



RUHR-UNIVERSITÄT BOCHUM

Lower limits on the magnetic field strength in the early universe

Reinhard Schlickeiser

Institut für Theoretische Physik IV: Weltraum- und Astrophysik, Ruhr-Universität Bochum, Germany

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Collaborators and topics

Collaborators: Tim Felten, Ulrich Kolberg, Steffen Krakau, Ulf Menzler (RUB), Peter H. Yoon (University of Maryland)

Topics:

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3. Lower EGMF bounds from γ -ray astronomy?
4. Lower bounds from fluctuation theory
5. From disordered to ordered magnetic field structures
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Origin of cosmic magnetic fields

Many astrophysicists believe that galactic and extragalactic magnetic fields (EGMF) are generated and maintained by dynamo action, whereby the energy associated with e.g. the differential rotation of spiral galaxies is converted into magnetic field energy.

However, the dynamo mechanism is only a means of amplification, and dynamos require finite **seed magnetic fields**. These seed fields are needed for possible instabilities from anisotropic plasma particle distribution functions, MHD instabilities (such as the magneto-rotational instability), kinetic plasma instabilities (such as the Weibel and filamentation instabilities (RS and Shukla 2003)) and/or the MHD dynamo process (e.g. Schober, Banerjee, Klessen et al. 2015), which grow according to $d(\delta B)^2/dt = 2\gamma(\delta B)^2$, so that

$$(\delta B)^2(t) = (\delta B)^2(t = 0)e^{2\gamma t} \quad (1)$$

Origin of cosmic magnetic fields (2)

Obviously, a nonvanishing initial $(\delta B)^2(t=0) \neq 0$ **seed magnetic field** energy density is required. Neither the dynamo process nor plasma instabilities generate magnetic fields without such seed fields.

Permanent ferromagnetism cannot operate in the early universe as it is a property of only a few densely packed materials, such as iron, in which the spin exchange interactions of individual atoms naturally line up in the same direction and create a residual persistent magnetic field. In the early universe, before iron and other magnetic materials had been created inside stars, such permanent magnetism did not exist.

Upper bounds on the EGMF

Contrary to magnetic fields in galaxies and galaxy clusters, EGMF in the intergalactic medium (IGM) have not been detected so far (Neronov and Semikoz 2009). Only upper limits exist, which are shown in Fig. 1.

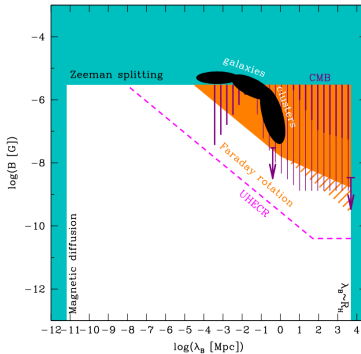


Figure 1: Present-day (redshift $z = 0$) observational upper limits on EGMF (from Neronov and Semikoz (2009, PRD 80, 123012)).

Lower EGMF bounds from γ -ray astronomy?

Neronov and Vovk (2010) have argued that lower bounds (shown in Fig. 2) on the EGMF can be derived from GeV-TeV detected blazars at cosmological distances.

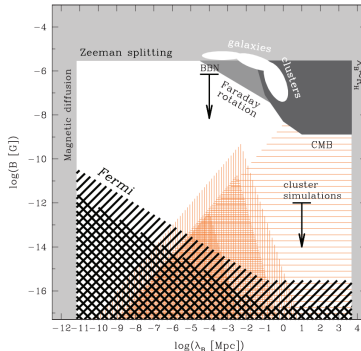


Figure 2: Observational bounds on EGMF (from Neronov and Vovk (2010, Science 328, 73).

Lower EGMF bounds from γ -rays (2)

The new generation of air Cherenkov TeV γ -ray telescopes (HESS, MAGIC, VERITAS) have detected about 30 cosmological blazars with strong TeV photon emission (see e.g. Fig. 3): the most distant ones are 3C279 (redshift $z = 0.536$), 3C66A ($z = 0.444$), PKS 1510-089 ($z = 0.361$) and 1ES 0412+009 ($z = 0.287$). Any of these more distant than $z = 0.16$ produces energetic e^\pm particle beams in double photon collisions $\gamma(\text{TeV}) + \gamma(\text{EBL}) \rightarrow e^+ + e^-$ with the extragalactic background light (EBL) once $E_\gamma \geq m_e^2 c^4 / E_{\text{EBL}}$: see Fig. 4.

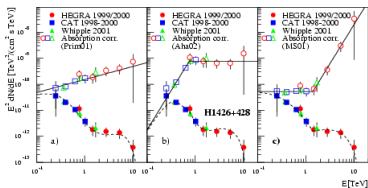


Figure 3: High-energy photon spectrum from blazar H1426+428

Lower EGMF bounds from γ -rays (3)

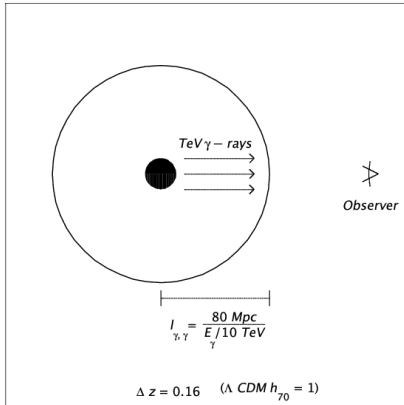


Figure 4: Intergalactic pair beam production: TeV photons from any blazar more distant away than $z = 0.16$ produce relativistic pairs by double photon collisions with the EBL soft photons.

Lower EGMF bounds from γ -rays (4)

These pairs with typical Lorentz factors $10^6 \Gamma_6$ are expected to inverse Compton (IC) scatter on the cosmic microwave background (CMB) radiation, on a typical length scale $l_{IC} \sim 0.75 \Gamma_6^{-1}$ Mpc (corresponding time scale $t_{IC} = l_{IC}/c = 2.5 \cdot 10^6 \Gamma_6^{-1}$ yrs), producing gamma-rays with energy of order 100 GeV. These inverse Compton gamma-rays then are still energetic enough for further pair-production interactions giving rise to a full electromagnetic cascade as in vacuum. But these inverse Compton gamma rays have **not** been detected by the FERMI satellite! Neronov and Vovk (2010) explained this non-detection by strong enough stochastic EGMF which scatter the produced pairs, so that the inverse Compton gamma rays are misdirected from the blazar direction.

However, Pfrommer et al. (2013) noted that the emission from all unresolved blazars overproduces the observed extragalactic gamma-ray background at GeV energies. The magnetic deflection processes of pairs and their inverse Compton emission out of our line-of-sight is on average

Lower EGMF bounds from γ -rays (5)

balanced by deflecting other pairs and their inverse Compton emission into our line-of-sight, so that the resulting isotropic extragalactic gamma-ray background remains invariant. A solution to this vacuum cascade overproduction problem, which also would invalidate the lower bounds of the EGMF by Neronov and Vovk (2010), is offered by accounting for the plasma effects of the relativistic pairs generated in the first double photon interaction with the production spectrum shown in Fig. 5.

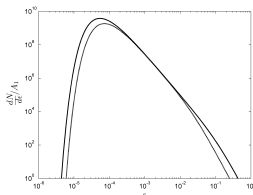


Figure 5: Differential pair production spectrum as a function of $\epsilon = 2p_{\parallel}c/10^{10}m_e c^2$ from a power-law distributed gamma-ray beam. From RS, A. Elyiv, D. Ibscher and F. Miniati (2012).

Lower EGMF bounds from γ -rays (6)

Because of the strong energy inversion $(\partial f / \partial \epsilon) > 0$ of the corresponding phase space density $f(\epsilon) = \epsilon^{-2}(dN/d\epsilon)$ below the maximum, this initially generated pair-beam distribution function is subject to two-stream-like instabilities of both electrostatic and electromagnetic nature in the unmagnetized, fully-ionized intergalactic medium (additional induced emission as in masers). Using linear reactive and kinetic instability analysis Broderick, Chang and Pfrommer (2012) and RS et al. (2012) have shown that the created pair beam distribution function is quickly unstable (on time scales $t_E \ll t_{IC}$).

The quasilinear backreaction of the excited electrostatic oscillations then relaxes (on time sales $\simeq 100t_E$) the initial distribution to the "plateau" distribution with $(\partial f / \partial \epsilon) = 0$ (see Fig. 6), which has only ≤ 50 percent total energy compared to the initial distribution (the other 50 percent are transferred to the electrostatic oscillations).

Lower EGMF bounds from γ -rays (7)

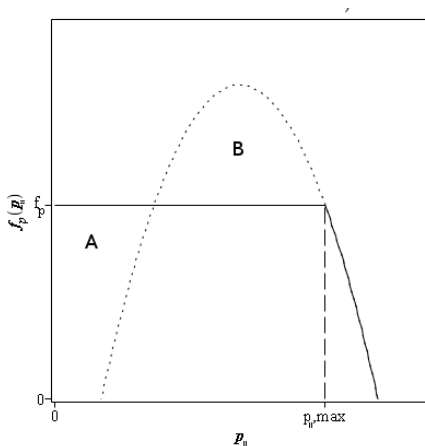


Figure 6: Geometrical representation of the plateauing effect in p_{\parallel} . The dotted line represents an illustrative initial pair spectrum. The solid line shows the final spectrum. Particle number conservation requires the areas A and B to be equal.

Lower EGMF bounds from γ -rays (8)

Hence the generation of inverse-Compton scattered GeV gamma-ray photons by the pair beam is significantly (by a factor 10 for full plateauing) suppressed. Less kinetic pair energy is available for inverse Compton interactions with the CMB (Menzler and RS 2015), in agreement with the FERMI observations, see Fig. 7.

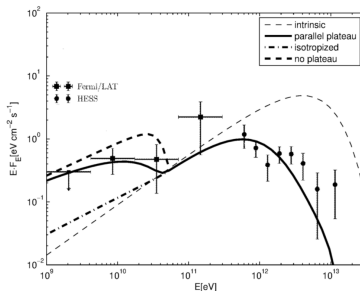


Figure 7: GeV-Tex emission from plateaued and non-plateaued pair distribution functions compared with the observations of the blazar 1ES 0229+200. From Menzler and RS (2015).

Lower EGMF bounds from γ -rays (9)

The generated electrostatic oscillation energy heats the IGM with important consequences for its thermal history (Chang et al. 2012) and the formation of cosmic structures.

Most importantly: there is no need to require the existence of small intergalactic magnetic fields, to scatter the produced pairs away from the line of sight, in order to explain the FERMI non-detection of the inverse Compton scattered GeV gamma rays. In particular, the various derived lower bounds for the EGMF in Fig. 2 need to be modified due to the pair beam instability argument, although we do not question the principal existence of turbulent intergalactic magnetic fields.

More work needed on: partial versus full plateauing, nonlinear beam stabilization processes, role of small but finite spread in perpendicular momentum of pair production spectrum (Miniati and Elyiv 2013), influence of excited transverse oscillations

Lower bounds from plasma fluctuation theory

Before the formation of the first stars but after the reionization at $z \simeq 20$, the luminous intergalactic matter consisted only of a fully ionised gas of protons, electrons, helium nuclei and lithium nuclei which were produced during the Big Bang. The physical parameters that describe the state of this gas are, however, not constant. Density and pressure fluctuate around certain mean values, and consequently electric and magnetic fields fluctuate around vanishing mean values, due to the thermal motion of the plasma particles. This small but finite dispersion in the form of random magnetic fields has now been calculated with kinetic plasma fluctuation theory.

The fluctuations are described by real wave vectors (\vec{k}) and complex frequencies $\omega(\vec{k}) = \omega_R(\vec{k}) + i\gamma(\vec{k})$, implying for the space- and time-dependence of e.g. magnetic fluctuations the superposition of

$$\delta\vec{B}(\vec{x}, t) \propto \exp[i(\vec{k} \cdot \vec{x} - \omega_R t) + \gamma t] \quad (2)$$

Plasma fluctuations

One distinguishes between

- **collective** modes with a fixed dispersion relation $\omega = \omega(\vec{k})$, e.g. electromagnetic waves in vacuum $\omega_R^2 = c^2 k^2$ and $\gamma = 0$,
- **non-collective** modes with no dispersion relation $\omega = \omega(\vec{k})$, and, regarding the real (ω_R) and imaginary (γ) part of the frequency,
- **weakly damped/amplified** wave-like modes with $|\gamma| \ll |\omega_R|$
- **weakly propagating** modes with $|\omega_R| \ll |\gamma|$, including **aperiodic** fluctuations ($\omega_R = 0$). Aperiodic oscillations fluctuate only in space, do not propagate as $\omega_R = 0$, but permanently grow or decrease in time depending on the sign of γ .

As in-situ plasma turbulence observations have shown the interplanetary medium is full with aperiodic fluctuations in the form of mirror, firehose and ordinary mode oscillations, so that there is no doubt that they exist in nature!

Weakly amplified/damped oscillations

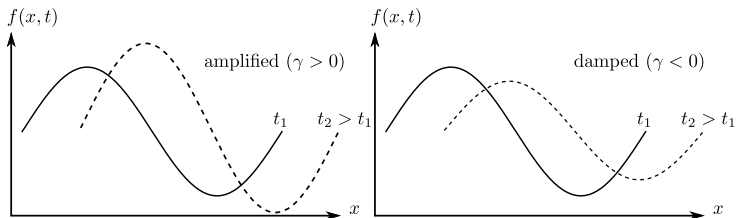


Figure 8: Sketch of weakly amplified ($\gamma > 0$, left) and weakly damped ($\gamma < 0$, right) monochromatic plasma wave ($\omega_R \gg |\gamma|$).

Weakly propagating amplified/damped oscillations

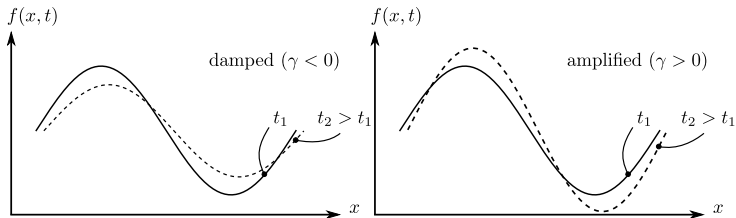


Figure 9: Sketch of weakly propagating damped ($\gamma < 0$, left) and weakly propagating amplified ($\gamma > 0$, right) monochromatic fluctuation ($\omega_R \ll |\gamma|$).

Weakly aperiodic oscillations

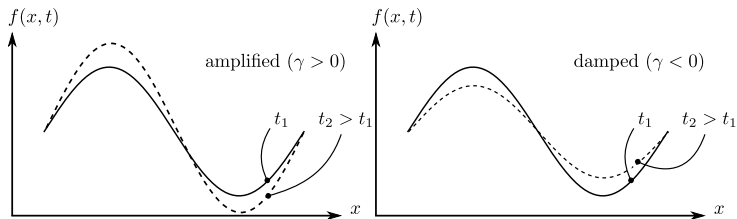


Figure 10: Sketch of aperiodic ($\omega_R = 0$) growing ($\gamma > 0$, left) and aperiodic damped ($\gamma < 0$, right) monochromatic fluctuation.

Fluctuation-dissipation theorem

Unlike for weakly amplified/damped modes (Salpeter 1960, Sitenko 1967, Ichimaru 1973, Kegel 1998) only recently general expressions for the electromagnetic fluctuation spectra from uncorrelated plasma particles in unmagnetized (RS and Yoon 2012) and magnetized (RS and Yoon 2015) plasmas for arbitrary frequencies have been derived using the system of the Klimontovich and Maxwell equations.

In the IGM the fluctuation spectra can be calculated from the fluctuation-dissipation theorem (FDT) in plasmas holding for isotropic equal-temperature thermal plasmas. For non-collective transverse oscillations with arbitrary complex frequencies $\omega = \omega_R + i\gamma$ the FDT in unmagnetized plasmas reads (RS and Kolberg 2015)

$$\langle (\delta B)^2 \rangle (k, \omega) = -\frac{4k_B T_0 k^2 c^2 \sigma}{(2\pi)^3 |\omega|^2} \Im \left(\frac{1}{\omega} \left[\frac{1}{\Lambda_T} - \frac{1 + \frac{k^2 c^2}{|\omega|^2}}{|\Lambda_T|^2} \right] \right) \quad (3)$$

in terms of the thermal transverse dispersion function $\Lambda_T(k, \omega)$.

Thermal aperiodic noise in the IGM

The present IGM has temperatures of about $T_0 = 10^4 T_4 K$ and ionized gas densities of $n_e = 10^{-7} n_{-7} \text{ cm}^{-3}$. The spontaneously emitted aperiodic transverse magnetic field fluctuation spectrum over the whole complex frequency calculated from Eq. (3) is shown in Fig. 11. Obviously, it is dominated by a damped mode with negative values of γ .

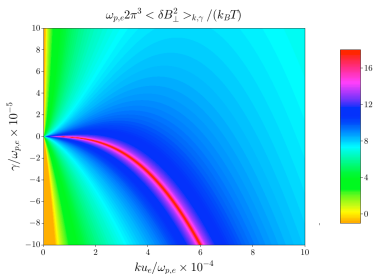


Figure 11: Spontaneously emitted thermal aperiodic magnetic noise in the IGM in units of $k_B T_e / (2\pi^3 \omega_{p,e})$. The colour scale is logarithmic in powers of e . From Felten et al. (2013).

Thermal aperiodic noise in the IGM (2)

Integrating over all frequencies γ provides the equilibrium thermal electric and magnetic field wavenumber fluctuation spectra shown in Fig. 12. The magnetic fluctuation spectrum is not of Kolmogorov form! It holds for maximum spatial magnetic turbulence scales of

$$\lambda < \lambda_{\max} = 2.4 \cdot 10^{15} T_4^{1/6} n_{-7}^{-1/3} \text{ cm} = 7.7 \cdot 10^{-10} T_4^{1/6} n_{-7}^{-1/3} \text{ Mpc.}$$

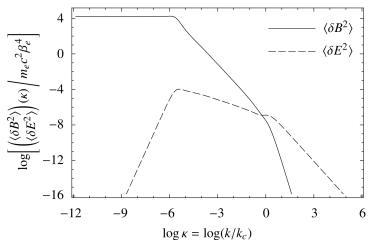


Figure 12: Thermal wavenumber spectra of electric (dashed curve) and magnetic (full curve) field fluctuations in units of $m_e c^2 \beta_e^4$ in an electron-proton plasma calculated for the plasma temperature $T_0 = 10^4 T_4$ K. From Yoon, RS and Kolberg (2014).

Total strength of fluctuating magnetic field

By integrating the wavenumber fluctuation spectrum over all wavenumber values we find for the total magnetic field strength at $z = 0$

$$|\delta B(z = 0)| = \sqrt{(\delta B)^2(z = 0)} = 6.3 \cdot 10^{-18} n_{-7}^{3/4} T_4^{1/8} \text{ G}, \quad (4)$$

With $n_{-7}(z) = n_{-7}(1+z)^3$ and $T_4(z) = T_4(1+z)$ we obtain at the onset of reionization ($z = 20$)

$$|\delta B(z = 20)| = 8.7 \cdot 10^{-15} \text{ G} \quad (5)$$

This guaranteed EGMF in the form of randomly distributed aperiodic oscillations with volume filling factor $\mathcal{V} \simeq 1$, produced by the spontaneous emission of the isotropic thermal IGM plasma, serves as seed fields for possible amplification by later possible plasma instabilities from anisotropic plasma particle distribution functions, MHD instabilities and/or the MHD dynamo process (RS 2012).

Total strength of fluctuating magnetic field (2)

The strength of the guaranteed spontaneously emitted magnetic seed fields (5) is orders of magnitude larger than the seed fields from the Biermann (1950) battery process (10^{-18} G) with tiny volume filling factor and cosmological phase transitions (Sigl et al. 1997) (10^{-20} G).

These spontaneously emitted fluctuations have typical plasma scale lengths $2.4 \cdot 10^{15} (1+z)^{-5/6}$ cm, but as argued below, the first hydrodynamical compression generates considerably longer correlation lengths of the compressed magnetic fields determined by the spatial scale of the compressor (see Fig. 13).

From disordered to ordered magnetic field structures

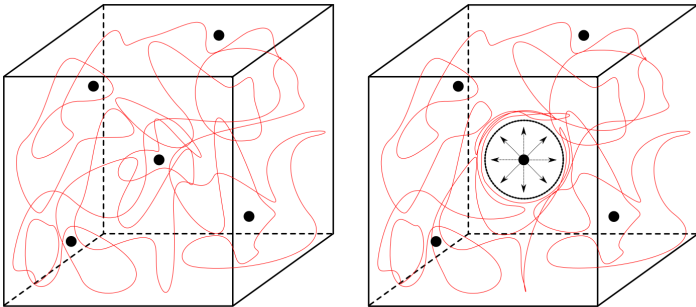


Figure 13: Illustration of the hydrodynamical stretching and ordering of cosmic magnetic fields. On the left figure a turbulent random magnetic field pervades the medium between five protostars. The right figure shows the ordering and stretching of the magnetic field as one of the stars explodes as a supernova. The outgoing shock wave compresses and orders the magnetic field in its vicinity. From RS and Yoon (2015).

From disordered to ordered magnetic field structures (2)

The unmagnetized, isotropic, thermal and steady IGM plasma by spontaneous emission generates steady tangled fields, isotropically distributed in direction, on small spatial scales $\leq 10^{15}$ cm. Because of its ultrahigh turbulent plasma beta value ($\beta_t = 10^{17} n_{-7}^{-1/2} T_4^{3/4}$), these seed fields are too weak to affect the dynamics of the IGM plasma, but are tied passively to the highly conducting IGM plasma as frozen-in magnetic fluxes.

Earlier analytical considerations and numerical simulations (Laing 1980, Hughes et al. 1985, Matthews and Scheuer 1990) showed that any shear and/or compression of the IGM medium enormously amplify these seed magnetic fields and make them anisotropic. Depending on the specific exerted compression and/or shear, even one-dimensional ordered magnetic field structures can be generated out of the original isotropically tangled field configuration.

From disordered to ordered magnetic field structures (5)

Hydrodynamical compression or shearing of the IGM medium arises from the shock waves of the supernova explosions of the first stars at the end of their lifetime, or from supersonic stellar and galactic winds. Fig. 13 sketches the basic physical process.

Obviously, this magnetic field stretching and ordering occurs only in gas regions overrun frequently by shocks and winds. Each individual shock or wind (with speed V_s) compression orders the field on spatial scales R on time scales given by the short shock crossing time R/V_s , but significant amplification requires multiple compressions. The ordered magnetic field filling factor is determined by the shock's and wind's filling factors which are large (80 percent) in the coronal phase of interstellar media (McKee and Ostriker 1977) and near shock waves in large-scale cosmic structures (Miniati et al. 2000).

From disordered to ordered magnetic field structures (4)

In cosmic regions with high shock/wind activity, this passive hydrodynamical amplification and stretching of magnetic fields continues until the magnetic restoring forces affect the gas dynamics, i.e. at ordered plasma betas near unity.

As a consequence, magnetic fields with equipartition strength are not generated uniformly over the whole universe by this process, but only in localized cosmic regions with high shock/wind activity.

Summary and conclusions

- Contrary to magnetic fields in galaxies and galaxy clusters, extragalactic magnetic fields (EGMF) in the intergalactic medium (IGM) have not been detected so far. We reviewed the upper and lower bounds on the strength and correlation length of the EGMF.
- The lower bounds from γ -ray astronomy need to be modified due to the pair beam instability argument which offers a different explanation of the FERMI non-detection of inverse Compton gamma rays from cascaded TeV emission of distant blazars.
- A lower bound of $|\delta B(z = 20)| = 8.7 \cdot 10^{-15}$ G at scales $\lambda < 6 \cdot 10^{-11}$ Mpc is set by plasma fluctuation theory, because the unmagnetized fully-ionized thermal IGM plasma emits transverse aperiodic fluctuations.
- The stochastic magnetic fields serve well as cosmological seed fields for further amplification processes once additional kinetic free energy becomes available in these plasmas (a new primary dynamo process).

Summary and conclusions (2)

- The shear and/or compression of the intergalactic medium exerted by the first supernova explosions amplify these seed fields and make them anisotropic, until the magnetic restoring forces affect the gas dynamics.
- Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

