

Quantum Computing for Space Plasmas: Applications to Vlasov-Maxwell Systems through Hamiltonian Simulation

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論文内容の要旨

Macro-scale space plasma phenomena triggered by micro-scale kinetic effects, such as magnetic reconnection, are abundant in the solar-terrestrial environment. Space plasma simulations have been developed with high precision and high resolution using large-scale computers to predict and simulate such space plasma phenomena. However, multi-scale space plasma simulations require computational resources that scale with a high order of the number of spatial grid points.

We focus on the Vlasov-Maxwell equations, which are the first-principles system governing space plasma, and have developed numerical simulations of the Vlasov-Maxwell equations using quantum computing.

In this thesis, we develop a quantum-classical hybrid Vlasov-Maxwell solver. Specifically, the Vlasov solver implements the Hamiltonian simulation based on Quantum Singular Value Transformation (QSVT), coupled with a classical Maxwell solver.

The computational complexity of our quantum algorithm can potentially be reduced from the classical $O(NT/\epsilon)$ to $O(\text{poly}(\log(N))(NT + T\log(T/\epsilon)))$ for the N grid system, simulation time T and error tolerance ϵ in the limit where the number of queries is large enough and the error is small enough.

Furthermore, the numerical analysis reveals that our quantum algorithm is robust under larger range compared with classical algorithms with the constraint of Courant-Friedrichs-Lewy (CFL) condition.

This thesis provides a clear implementation method using existing quantum algorithms and presents concrete numerical evaluations, in order to apply quantum computing to space plasma simulations when future fault-tolerant quantum computing (FTQC) possesses ideal quantum resources.

In particular, the novelty of this study lies in newly clarifying the requirements and benefits of quantum algorithms in general space plasma simulations through numerical evaluations.

Finally, this doctoral thesis proposes a conceptual new approach to numerical simulations and observational methods in the academic area of space plasma for future applications.