# Intergalactic Magnetic Fields

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# ABSTRACT

We discuss the properties and possible mechanisms for generation of intergalactic magnetic fields in the hot Universe. The spontaneous vacuum magnetization is investigated in details. The field strengths and scales at different temperatures are estimated.

# OUTLINE

- INTERGALACTIC MAGNETIC FIELDS
- MECHANISMS FOR GENERATION of MAGNETIC FIELDS IN HOT UNIVERSE
- SPONTANEOUS VACUUM MAGNETIZATION at HIGH TEMPERATURE
- MAGNETIC FIELD CHARACTERISTICS
- QUALITATIVE CONSIDERATION of PHENOMENA
- CONCLUSION

# INTERGALACTIC MAGNETIC FIELDS

Magnetic fields $B \sim \mu G$ presence everywhere – in galaxies, clusters of galaxies
Determination of intergalactic magnetic fields $B_0 \sim 10^{-15} G$**:**

[S. Ando, A. Kusenko, Astrophys. J. Lett. **722 (2010) L 39**][arXiv:1005.1924] looked at the source morphology (hallo, $\gamma$ cascades: $\gamma \to e^+e^- \to \gamma^*, \gamma^*, ...$);

[S. Ando, A. Kusenko, [arXiv:1012.5313]] looked at blazer spectra.

Complementary and independent methods.

This value was estimated either as lower or upper limit. So, it is actual value at $3.5\mathrm{CL}$ accuracy.

[A. Neronov, E. Vovk. Science **328 (2010) 73.**] $B_0 \sim 10^{-16} G$.
To be amplified by dynamo action of large-scale convective motions the fields must be coherent on the scale $1\mathrm{mPc}$.

Zeeman splitting and/or Faraday rotation are operating if $B \geq 10^{-9} G$.

## ASTROPHYSICAL CONSTRAINTS

- Bing Bang Nucleosynthesis (BBN) limit $B \leq 10^{11} G$ or $B \leq 7 \cdot 10^{-7} G$ at galaxy formation;
- Cosmic microwave background (CMB) limit $B \leq 10^{-9} G$.

# MECHANISMS for GENERATION of B

Popular mechanisms for generation of seed magnetic fields at high temperature in the early universe:

- metric perturbations
- strong first order EW phase transition [Hogan (1980)]
- stochastic electric currents
- paramagnetic resonances in scalar (or axion) - electromagnetic field system
- Born-Infield electrodynamics, HE effective Lagrangian
- inflation
- cosmic strings
- trace anomaly
- extradimensions
- gravitational couplings of gauge field potentials

In all these considerations it is **ASSUMED**

*magnetic flux is conserved* and therefore the dependence of $B \sim T^2$

takes place at cooling of the universe.

**OUR MAIN IDEA:**

seed (primordial) magnetic field is *spontaneously generated* at high temperature due to

*vacuum polarization and asymptotic freedom* of non-Abelian gauge fields.

These magnetic fields are temperature dependent [Starinets, Vshivtsev, Zhukovsky(1994)], [Skalozub(1996)], [Bordag, Skalozub (2000)],

[Demchik, Skalozub (2008)] **(in lattice simulations)**:

$$B(T) \sim \frac{g^3 T^2}{\log \frac{T}{\tau}}. \tag{1}$$

So, **there is no magnetic flux conservation at high temperature!**

# SPONTANEOUS VACUUM MAGNETI-ZATION at HIGH TEMPERATURE

On a lattice, the main continuous object is a magnetic flux. We relate the free energy density of the flux to the effective action [Demchik, Skalozub (2008)],

$$F(\varphi) = \bar{S}(\varphi) - \bar{S}(0), \qquad (2)$$

where $\bar{S}(\varphi)$ and $\bar{S}(0)$ are the effective lattice actions with and without chromomagnetic field, $\varphi$ is the field flux.

**The spontaneous creation of the field follows if free energy has a global minimum at non-zero flux, $\varphi_{min} \neq 0$.**

# MAGNETIC FIELD CHARACTERISTICS

The most essential for what follows characteristics of the field:

*Stability*

*To verify stability* we substituted the value of $B_{min}(T)$ in the one-loop EP, the imaginary part was of the order $10^{-12}$ of the real one.

This means the stable state!

*Temperature dependence*

In $SU(2)$ gluodynamics, from the EP $V(B,T) = V^{(1)}(B,T) + V^{(ring)}(B,T)$ it was determined

$$(gB)^{1/2} = \frac{g^2}{2\pi}\frac{T}{\log(T/\mu)}. \tag{3}$$

Thus, a temperature dependent chomomagnetic field is spontaneously created at high temperature.

*Masslessness (long-range magnetic fields)*

[Antropov, Bordag, Demchik, Skalozub (2010)].

# QUALITATIVE CONSIDERATION

*The most relevant aspects* of the phenomena of interest are *consequences of asymptotic freedom and spontaneous symmetry breaking* at finite temperature – the basic principles of modern QFT.

*Our main assumption* is that the intergalactic magnetic field had been spontaneously created at high temperature.

This is a reasonable because physically the magnetization is the consequence of a large magnetic moment for charged non-Abelian gauge fields (remind the gyromagnetic ratio $\gamma = 2$ for $W$-bosons). Just this property results in the asymptotic freedom of the model.

*First*, in non-Abelian gauge theories at high temperatures the magnetic flux conservation does not hold. The vacuum acts as a specific source generating classical fields.

*Second*, the spontaneous vacuum magnetization takes place for small scalar field $\phi \neq 0$, only. For the values of $\phi$ corresponding to any first order phase transition it does not happen.

After the electroweak phase transition, the vacuum polarization ceases to generate magnetic fields and magnetic flux conservation holds. As a result, the familiar dependence on the temperature $B \sim T^2$ is restored.

# CONCLUSION

- At the $T_{ew}$, magnetic fields of the order $B(T_{ew}) \sim 10^{14} G$ did exist.
- The key point is the spontaneous vacuum magnetization, it eliminates the magnetic flux conservation principle at high temperature. Vacuum polarization is responsible for the value of $B(T)$ at each temperature and serves as a source of it.
- After symmetry breaking, $\phi$-condensate suppresses the magnetization.
- Due to stability and zero magnetic mass of the spontaneously created magnetic fields, there are no problems with creating of long-range magnetic fields at high temperature.

These statements change ubiquitous scenario with magnetic flux conservation. In the latter case, the temperature dependence ($B \sim T^2$) is regulated by magnetic flux conservation, only.