Asymmetric multi-species alignment in drift wave turbulence

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Particle aggregation and transport in turbulence is widely studied in fluid dynamics [1]. In turbulent plasmas the aggregation of charged particles is in addition influenced by static and dynamic electric and magnetic fields. For drift wave turbulence in inhomogeneous magnetized plasmas it has been observed by Scott [2] that light positive trace ions (in addition to electrons and a main ion species) in three-species fusion plasma drift wave turbulence tend to dynamically align with the fluctuating electron density, so that fluctuation amplitudes of the electron and trace ion densities are spatiotemporally closely correlated. Moreover, in a nearly collisionless plasma with cold ions and low parallel electron resistivity the electrostatic potential closely follows changes in the electron density. Our present analysis shows that this dynamical alignment in drift wave turbulence is sign selective with respect to the vorticity of trapping eddies, for any given trace species charge, their large-scale background distribution, and background magnetic field direction. The resulting asymmetric effects on transport and aggregation of charged particles are discussed for applications to fusion and space plasmas.

A global electrostatic isothermal gyrofluid model [3] is here adapted for numerical computation of three-species drift wave turbulence in a quasi-2D approximation in the cold ion limit (neglecting finite Larmor radius effects) with a dissipative parallel coupling model.

The fluid particle densities n_s for (electron, main ion, and trace ion) species $s \in (e,i,z)$ are evolved by nonlinear advection equations $(\partial_t + \mathbf{v} \cdot \boldsymbol{\nabla}) n_s = C_s$, where all C_s include hyperviscous dissipation terms for numerical stability. The parallel gradient of the parallel fluid velocity components are for simplicity expressed by assuming a single parallel wave vector $k_{||}$ in the force balance equation along the magnetic field B [4]. Then C_e in addition includes the coupling term $d(\phi - n_e)$, where d is the parallel coupling coefficient proportional to $k_{||}^2/\nu_{ei}$. For weakly dissipative plasmas d is well larger than unity, but for practical purposes $d = 2$ already sufficiently supports nearly adiabatic coupling between n_e and ϕ while allowing reasonable time steps. The electrostatic potential is derived from the Poisson equation $\rho_m \nabla^2 \phi = n_e - n_i - a_z n_z$, where $\rho_m = 1 + a_z \mu_z$ with $a_z = Z n_z / n_e$ and $\mu_z = m_z/(Z m_i)$. In the local model only the density perturbations are evolved in the advection equation, which then gain an additional background advection term $(L_\perp / L_{ns}) \partial_y \phi$ on the right hand side, where $L_\perp$ is a normalising perpendicular scale (here set identical to L_{ne}) and y is the coordinate perpendicular to both the magnetic field and the background gradient directions. The numerical scheme for solution of the advection and Poisson equations is described (for a similar "Hasegawa Wakatani" type code where the ion density equation is replaced by a vorticity equation) in refs. [5]. The present computations use a 512×512 grid corresponding to $(64\, \rho_s)^2$ in units of the drift scale. Other nominal parameters were set to $(L_\perp/L_{nz}) = 0.001$, $a_z = 0.0001$, $\mu_z = 10$. The computations are initialised with quasi-turbulent random density fields and run until a saturated state is achieved.

In accordance with ref. [2] we observe in drift wave turbulence simulations that trace ion species dynamically align with n_e. In the adiabatic limit the electrons can be assumed to follow a Boltzmann distribution with $(n_0 + n_e) = n_0 \exp[-e\phi/T_e] \approx 1 + e\phi/T_e$, so that (for given T_e and n_0) a positive n_e perturbation corresponds to a positive localised potential perturbation ϕ. ExB drift vortices around a localised ϕ perturbation possesses a vorticity $\mathbf{\Omega} = \mathbf{\nabla} \times \mathbf{v} = (\mathbf{B}/|B|)\nabla^2\phi$, related to the Laplacian of the electrostatic potential, and thus (depending on the sign of ϕ) a definite sense of rotation with respect to the background magnetic field $\mathbf{B}$.

In ref. [2] the absolute correlation $|r|$ between the small density perturbations of electrons n_e and trace ions n_z has been determined. The present analysis shows that under specific conditions a definite sign relation appears for the sample correlation coefficient $r(n_e, n_t) = \sum(n_e - \overline{n}_e)(n_z - \overline{n}_z)/\sqrt{\sum(n_e - \overline{n}_e)^2 \sum(n_z - \overline{n}_z)^2}$, where the sum $\sum$ is taken over all grid points of the computational domain, and the bar $\overline{n}_s$ denotes the domain average of the specific particle density. We specifically observe that in local computations, where the densities are split into a static spatially slowly varying background component n_0 with perpendicular gradient lengths $L_n = (\nabla \ln n_0)^{-1}$ and a fluctuating part with small amplitudes n (typically in the range of a few percent), the sign of $r \approx \pm(0.90 \pm 0.02)$ only depends on the relative sign but not the magnitude of the gradient lengths L_{ne} and L_{nt}, for a given direction of the background magnetic field. The result for r changes only marginally for most other parameter variations. In particular, the sign of the impurity charge Z has no effect on the alignment property. Stronger adiabaticity leaves $r(d = 10) \approx \pm(0.90 \pm 0.02)$ largely unchanged, while a smaller dissipative coupling coefficient results in $r(d = 0.01) \approx \pm(0.79 \pm 0.02)$.

The observed sign-selective multi-species dynamical alignment effect is basically caused by the (linear) drive of density fluctuations $\partial_t n_s \sim (L_\perp/L_{ns})\partial_y \phi$ by this background advection term, where the potential ϕ is for each species just acting on the respective background gradients with length L_{ns}. The species densities are enhanced (positive partial time derivative) when the background advection is positive, and decreased when negative. Co-aligned gradients of electrons and trace ions thus dynamically also imply co-alignment of the density perturbations. In case of adiabatic electrons this additionally implies alignment with vorticity.

The situation is different if there is no background distribution of the trace ion species, but only a smaller localised cloud (diffusing over time) with an initial spatial extension in the same order of magnitude as the turbulence scales. Then the cloud has global gradients of its density in all directions with respect to the background electron (and primary ion) gradient, and the signs of r approximately cancel to zero by integration over the computational domain, while the absolute correlation coefficient $|r|$ remains near unity.

The basic conclusion is that for given ∇n_{s0} and $\mathbf{B}$ directions the perturbed trace ion n_s (like charged molecules or dust) dynamically aligns with a definite sign of the n_e and thus of ϕ fluctations, and consequently of vorticity Ω: for example, an excess of trace ions aggregates within vortices of clockwise direction, and a deficit is found in vortices with anti-clockwise direction (or vice versa, depending on global parameters). While, as usual in a fully developed turbulent state, vortices of both signs appear equally likely and evenly distributed over all turbulent scales, the trace particle aggregation on drift scales emerges only with one rotationality with respect to the background magnetic field and background particle gradients.

In the following we discuss two possible applications of this effect, on turbulent fusion edge plasma transport and on molecular aggregation in magnetized space plasmas.

First, consider transport of impurities in the edge of tokamaks. The impurity density can be peaked in the core or around the edge, depending on the species, charge state, and plasma parameters. The present asymmetric alignment with electrons also carries implications for the life time of impurities, whose recombination rates depend on the electron density (and temperature), and of dust particles, which are heated and evaporated mainly by collisions with electrons. Alignment or misalignment between impurities and electrons depend on the co- or counter-directionality of the respective gradients, which thus also determine the survival rate of impurities. Effects like recombination or ablation are not included in our present simulations, and should be considered in future.

In connection with outward propagating density blobs from the edge to scrape-off-layer (SOL) in bursty transport or edge localized mode (ELM) filaments, also inward propgating holes can be found in simulations. In the case of co-directed electron and impurity background gradients the fluctuating impurity density is co-aligned with electrons, and tendentially carried outwards by SOL blob transport. For counter-directed gradients, the impurities are rather carried inwards by holes. The potential consequences of this effect will have to be explored with more realistic models than in the present principle demonstration. We here just preliminarily conjecture that impurities (or dust particles), when sucked by holes into the pedestal region, can further decrease the electron temperature in the holes by radiative cooling and recombination (or absorption by dust), and should on a low-order rational surface cause a local temporal reduction of the parallel current on a (closed) helical filament. We here suggest this mechanism as an explanation for the origin of “palm tree modes” that have occasionally been observed in JET after ELMs [6].

Finally, we discuss a possible relevance of the asymmetric alignment effect on molecular chemistry in a magnetized space plasma environment.

The origin of homochirality in biomolecules requires a truly chiral physical effect during synthesis. Several mechnanisms have been suggested which most likely occur extraterrestrially. For example, it has been experimentally demonstrated that chirality can be imposed on aggregating molecules by rotational forces in fluids. However, it has been left an open question what mechanism could invoke a specific directionality in natural (space or terrestrial) fluids or plasmas, where vortices of both senses of rotation usually occur mixed across all scales.

Here we argue that rotation asymmetric ion aggregation in drift vortices in magnetised space plasmas constitutes a mechanism for fostering a truly chiral environment for enantiomeric selective extraterrestrial formation of biomolecules. The drift wave turbulence aggregation effect is found to be truly chiral, but would depend in sign on the directionality between background plasma and molecular gradients and B field direction, so that any resulting specific enantiomeric excess would only be a local effect, and would e.g. be different in opposite parts of a large molecular cloud in (warm ionised) interstellar matter. A detailed case on this possible chiral mechanism is made in the preprint ref. [7].

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