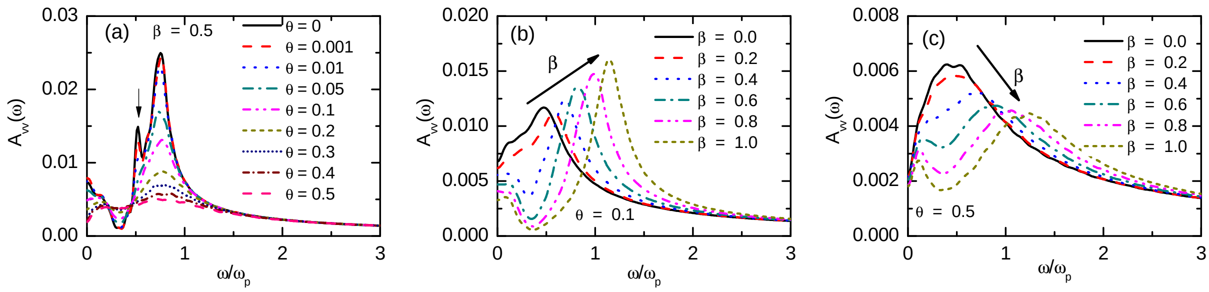

Figure 2: Fourier transform of VACFs (a)-(c) for a wide range of system parameters.

of the dominant frequency in the magnetized plasma was shown in the previous work [11], the present data convey additional information about the damping of the oscillations in the magnetized plasma due to the friction force. For a fixed magnetic field, the increasing friction was found to cause a decrease in the dominant peak, corresponding to the combined effect of magnetic field and strong correlations, and a complete disappearance of the peak, corresponding to cyclotron oscillations, which was found at $\theta = 0$ Figure 2(a).

We have shown that at small friction, the amplification of the magnetic field leads to a monotonous increase in the height of the dominant peak, and at a large value of friction, in contrast, to its fall (Figure 2(b),(c)). We explain these observations based on the fact that the attenuation of the ultrasonic waves in the medium increases with an increase in the frequency; however, a more detailed description of this effect can be the topic of the further studies.

The simultaneous effect of friction as well as a homogeneous external magnetic field on the quasi-localization, on the VACF and the Fourier transform of VACF of the dust particles in a 2-dimensional layer was investigated. The Langevin dynamics computer simulation method was used for this purpose. The corresponding conclusions were drawn on the basis of the obtained results.

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References

[1] G. J. Kalman, K. Blagoev, M. Rommel Eds., Strongly Coupled Coulomb Systems, Plenum Press, New York 1998;

[2] J. H. Chu, I. Lin, Phys. Rev. Lett. **72**, 724009 (1994)

[3] H. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, D. Móhlmann, Phys. Rev. Lett. **73**, 652 (1994)

[4] K. N. Dzhumagulova, T. S. Ramazanov, Y. A. Ussenov, M. K. Dosbolayev, R. U. Masheyeva, Contrib. Plasma Phys. **53**, 419 (2013)

[5] Q. Spreiter, M. Walter, J. Comput. Phys. **152**, 102 (1999)

[6] K. N. Dzhumagulova, T. S. Ramazanov, J. Phys.: Conf. Ser. **905**, 012022 (2017)

[7] E. Rabani, J. D. Gezelter, B. J. Berne, J. Chem. Phys. **107**, 6867 (1997)

[8] E. Rabani, J. D. Gezelter, B. J. Berne, Phys. Rev. Lett. **82**, 3649 (1999)

[9] O. S. Vaulina, X. G. Adamovich, O. F. Petrov, V. E. Fortov, Phys. Rev. E. **77**, 066404 (2008)

[10] K. N. Dzhumagulova, T. S. Ramazanov, R. U. Masheeva, Contrib. Plasma Phys. **52**, 182 (2012)

[11] K. N. Dzhumagulova, R. U. Masheeva, T. S. Ramazanov, Z. Donkó,Phys. Rev. E. **89**, 033104 (2014)