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Reply to "Comment on 'Temperature inversion in long-range interacting systems' "

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We present evidence that the mechanism proposed in Teles *et al.* [Phys. Rev. E **92**, 020101 (2015)], referred to as the TGDC mechanism, does apply to a model with repulsive mean-field interactions where it produces temperature inversion in a state whose inhomogeneity is due to an external field. Such evidence contradicts the core statement of the Comment. We also discuss a related issue, concerning the possible application of the TGDC mechanism to the solar corona.

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The core statement of the Comment is that the mechanism we proposed in Ref. [1], referred to as the TGDC mechanism, cannot be applied to systems where the stratification of the spatial density $n(\mathbf{r}) = \int d\mathbf{p}\, f(\mathbf{r},\mathbf{p})$, where $f(\mathbf{r},\mathbf{p})$ is the distribution function, is due to an external potential. In the following, we present evidence that contradicts this statement.

In a previous paper [2], it was shown that velocity filtration does apply and does produce temperature inversion also in a system where the stratification of the density is due to an external potential. The system referred to in Ref. [2] is the same toy model of long-range-interacting particles on a circle considered in Ref. [1], that is, the Hamiltonian mean-field (HMF) model but with repulsive interactions instead of attractive ones [also referred to as the antiferromagnetic HMF model (AHMF)]. Its Hamiltonian is

$$\mathcal{H} = \sum_{i=1}^{N} \left\{ \frac{p_i^2}{2} - \frac{1}{N} \sum_{j>i}^{N} [1 - \cos(\vartheta_i - \vartheta_j)] - h \cos \vartheta_i \right\}, \tag{1}$$

where $\vartheta_i \in (-\pi,\pi]$ is the angular coordinate of the ith particle on the circle and p_i is the conjugated momentum. In that system, particles are clustered only due to the external field h: In the absence of an external field the thermal equilibrium state of the AHMF model is a uniform homogeneous one for any energy or temperature at variance with the ferromagnetic case. Hence there is no reason to believe that the TGDC mechanism cannot be applied to a system where the nonconstant density is due to an external field. However, in Ref. [2] the situation was different than the one considered in the TGDC context [1]: There, a velocity distribution with fat tails was imposed as the initial condition of the dynamics, whereas in Ref. [1] we considered a thermal state that is perturbed by a "kick." To check that our mechanism also does apply when the stratification is due to an external field, we applied the same protocol used in Ref. [1] to the AHMF model with an external field, prepared in a thermal state and then subjected to an impulsive perturbation. We prepared the system (1) in a thermal equilibrium state with $N = 10^7$ particles, temperature $T = 1$, and external field $h = 1$. We let the system evolve until $t = t_0 = 100$ and then kicked it out of equilibrium by applying, during a short time interval $\tau = 1$, an additional external field $h' = 10$. For times of $t > t_0 + \tau$, the field again has the value of $h = 1$. Shortly after the kick the system settles in a quasistationary state (QSS). A plot of the temperature profile and of the density profile at $t = 10^4$ is shown in Fig. 1. Temperature inversion is well apparent and very similar to that obtained in the ferromagnetic HMF as well as in the two-dimensional self-gravitating system in Ref. [1]. Moreover, the velocity distribution has the same features as in the HMF case (data not shown). Hence, the TGDC mechanism does apply equally well also when the stratification of the density is due to an external field.

We would like to stress that the above result does not imply that our mechanism can be applied as such to explain the temperature profile of the solar corona. However, the mechanism of velocity filtration was suggested by Scudder [3–5] just to explain the temperature profile in the solar corona, and velocity filtration is a crucial ingredient of the TGDC mechanism: One could say that our mechanism is a way of letting velocity filtration take place without the need for the nonthermal boundary condition required in Scudder's model since it is the response of the system to a perturbation that drives the velocity distribution function towards a nonthermal shape where velocity filtration occurs, producing the inversion. If Scudder's mechanism is at least partially relevant for the

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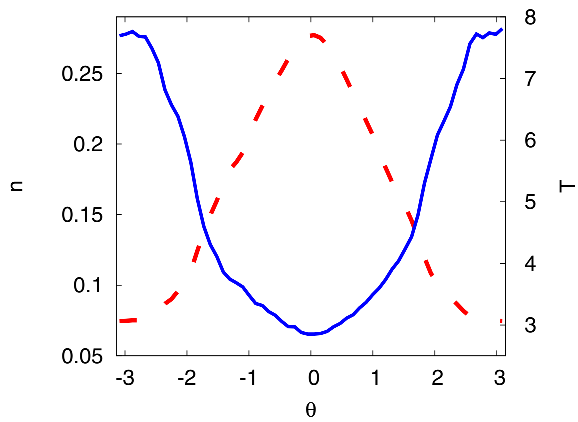

FIG. 1. AHMF: temperature profile $T(\vartheta)$ (blue solid line) and density profile $n(\vartheta)$ (red dashed line), measured in the QSS at $t = 10^4$.

solar corona, then also our mechanism may well be relevant since it does not even require a nonthermal boundary condition.

This said, the solar corona is a very complex system, and our simple models cannot completely explain its phenomenology. Just to mention two important aspects, in our simple models we consider only one species of interacting particles instead of two species with opposite charges, and we completely neglect the role played by the magnetic field. In this respect we agree with the author of the Comment that our mechanism instead can be much more relevant to simpler and "cleaner" systems as is the case of self-gravitating systems, such as molecular clouds, where it can really capture much of the physics involved. But it may be relevant also for the solar corona, at least as far as Scudder's mechanism [6] is, and this was what we stated in Ref. [1].

To summarize, we do agree with the final sentence of the Comment: Any possible physical mechanism has its own limited scope of applicability, and the latter should be identified as carefully as possible, but the scope of applicability of the TGDC mechanism also does include long-range-interacting systems where the stratification of the density is due to an external field.

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[6] It is worth recalling that Scudder's original model [3,4] just considered particles in an external potential.