Late-time magnetogenesis with ALP dark matter and dark photon

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KC, Hyungjin Kim, Toyokazu Sekiguchi, [arXiv:1802.0xxxx]

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Outline

- Introduction

- Latetime magnetogenesis driven by axion-like particle constituting dark matter, and hidden U(1) gauge boson

- Conclusion
Magnetic fields are ubiquitous in the Universe.

B fields at large scales:

* Galactic B fields $B \sim 1 - 10 \mu \text{G}$ which may originate from a tiny seed field amplified by dynamo, compression, ...  
  [For a review, Durrer, Neronov ’13 ]

\[
B_{\text{seed}} \gtrsim \mathcal{O}(10^{-30}) \text{ G} \quad (\lambda \gtrsim \mathcal{O}(0.1) \text{ kpc})
\]
  [Davis, Lilley, Tornkvist ’99]

* Intergalactic B fields which may explain the lack of secondary GeV gamma rays in TeV blazar observations:

\[
B_{\text{void}} \times \min[1, \sqrt{\lambda/0.1 \text{Mpc}}] \gtrsim \mathcal{O}(10^{-19} - 10^{-16}) \text{ G}
\]
  [Finke et al ‘15; Wood et al ‘17]
It is an interesting possibility that those large scale B fields have a cosmological origin related to BSM physics.

* Inflationary magnetogenesis  [Turner, Widrow ’88; Ratra ’92, ...]

  Inflaton couplings: \(\sigma F^{\mu\nu} F_{\mu\nu}, \sigma F^{\mu\nu} \tilde{F}_{\mu\nu}, \ldots\)

  Implications, constraints, ... are still under active investigation.  
  [Barnaby et al ’12; Ferreira et al ’14; Fujita et al ‘15; Adshead et al ’16; Caprini et al ’17; ... ]

* Phase transition  [Vachaspati ’91; Enqvist, Olesen ’93, ...]

  Bubble dynamics in 1\(^{st}\) order phase transition, topological defects, ....

  However, lack of concrete model

Less explored possibility:

  Cosmological magnetogenesis by BSM physics might occur much later, e.g. well after the BBN, as suggested by large coherent length scale.
Late-time magnetogenesis after the electron/positron annihilations driven by ALP dark matter $\phi$ & hidden U(1) gauge boson $X_\mu$

[KC, H. Kim, T. Sekiguchi]

\[ L_{\text{eff}} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{1}{2} m^2 \phi^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} \]

\[-\frac{g_{AA}}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{XX}}{4f} \phi X_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{g_{AX}}{2f} \phi F_{\mu\nu} \tilde{X}^{\mu\nu} + J_{\text{em}}^\mu A_\mu \]

$\phi_{\text{initial}} \equiv f$

1) Coherent oscillation of ALP

2) Exponential amplification of $X$ by oscillating ALP

3) Conversion of $X$ to $A$
Equations of motion:

\[
\begin{align*}
\frac{d^2 s^2}{d\tau^2} &= a^2(\tau)(d\tau^2 - dx^2) \\
\mathcal{H} = \frac{\dot{a}}{a} &= \frac{da/d\tau}{a} \\
\ddot{\phi} + 2\mathcal{H}\dot{\phi} - \nabla^2 \phi + a^2 m^2 \phi &= -\frac{1}{a^2} \left( \frac{g_{AA}}{f} \dot{A} \cdot \nabla \times A \\
+ \frac{g_{XX}}{f} \dot{X} \cdot \nabla \times X + \frac{g_{AX}}{f} (\dot{A} \cdot \nabla \times X + \dot{X} \cdot \nabla \times A) \right) \\
\ddot{\dot{A}} + \sigma \left( \dot{A} + \nu \times (\nabla \times A) \right) + \nabla \times (\nabla \times A) \\
+ \frac{g_{AA}}{f} \left( \dot{\phi} \nabla \times A - \nabla \phi \times \dot{A} \right) + \frac{g_{AX}}{f} \left( \dot{\phi} \nabla \times X - \nabla \phi \times \dot{X} \right) \\
(A_\mu = (0, A), \quad X_\mu = (0, X), \quad J = \sigma(E + \nu \times B) \right) \\
\end{align*}
\]

Conductivity of the cosmic plasma

\[
\begin{align*}
\ddot{\dot{X}} + \nabla \times (\nabla \times X) &= \frac{g_{XX}}{f} \left( \dot{\phi} \nabla \times X - \nabla \phi \times \dot{X} \right) \\
+ \frac{g_{AX}}{f} \left( \dot{\phi} \nabla \times A - \nabla \phi \times \dot{A} \right),
\end{align*}
\]
Brief sketch of the mechanism

* Beginning of ALP oscillation when \( \frac{3H(t_{osc})}{a(t_{osc})} \approx m_\phi \)

\[
\theta(t) \equiv \frac{\phi(t)}{f} \approx \left( \frac{a(t)}{a(t_{osc})} \right)^{-3/2} \cos(m_\phi(t - t_{osc})) \quad \left( t = \frac{a(t) \tau}{2} \right)
\]

* Exponential amplification of \( X_\mu \) by oscillating ALP:

\[
\ddot{X}_{k_\pm} + k(k \mp g_{XX} \dot{\theta}) X_{k_\pm} \approx 0
\]

\( \Rightarrow \quad k \sim g_{XX} \dot{\theta} \sim g_{XX} m_\phi a(t_{osc}) \)

* Soon after \( t_{osc} \), \( \rho X \) catches up \( \rho_\phi \) and some fraction of the produced \( X_\mu \) is converted to \( A_\mu \):

\[
\sigma \dot{A} \simeq g_{AX} \left( \dot{\theta} \nabla \times X - \nabla \theta \times \dot{X} \right)
\]

\( \Rightarrow \quad B \propto g_{AX} \frac{\dot{\theta}}{\sigma} \sim g_{AX} \frac{m_\phi}{\sigma_{\text{phys}}} \quad \text{at} \quad \tau \sim t_{osc} \quad \left( \frac{\sigma_{\text{phy}}}{\sigma} = \frac{\sigma}{a(\tau)} \right) \)
The mechanism is most efficient when the conversion factor \( \frac{m_\phi}{\sigma_{\text{phys}}} \) at \( \tau \sim \tau_{\text{osc}} \) is maximal, but under the constraint \( \lambda \gtrsim 0.1 \) kpc.

\[
\sigma_{\text{phy}} \begin{cases} 
T \quad (T \gg m_e) \\
10^{-g\frac{m_e^2}{T}} \quad (T \ll m_e)
\end{cases}
\]

\( \frac{m_\phi}{\sigma_{\text{phys}}} \) at \( \tau \sim \tau_{\text{osc}} \)

\[
10^{-22} \left( \frac{m_\phi}{10^{-16}\text{eV}} \right)^{1/2} \quad (T_{\text{osc}} \gg m_e \leftrightarrow m_\phi \gg 10^{-16}\text{eV})
\]

\[
10^{-12} \left( \frac{m_\phi}{10^{-16}\text{eV}} \right)^{3/2} \quad (T_{\text{osc}} \ll m_e \leftrightarrow m_\phi \ll 10^{-16}\text{eV})
\]

\[
\frac{\lambda}{1\text{ kpc}} \sim \frac{1}{g_{XX}} \left( \frac{m_\phi}{10^{-16}\text{eV}} \right)^{-1/2}
\]

\( m_\phi \sim 10^{-17}\text{eV} \) is the sweet spot point, and yet we can extend the ALP mass range to \( 10^{-21}\text{eV} \lesssim m_\phi \lesssim 10^{-17}\text{eV} \).
The existence of $X_\mu$, which is exponentially amplified by oscillating ALP is the key ingredient of our mechanism.

Instead, one may attempt to amplify $A_\mu$ through $g_{AA} \phi \tilde{F} \tilde{F}$, without introducing $X_\mu$. However then the high conductivity $\sigma_{\text{phy}} \gg m_\phi$ places a strong obstacle to the amplification of $A_\mu$, and we can never get $B > 10^{-30} \text{G}$.

On the other hand, if $X_\mu$ is amplified enough, the back reaction from the amplified $X_\mu$ becomes strong, and one needs a lattice calculation for quantitative analysis of the combined dynamics of ALP and $X_\mu$. 
Lattice results for $g_{XX} = 100$

\[ ds^2 = a^2(\tau)(d\tau^2 - dx^2) \]

$\langle \rho_\phi \rangle_{g=0} = \rho_\phi$ in the absence of gauge field production, i.e. when $g_{AA} = g_{XX} = g_{AX} = 0$

$\tau_X / \tau_{osc} =$ moment when $X_\mu$ is amplified enough

$\langle B \rangle / \langle B_X \rangle (g_{AX} = 1)$
Evolution of the spectral shape of the produced magnetic fields
(from $\tau_{\text{osc}}$ to $30\tau_{\text{osc}}$)

\[
\lambda = \frac{a(\tau_0)}{a(\tau_{\text{osc}})} \frac{2\pi}{k} \sim \frac{a(\tau_0)}{a(\tau_{\text{osc}})} \frac{2\pi}{0.1g_{XX}m_{\phi}}
\]
\[
\sim \frac{1}{g_{XX}} \left( \frac{10^{-16}\text{eV}}{m_{\phi}} \right)^{1/2} \text{kpc}
\]
Due to the exponential sensitivity and strong back reactions, parametric dependence of the results on $g_{XX}$ can be determined only by lattice simulations.

On the other hand, other parameter dependences can be read off by simple dimensional analysis.

\begin{align*}
    a(\tau_X) &\propto \tau_X \propto 1/T_X \propto a(\tau_{osc}) \propto m_\phi^{-1/2}, \\
    B_X^2 &\propto a^4 \langle \rho_X(\tau_X) \rangle \propto a^4 \langle \rho_\phi(\tau_X) \rangle \propto a^4(\tau_X) m_\phi^2 f^2 \propto f^2, \\
    \sigma(\tau_X) &= a(\tau_X) \sigma_{phy}(\tau_X) \propto a(\tau_X)/T(\tau_X) \propto m_\phi \frac{1}{2}, \\
    k_* &\sim g_{XX} \dot{\theta}(\tau_X) \propto a(\tau_X) m_\phi \propto m_\phi^{1/2},
\end{align*}
Our scheme predicts (for $g_{XX} = 100$) (The coefficients change for different $g_{XX}$, but not dramatically.)

* ALP dark matter with $\Omega_{\phi} h^2 \simeq 1.5 \times 10^{-2} \left( \frac{m_\phi}{10^{-17} \text{eV}} \right)^{1/2} \left( \frac{f}{10^{16} \text{GeV}} \right)^2$

* Seed B field: $B_{\text{seed}} \simeq 3 \times 10^{-24} \left( \frac{g_{AX}/f}{10^{-15} \text{ GeV}^{-1}} \right) \left( \frac{m_\phi}{10^{-17} \text{eV}} \right) \left( \frac{\Omega_{\phi} h^2}{0.12} \right) \text{ G}$

* Dark radiation existing in the form of long range classical field:

$$B_X \simeq 20 \left( \frac{m_\phi}{10^{-17} \text{eV}} \right)^{-1/4} \left( \frac{\Omega_{\phi} h^2}{0.12} \right)^{1/2} \text{ nG}$$

$$N_{\text{eff}} \simeq 6 \times 10^{-3} \left( \frac{m_\phi}{10^{-17} \text{eV}} \right)^{-1/2} \left( \frac{\Omega_{\phi} h^2}{0.12} \right)$$

* Common coherent length of ALP dark matter, dark U(1) gauge field, and seed B-field:

$$\lambda \simeq \left( \frac{m_\phi}{10^{-17} \text{eV}} \right)^{-1/2} \text{ kpc}$$
Observational constraints on the ALP couplings

\[ -\frac{g_{AA}}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{XX}}{4f} \phi X_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{g_{AX}}{2f} \phi F_{\mu\nu} \tilde{X}^{\mu\nu} \]

* Star cooling by ALP emission

\[ \frac{g_{AA}}{f} \lesssim 10^{-10} \text{GeV}^{-1}, \quad \frac{g_{AX}}{f} \lesssim 10^{-9} \text{GeV}^{-1} \text{ (from } \gamma_* \rightarrow \phi + X) \]

* ALP-photon conversion induced by background B or B_X

Cosmic opacity, spectral modulation, polarization rotations of X rays from AGN; CMB spectral distortion, ... [Mirizzi et al ‘05; Ostman et al ‘05; Avgoustidis et al ‘10; Tashiro et al ‘13; Wouters et al ‘13; Tiwari ‘16; Conlon et al ‘17; Mukherjee et al ‘18, ...]

\[ \Rightarrow \frac{g_{AX}}{f} \left( \frac{\langle B_X \rangle}{10 \text{nG}} \right) \lesssim 10^{-15} \text{GeV}^{-1} \]

[Most stringent bound obtained by combining Tashiro et al ‘13 & Tiwari ‘16]
For the ALP mass range relevant for us,

\[ 10^{-21} \text{ eV} \lesssim m_\phi \lesssim 10^{-17} \text{ eV} \]

our scheme can generate

\[ B \sim 2 \times 10^{-24} \left( \frac{m_\phi}{10^{-17} \text{ eV}} \right)^{5/4} \text{ G} \]

\[ \lambda \sim \left( \frac{m_\phi}{10^{-17} \text{ eV}} \right)^{-1/2} \text{ kpc} \]

which is large enough to be identified as the seed of galactic B fields:

\[ B_{\text{seed}} \gtrsim \mathcal{O}(10^{-30}) \text{ G} \quad (\lambda \gtrsim \mathcal{O}(0.1) \text{ kpc}) \]

but not enough to provide

\[ B_{\text{void}} \times \min[1, \sqrt{\lambda/0.1 \text{Mpc}}] \gtrsim \mathcal{O}(10^{-19} - 10^{-16}) \text{ G} \]

(any astrophysical amplification of B at intergalactic voids?)
UV completion:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi + \frac{1}{2} m_{\phi}^2 \phi^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu}$$
$$- \frac{g_{AA}}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{XX}}{4f} \phi X_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{g_{AX}}{2f} \phi F_{\mu\nu} \tilde{X}^{\mu\nu} + J_{\text{em}}^{\mu} A_{\mu}$$

$$\left( f \equiv \phi_{\text{initial}} \sim \Delta \phi \right)$$

Naive field theoretical consideration suggests

$$g_{t,t} \sim \frac{\alpha}{2\pi} \sim 10^{-2}$$

while our scheme requires

$$g_{XX} \sim \mathcal{O}(1 - 100), \quad g_{AX} \sim \mathcal{O}(1 - 10) \quad (f = 10^{16} - 10^{17} \text{ GeV})$$
Clockwork mechanism:  \([KC, \text{Kim, Yun} \ '14; \ KC, \text{Im} \ '15, \text{Kaplan, Rattazzi} \ '15]\)

Exponential localization in theory space of an unbroken symmetry and also of the symmetry-protected light particle:

\[
\mathcal{L}_{\text{CW}} = \frac{1}{2} \left( \sum_{i=0}^{N} (\partial_\mu \phi_i)^2 - 2 \sum_{i=0}^{N-1} \Lambda_i^4 \cos \left( \frac{\phi_{i+1}}{f_*} - \frac{q \phi_i}{f_*} \right) \right) \\
(\phi_i \equiv \phi_i + 2\pi f_*)
\]

\[\text{[Giudice, McCullgh} \ '16 ]\]

\[\implies \text{Localized lightest axion } \phi \text{ with an exponentially enlarged field range}\]

\[\phi_i \propto q^i \phi, \quad \Delta \phi \equiv f \sim q^N f_*\]

\[\Delta \mathcal{L} = -\mu^4 \cos \left( \frac{\phi_0}{f_*} \right) - \frac{1}{16\pi^2} \frac{\phi_N}{f_*} \left( c_{AA} F \tilde{F} + c_{AX} F \tilde{X} + c_{XX} X \tilde{X} \right) \quad (c_{IJ} = \mathcal{O}(1))
\]

\[\text{[Hikaki et al} \ '15; \text{Farina et al} \ '16 ]\]

\[\implies \mathcal{L}_{\text{eff}} = \frac{1}{2} (\partial_\mu \phi)^2 + \frac{1}{2} m^2_\phi \phi^2 - \frac{\phi}{4f} \left( g_{AA} F \tilde{F} + 2g_{AX} F \tilde{X} + g_{XX} X \tilde{X} \right)\]

\[g_{IJ} \sim 10^{-2} q^N c_{IJ} = \mathcal{O}(1 - 100)\]