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Comment on "Paleoclassical Transport in Low-Collisionality Toroidal Plasmas"

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Physics of Plasmas

Disclaimer

Comment on "Paleoclassical transport in low-collisionality toroidal plasmas" [Phys. Plasmas 12, 092512 (2005)]

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Paleoclassical transport [1] is a recently proposed fundamental process that is claimed to occur in resistive plasmas and to be missing in the collisional drift-kinetic equations (DKE) in standard use. In this Comment we raise three puzzles presented by paleoclassical transport as developed in [1], one to do with conservation and two concerning uniqueness.

For convenient reference below, we highlight selected features of paleoclassical transport as developed in [1] (these statements are not a complete description of either paleoclassical processes or the magnetic configurations in which they occur):

S-I. Paleoclassical transport occurs in a strictly axisymmetric torus.

S-II. If $\left(\frac{\partial\psi}{\partial t}\right)_{\mathbf{x}}$ is taken to be zero in [1] (ψ is the poloidal flux), terms are absent in some equations but the calculations appear to go through straightforwardly; i.e., without a structural change.

S-III. The electron thermal diffusivity χ_e^{pc} is independent of the loop voltage.

S-IV. The 6D kinetic equation—Vlasov operator plus Fokker-Planck collisions—is said to be correct and to contain paleoclassical transport.

S-V. Particles which are collisionless on the magnetic flux-diffusion timescale diffuse with the flux.

From Statement S-V it is clear that paleoclassical transport is not a correction to the collision operator. Rather, paleoclassical transport is due to particles' gyro-centers being nearly tied to ψ as it convects and diffuses. This is the key hypothesis of the paleoclassical model. It is the guiding-center motion in the DKE for collisional plasmas that is said to be in error.

Re S-I, note that the small helical distortions arising from the transport [1] are not necessary to cause the transport. (Helical resonances lead to large multiplier on the axisymmetric result.)

From S-II, we are free to apply the model to configurations with vanishing inductive electric field. For our first two puzzles we shall restrict the discussion to 100% non-inductively driven steady states (NISS); i.e., to the case with static electric and magnetic fields.[3] The poloidal flux still satisfies a steady-state diffusion equation, and the expression for χ_e^{pc}, which depends only on the q- and local plasma profiles and not any time-dependence [in particular, not on the loop voltage (S-III)], is unaffected by the steady-state condition.

Paleoclassical puzzle 1: In an axisymmetric NISS plasma, the angular momentum of a collisionless particle is conserved, so a collisionless particle cannot diffuse with χ_e^{pc}, contrary to S-V.

Paleoclassical puzzle 2: Whether or not ψ solves a diffusion equation, collisionless particle orbits depend only on $\mathbf{B}$ and $\mathbf{E}$. Consider now a NISS force-free plasma ($\beta \to 0,\ \mathbf{v} \to 0,\ \upsilon \to 0$, where β is the ratio of material-to-magnetic pressure, $\mathbf{v}$ the fluid velocity, and υ the viscosity). In this case, $\mathbf{B}$ depends only upon $\mathbf{J}_{\parallel}(\mathbf{x})$. Given flexibility in electron and ion heat- and particle-sources, one can construct solutions of the steady-state transport equations with different resistivity profiles but identical $\mathbf{E}$, while adjusting the current sources as needed in response to the density- and temperature-profile changes so that $\mathbf{J}_{\parallel}$ does not change. These solutions lead to different predictions for the rate of paleoclassical diffusion for a collisionless particle. In a gyro-averaged description of the motion, the paleoclassical diffusion of gyro-centers is in addition to the usual guiding-center drifts, which do not change as the resistivity changes; but the full orbit is unique for given $\mathbf{B}$ and $\mathbf{E}$. How is this resolved?

Paleoclassical puzzle 3 arises from the key hypothesis S-V itself and the related comments, "The introduction of plasma resistivity leads to radial diffusion of magnetic field lines" [1, below Eq. (64)], and "Paleoclassical transport will be caused by electrons... being nearly 'frozen to' and hence carried with the poloidal flux" [1, Sec. VI]. As is well known, magnetic field-lines do not have a physical identity that survives from one instant to the next. A velocity field $\mathbf{v}_{\mathrm{f.l.}}$ can always be ascribed to them for convenience, but this velocity is not a measurable quantity and there is freedom in its choice. Even in ideal MHD (where $\mathbf{E}_{\parallel} = 0$ and the perpendicular fluid velocity equals the $\mathbf{E}\times\mathbf{B}$ drift velocity), a slip between the $\mathbf{E}\times\mathbf{B}$ drift and the field-lines can be included. In Ref. [2], the constraints on the possible $\mathbf{v}_{\mathrm{f.l.}}$ are given for flux conserving or line-preserving (i.e., a line initially a field-line remains a field-line) choices. A flux-conserving choice will be line-preserving, but not necessarily vice versa. The freedoms in the choices in each case are clearly given in [2]. (For a static $\mathbf{B}$, $\mathbf{v}_{\mathrm{f.l.}} = 0$ is a permissible but not unique flux-conserving choice.) The question then arises for the paleoclassical hypothesis (static or dynamic): *Which* field-line velocity is it hypothesized that the electrons are stuck to?

We conclude with a remark upon S-IV. If "paleoclassical transport" is taken to mean the response of a collisionless particle to collisional processes (which necessarily involve two other particles), a description in terms of a three-particle distribution function, rather than the two-particle effects contained the standard 6D collisional kinetic equation, would seem to be indicated.

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[1] J. D. Callen, Phys. Plasmas **12**, 092512 (2005).
[2] William A. Newcomb, Ann Phys. **3**, 347 (1958).
[3] Current drive is discussed in [1] below Eq. (67). Strict steady state is not required for the argument here, merely steady state on the resistive-diffusion timescale. In principle, particle-, heat- and current-drive sources can be arranged to accomplish this.