Thin layer axion dynamo

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Plan of talk

- Axions and axion-like-particles (ALP).
- Axion magneto-hydrodynamics (MHD). New induction equation.
- Axion dynamo in a spherical clump accounting for poloidal and toroidal magnetic fields.
- Thin layer approximation.
- Low mode approximation.
- Application to solar plasma.
- Flashes in solar corona and corona heating.

References

- M.Dvornikov, Thin layer axion dynamo, arXiv:2401.03185.
- P.Akhmetiev & M.Dvornikov, Magnetic fields in inhomogeneous axion stars, Int.J.Mod.Phys.D **33**, 2450001 (2024), arXiv:2303.09254.
- M.Dvornikov & P.Akhmetiev, Evolution of the magnetic field in spatially inhomogeneous axion structures, Theor.Math.Phys. **218**, 515 (2024).

Axions and ALP

- Historically, a QCD axion is introduced to explain almost vanishing electric dipole moment of a neutron: $d < 1.8 \times 10^{-26}$ e cm.
- Axions are pseudoscalar particles.
- Mass of axions is 10^{-4} eV < m < 10^{-6} eV. Buschmann et al. (2022) established the experimental upper bound m < 16 meV.
- One can also consider ALP with much smaller masses
  $m = (10^{-21} - 10^{-23})$ eV.
- Axions and ALP are the most plausible candidates for dark matter.
- Electric charge of axions and ALP is zero, but they can weakly interact with electromagnetic fields.

Axion MHD

- Lagrangian for axions and photons:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\varphi\partial^\mu\varphi - m^2\varphi^2) - \frac{g_{a\gamma}\varphi}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} - A^\mu J_\mu$$

- Modified Maxwell equations (axion electrodynamics):

$$(\nabla \times \mathbf{B}) = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} + g_{a\gamma}\mathbf{B}\frac{\partial\varphi}{\partial t} + g_{a\gamma}(\nabla\varphi \times \mathbf{E}), \quad (\nabla \times \mathbf{E}) = -\frac{\partial \mathbf{B}}{\partial t}, \quad (\nabla \cdot \mathbf{E}) = -g_{a\gamma}(\mathbf{B}\cdot\nabla)\varphi + \rho, \quad (\nabla \cdot \mathbf{B}) = 0$$

- New induction equation (axion MHD):

$$\dot{\mathbf{B}} = \nabla \times [\mathbf{b} \times (\nabla \times \mathbf{B}) + \alpha\mathbf{B} - \eta(\nabla \times \mathbf{B})], \quad \alpha = g_{a\gamma}\eta\dot{\varphi}, \quad \mathbf{b} = g_{a\gamma}\eta^2\nabla\varphi$$

- Here η is the magnetic diffusion. Magnetic field is divergenceless.
- One can see that dynamo amplification is possible since $\alpha \neq 0$.
- Inhomogeneous Klein-Gordon equation for axion:

$$\ddot{\varphi} - \Delta\varphi + m^2\varphi = g_{a\gamma}(\mathbf{EB})$$

Axion vs classical MHD

New induction equation

$$\dot{\mathbf{B}} = \nabla \times [\mathbf{b} \times (\nabla \times \mathbf{B}) + \alpha \mathbf{B} - \eta(\nabla \times \mathbf{B})]$$

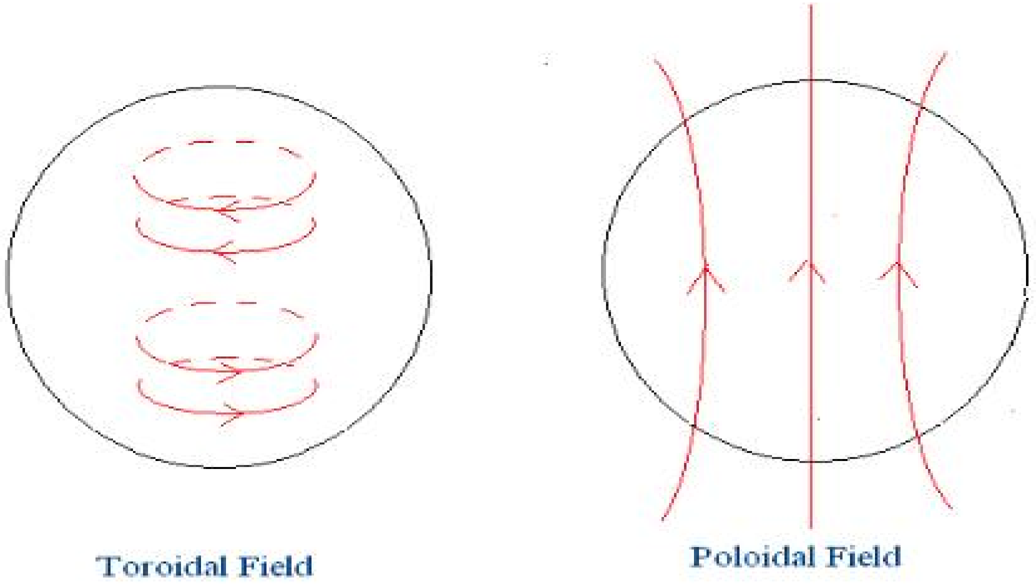
Standard induction equation

$$\dot{\mathbf{B}} = \nabla \times [(\mathbf{v} \times \mathbf{B}) + \alpha \mathbf{B} - \eta(\nabla \times \mathbf{B})]$$

v is the plasma velocity

Toroidal and poloidal fields

- We consider the evolution of the magnetic field and axions in a spherical volume (an axion star).
- All the quantities are axially symmetric.
- We decompose the the magnetic field in the toroidal and poloidal componets



$$\mathbf{B}_t = B\mathbf{e}_\phi \quad \mathbf{B}_p = \nabla \times (A\mathbf{e}_\phi)$$

$$B(r,\pi-\theta,t) = -B(r,\theta,t),\ A(r,\pi-\theta,t) = A(r,\theta,t)$$

Symmetry of axion wavefunction $\varphi(r,\pi-\theta,t) = -\varphi(r,\theta,t)$

since it is a pseudoscalar field

Thin layer approximation

- Equations for A, B, and an axion are quite complicated.
- Parker (1955) suggested to study the evolution of magnetic fields in a thin spherical layer R < r < R + dr, where R is the typical radius of a (axion) star.
- We keep the dependence on the latitude.

$$\frac{\partial\mathcal{A}}{\partial\tau} = -\frac{\partial\Phi}{\partial\theta}\left[\frac{\partial\mathcal{B}}{\partial\theta} + \cot\theta\mathcal{B}\right] + \frac{\partial\Phi}{\partial\tau}\mathcal{B} + \frac{\partial^2\mathcal{A}}{\partial\theta^2} + \cot\theta\frac{\partial\mathcal{A}}{\partial\theta} - \frac{\mathcal{A}}{\sin^2\theta}$$

$$\begin{aligned}\frac{\partial\mathcal{B}}{\partial\tau} = {} & \frac{\partial^2\Phi}{\partial\theta^2}\left(\frac{\partial^2\mathcal{A}}{\partial\theta^2} + \cot\theta\frac{\partial\mathcal{A}}{\partial\theta} - \frac{\mathcal{A}}{\sin^2\theta}\right) + \frac{\partial\Phi}{\partial\theta}\left(\frac{\partial^3\mathcal{A}}{\partial\theta^3} + \cot\theta\frac{\partial^2\mathcal{A}}{\partial\theta^2} - \frac{2}{\sin^2\theta}\frac{\partial\mathcal{A}}{\partial\theta} + \frac{2\cot\theta}{\sin^2\theta}\mathcal{A}\right) \\ & - \frac{\partial^2\Phi}{\partial\tau\partial\theta}\left(\frac{\partial\mathcal{A}}{\partial\theta} + \cot\theta\mathcal{A}\right) - \frac{\partial\Phi}{\partial\tau}\left(\frac{\partial^2\mathcal{A}}{\partial\theta^2} + \cot\theta\frac{\partial\mathcal{A}}{\partial\theta} - \frac{\mathcal{A}}{\sin^2\theta}\right) + \frac{\partial^2\mathcal{B}}{\partial\theta^2} + \cot\theta\frac{\partial\mathcal{B}}{\partial\theta} - \frac{\mathcal{B}}{\sin^2\theta}\end{aligned}$$

$$\frac{\partial^2\Phi}{\partial\tau^2} = -\mu^2\Phi + \kappa^2\left(\frac{\partial^2\Phi}{\partial\theta^2} + \cot\theta\frac{\partial\Phi}{\partial\theta}\right) + \left(\frac{\partial\mathcal{B}}{\partial\theta} + \cot\theta\mathcal{B}\right)\left(\frac{\partial\mathcal{A}}{\partial\theta} + \cot\theta\mathcal{A}\right) + \mathcal{A}\mathcal{B} - \mathcal{B}\left(\frac{\partial^2\mathcal{A}}{\partial\theta^2} + \cot\theta\frac{\partial\mathcal{A}}{\partial\theta} - \frac{\mathcal{A}}{\sin^2\theta}\right)$$

Low mode approximation

- Following Nefedov & Sokoloff (2010), we decompose magnetic fields and axions into the harmonics keeping two of them

$$\mathcal{A} = a_1(\tau)\sin\theta + a_2(\tau)\sin 3\theta + \ldots,$$
$$\mathcal{B} = b_1(\tau)\sin 2\theta + b_2(\tau)\sin 4\theta + \ldots,$$
$$\Phi = \phi_1(\tau)\sin 2\theta + \phi_2(\tau)\sin 4\theta + \ldots$$

- This decomposition takes into account the symmetry properties of the fields.
- Inserting this decomposition to the general equations, and accounting for the orthonormality of $\sin(n\theta)$, we get the system of nonlinear ordinary differential equation for the amplitudes.
- This system is quite cumbersome. One can find it in arXiv:2401.03185 in the explicit form. We solve this system numerically for given initial conditions.

Solar plasma

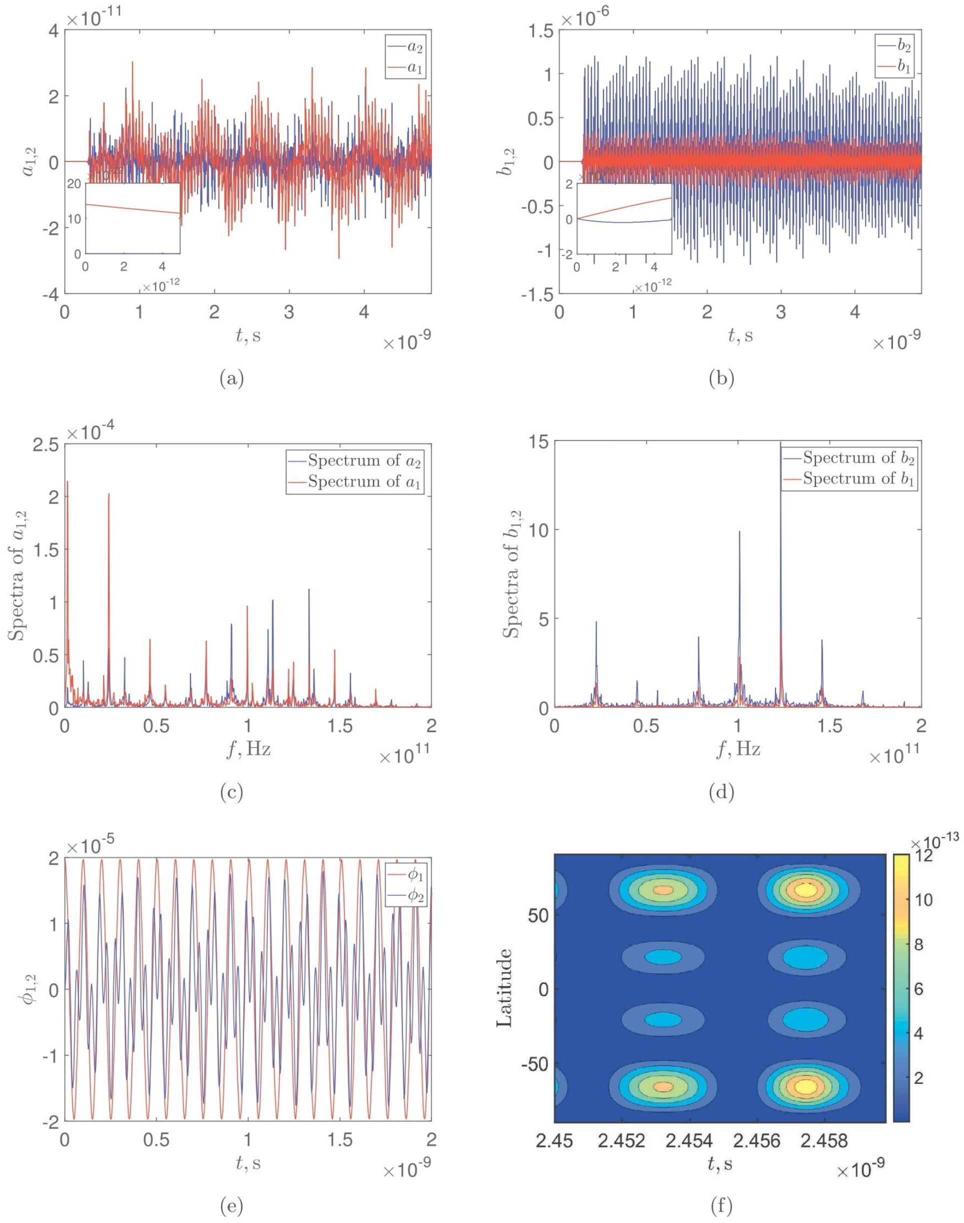
- We consider evolution of the system in solar plasma.
- Seed magnetic fields can range from ~ a few G (poloidal field in to quiet Sun) to a few kG in sunspots areas. We take $B_0 = 1G$.
- We studied much stronger seed fields > 1 kG. The dynamics of magnetic fields does not qualitatively change in this case.
- Both poloidal and toroidal seed magnetic fields are probed.
- Molecular magnetic diffusion $\eta = \sigma^{-1}$ is much smaller than the turbulent one. We take $\eta = 10^{10} cm^2/s$.

Axion star properties

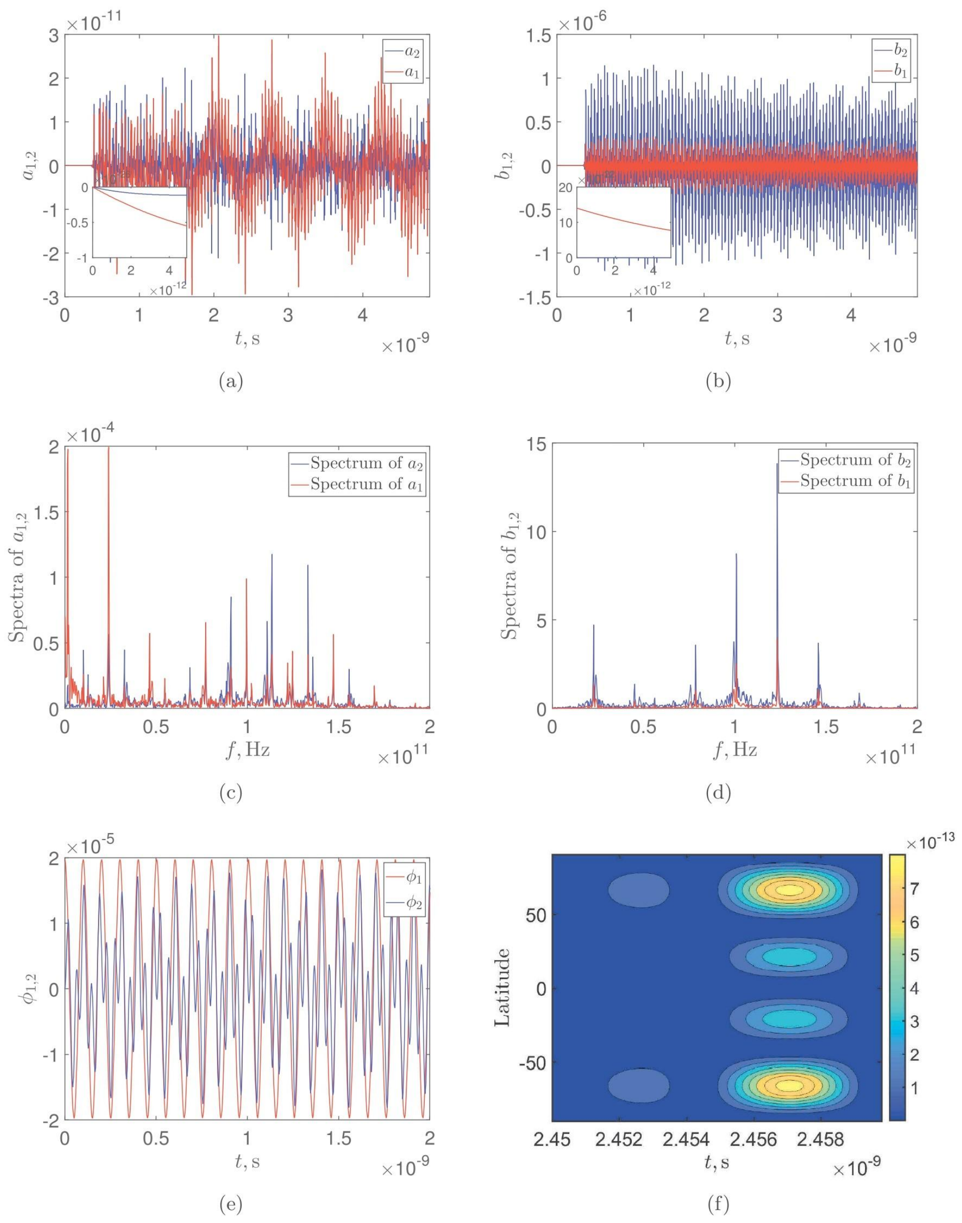
- We take such parameters of the system in order to excite oscillations of magnetic fields. Note that magnetic oscillations appear not in any case.
- One should take the radius of the axionic clump R ~ 1 cm. Braaten et al. (2015) showed that such small dense axion stars are stable. In this case, magnetic fields oscillations can be excited.
- The energy density in axion star is $\rho = 10^{-2} m^2 f_a^2$, where f_a is the Peccei-Quinn constant, and $m = 10^{-5} eV$ is the axion mass. It gives us $\phi_1(0) = 2\times 10^{-5}$
- We assume that an axion clump appears in the solar convective zone. The magnetic diffusion length ~ a few cm. Thus, magnetized plasma with the length scale ~ 1 cm may well exist.

Results

The typical frequencies of poloidal field harmonic is in the range $(10^9 - 10^{10})$ Hz

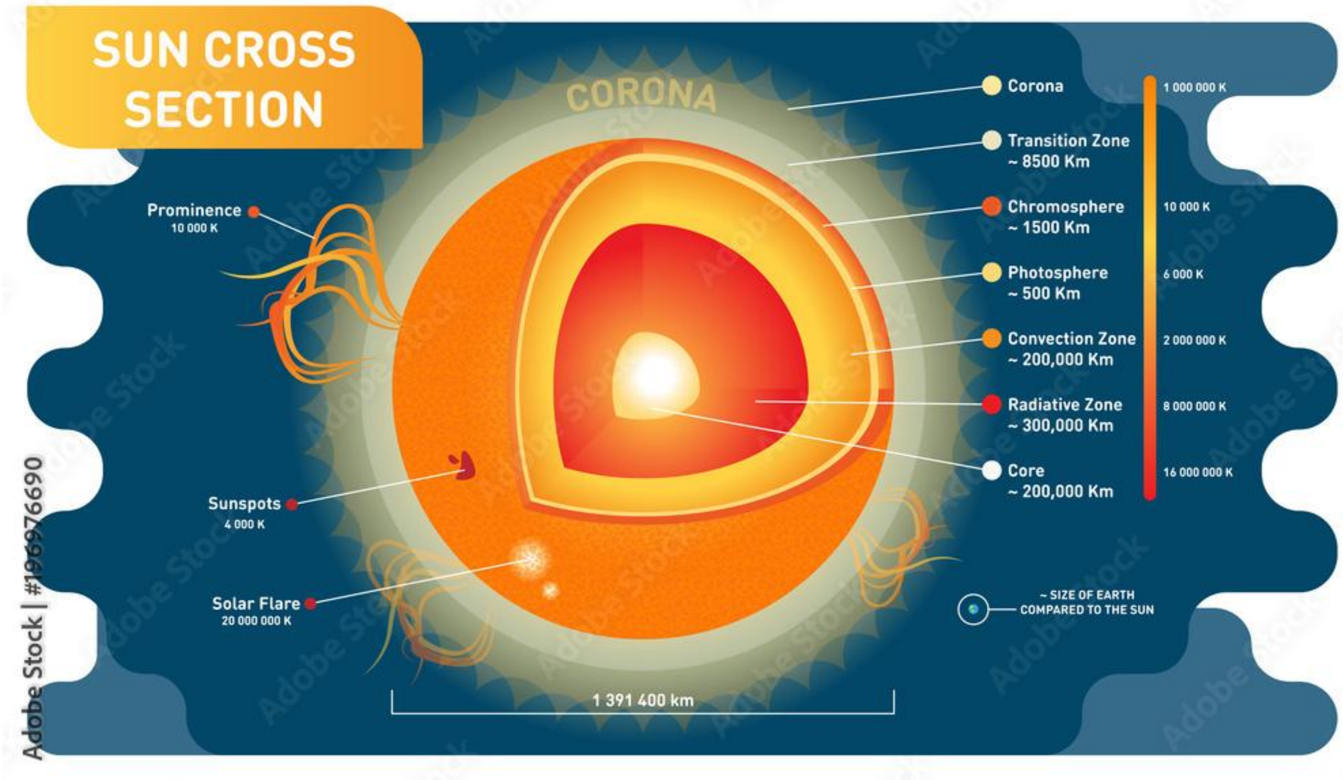


Seed poloidal field



Seed toroidal field

The Sun


SUN CROSS SECTION
CORONA
Corona
Transition Zone
~ 8500 Km
Chromosphere
~ 1500 Km
Photosphere
~ 500 Km
Convection Zone
~ 200,000 Km
Radiative Zone
~ 300,000 Km
Core
~ 200,000 Km
1 000 000 K
10 000 K
6 000 K
2 000 000 K
8 000 000 K
16 000 000 K
Prominence
10 000 K
Sunspots
4 000 K
Solar Flare
20 000 000 K
~ SIZE OF EARTH COMPARED TO THE SUN
1 391 400 km
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Evolution of an axionic clump

- We suppose that a magnetized axion clump appears in solar convective zone. The conditions for exitations of magnetic fields oscillations are appropriate there.
- Then, this clump floats up towards the solar surface. Then it reaches the corona of the Sun, the magnetic diffusion changes. Oscillations of magnetic fields become unstable and the axion clump decays.
- The energy of magnetic oscillations is released to the outer space. It should be converted to the electromagnetic radiation.
- The emission of such electromagnetic waves should have the form of a flash in the point of a clump destruction.
- The radiation frequencies of a flash should be $<(10^9 - 10^{10})$ Hz

Relation to the corona heating

- Explanation of the high temperature $>10^6$ K of the solar corona is a puzzle for modern astrophysics (De Moortel & Browning, 2015).
- There are models of the corona heating based on microflashes.
- Mondal et al. (2020) observed such flashes. The frequencis are < 160 MHz.
- The frequencies of magnetic fields oscillations in our model are slightly above the observed ones.
- We suggest that the decay of a small magnetized axionic clump can be interpreted as a coronal flash and contribute to the corona heating.
- Zhitnitsky et al. (2020) studied the implication of dark matter (axion quark nuggets) to the solar corona heating.

Summary

- We derived the new induction equation accounting for the axion wavefunction inhomogeneity.
- This equation was used to study the magnetic fields evolution in an axion star.
- Applying the thin layer and low mode approximations, we simulated the behavior of magnetic fields.
- Magnetic fields were found to enter to the oscillations regime for certain parameters of the system and initial condition.
- We applied our results for axion star in solar plasma.
- We showed that, in frames of our model, one can explain flashes in solar corona.
- We also discussed the application to the corona heating.