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Quantum physics of classical waves in plasma[1]

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The Lagrangian approach to plasma wave physics is extended to a universal nonlinear theory which yields generic equations invariant with respect to the wave nature. The traditional understanding of waves as solutions of the Maxwell-Vlasov system is abandoned. Oscillations are rather treated as physical entities, namely, abstract vectors $|\psi\rangle$ in a specific Hilbert space. The invariant product $\langle\psi|\psi\rangle$ is the total action and has the sign of the oscillation energy. The action density is then an operator. Projections of the corresponding operator equation generate assorted wave kinetic equations; the nonlinear Wigner-Moyal equation is just one example and, in fact, may be more delicate than commonly assumed. The linear adiabatic limit of this classical theory leads to quantum mechanics in its general form. The action conservation theorem, together with its avatars such as Manley-Rowe relations, then becomes manifest and in partial equilibrium can modify statistical properties of plasma fluctuations. In the quasi-monochromatic limit geometrical optics (GO) is recovered and can as well be understood as a particular field theory in its own right. For linear waves, the energy-momentum equations, in *both* canonical and (often) kinetic form, then follow automatically, even without a reference to electromagnetism. Yet for waves in plasma the general GO Lagrangian is also derived explicitly, in terms of single-particle oscillation-center Hamiltonians. Applications to various plasma waves are then discussed with an emphasis on the advantages of an abstract theory. Specifically covered are nonlinear dispersion, dynamics, and stability of BGK modes, and also other wave transformations in laboratory and cosmological plasmas.

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