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Quasilinear theory, collisions, and ponderomotive forces: a unification for general plasmas and beyond

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Nonlinear effects produced by electromagnetic waves in plasmas are often modeled within the quasilinear (QL) approximation, meaning that the nonlinearities are retained in the low-frequency ('average') dynamics but neglected in the high-frequency dynamics. Two separate paradigms exist within this approach. In the *first paradigm*, commonly known as 'the' QL theory (QLT), the focus is made on resonant interactions. Nonresonant particles are considered as a background that is homogeneous in spatial or generalized coordinates; then the oscillating fields can be described in terms of global modes. This approach has the advantage of simplicity, but its applications are limited in that real plasmas are never actually homogeneous in any predefined variables (and, furthermore, tend to exhibit nonlinear instabilities in the presence of intense waves). The 'ponderomotive' dynamics determined by the gradients of the wave and plasma parameters are lost in this approach. The *second paradigm* successfully captures the ponderomotive dynamics by introducing 'dressed' particles called 'oscillation-centers' (OCs), which are governed by effective Hamiltonians. But OC Hamiltonians are singular for resonant interactions, so this approach has limited reach as well. As a result, remarkable subtleties are still found even in basic QL problems, which indicates that a clear comprehensive theory of QL wave–plasma interactions remains to be developed.

The framework that subsumes both resonant and nonresonant interactions in inhomogeneous plasmas is known as OC QLT. It was originally proposed for electrostatic turbulence in nonmagnetized plasma [1] and later extended to nonrelativistic magnetized plasma [2]. But the traditional approach to OC QLT is limited and partly heuristic. For example, resonant and nonresonant particles are separated there arbitrarily, the waves are assumed to be governed by a QL wave-kinetic equation (WKE), so they can only be *weakly* dissipative, or 'on-shell'. This means that collisions and microscopic fluctuations are excluded. Attempts to merge QLT and the WKE with theory of plasma collisions were made but have not yielded a local theory applicable to inhomogeneous plasma: the existing models still rely on global-mode decompositions and treat complex frequencies heuristically. Thus, the challenge of developing a comprehensive QLT still stands.

I will introduce a reformulation [3] of the traditional QLT that is free of the said limitations and provides an intuitive local theory. This reformulation replaces the traditional Fourier–Laplace approach and the variational approach with more flexible methods from operator analysis, which have also proven useful in related wave and turbulence problems in the past [4-6]. The resulting theory is not restricted to any specific plasma model or even to electromagnetic waves; for example, gravitational interactions are subsumed on the same footing with electromagnetic interactions. The new formulation captures QL diffusion and ponderomotive effects simultaneously, as well as the interaction with background fields. The QL-diffusion coefficient in this modern approach is always positive-semidefinite, which eliminates the common problem of spurious negative entropy production in inhomogeneous plasma. Waves are allowed to be off-shell, and a collision integral of the Balescu–Lenard type emerges for general Hamiltonian interactions. This operator conserves particles, momentum, and energy, and it also satisfies the *H*-theorem, as usual. As a bonus, one also obtains a general expression for the spectrum of microscopic fluctuations of a general interaction field. For on-shell waves governed by the WKE, the theory conserves the momentum and energy of the wave–plasma system. The action of nonresonant waves is conserved to, unlike in standard QLT, which is erroneous in this regard (something that is usually overlooked).

I will overview this new QLT and discuss how it improves modeling of the wave energy–momentum deposition into plasma – a problem of common interest for fusion applications and plasma physics in general. I will also discuss connections with other formulations of QLT and with the theory of collision operators for common plasma models. Finally, I will introduce QLT for gravitational waves as an example that demonstrates the power of the new framework even beyond the contexts within which QLT is usually considered.

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References

[1] R. L. Dewar, Phys. Fluids **16**, 1102 (1973).
[2] S. W. McDonald *et al.*, Phys. Lett. A **111**, 19 (1985).
[3] I. Y. Dodin, arxiv:2201.08562, to appear in J. Plasma Phys.
[4] I. Y. Dodin *et al.*, Phys. Plasmas **26**, 072110 (2019).
[5] D. E. Ruiz and I. Y. Dodin, Phys. Rev. A **95**, 032114 (2017).
[6] H. Zhu and I. Y. Dodin, Phys. Plasmas **28**, 032303 (2021).