8th Asia-Pacific Conference on Plasma Physics, 3-8 Nov, 2024 at Malacca

Seed magnetogenesis through the canonical battery effect

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Magnetic fields are ubiquitous in our Universe and governs the dynamics of most plasmas. Despite its ubiquity, the exact origin of primordial magnetic fields is a mystery. Although turbulent dynamo mechanisms may amplified magnetic fields, they require a seed magnetic field to begin with whose origins are not clear.

There are two popular mechanisms for seed magnetogenesis. The first one is the Biermann battery effect [1], which describe spontaneous generation of magnetic fields due to a misalignment of density and pressure gradients. The second one is the Weibel instability [2], which arises due to pressure anisotropy, or equivalently, counterpropagating beams.

A seemingly unrelated physical quantity is the canonical vorticity, which is the curl of canonical momentum and is a weighted sum of the fluid vorticity and the magnetic field. By taking the curl of the fluid equation of motion of any species under the Lorentz force, the equation can be reduced to an equation describing the time evolution of canonical vorticity, i.e.,

$$\frac{\partial \boldsymbol{Q}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{Q}) - \nabla \times \frac{\nabla \cdot \boldsymbol{p}}{n}$$

where $\boldsymbol{Q} = m\nabla \times \boldsymbol{u} + q\boldsymbol{B}$ is the canonical vorticity which is like a proxy for the magnetic field, $\boldsymbol{u}$ is the fluid velocity, $\boldsymbol{p}$ is the pressure tensor, and n is the density. It can be seen that when the system is initial vorticity-free and has no magnetic field, the only term that can spontaneously generate magnetic field is the last term, which is the canonical battery term.

This canonical battery term is shown to generalize both Biermann battery and Weibel instability, and predicts new mechanism that is 2D-localized pressure anisotropy. The predictions are further verified through particle-in-cell simulations

References

[1] L. Biermann, "Uber den Ursprung der Magnetfelder auf Sternen und im interstellaren". *Zeitschrift für Naturforschung*. **5**: 65 (1950)
[2] E. S. Weibel, "Spontaneously Growing Transverse Waves in a Plasma Due to an Anisotropic Velocity Distribution". *Physical Review Letters*. **2**: 3 (1959)