Title: Cosmological Magnetic Fields

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Abstract:

Magnetic fields in the Universe

Hector Rubinstein
Albanova Center
Fysikum,Stockholm

Perimeter Institute, September 2007

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Stability of magnetic fields

a) intrinsic stability against decay

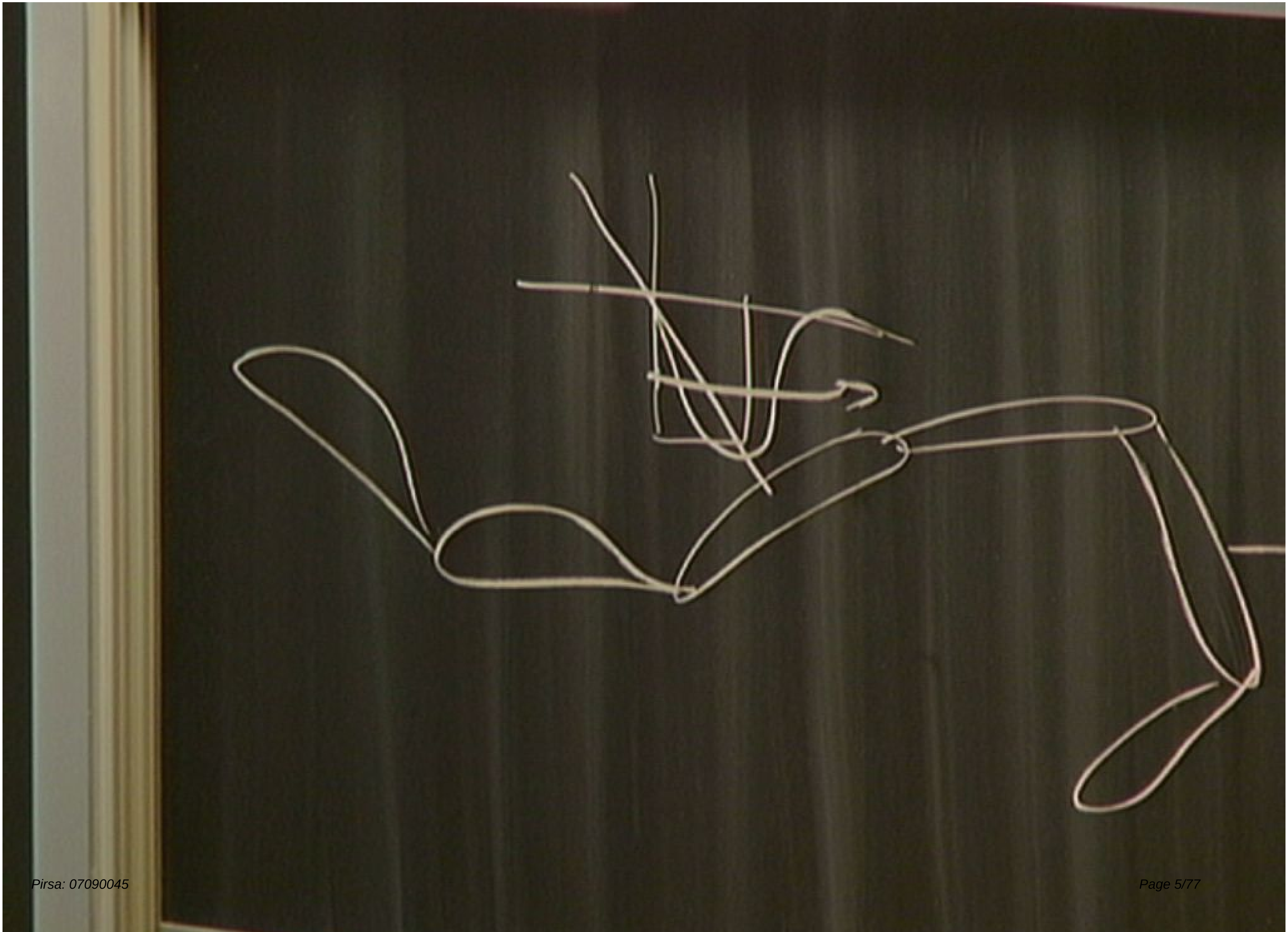
The stability of the fields can be studied as follows:

1. Electric fields are unstable at $E > m_e^2$ by tunneling. Easily seen combining the potential -eEx with a well of depth $2m_e$ necessary to create a pair. The probability to create a pair is proportional to exp(-1/E)

2. For a magnetic field things are not so simple for a spin 1/2 particle. The Lorentz force is momentum dependent and there there is no such a vector in the vacuum.

One must find an elementary particle with the appropriate properties and there is no elementary one lighter than the W boson. In that case there is a term in the Lagrangian of the form $ief_{\mu\nu} W_\mu W_\nu$ and this magnetic moment coupling produces an instability at m_W^2/e.

This value corresponds to $B = 10^{24}$ T



Observational and theoretical considerations concerning cosmological magnetic fields

Cosmic fields are very widespread but they present great puzzles observationaly and theoretically.

The main observational problems are two: the foregrounds are not distinguishable from the quantity to be measured.

The only method we have (Faraday rotation) measures Bμl where B is the field, μ is the electron density and l is distance travelled. These dependences makes the measurements difficult and many times model dependent.

Nevertheless the presence of fields as described in the table is largely probable.

We will assume that they exist at all scales in galaxies, clusters and superclusters but we leave open the question of fields througout.

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Magnetic fields here and there
magnetic fields everywhere

Planets, stars, galaxies, galaxy clusters and probably in the Universe at large have magnetic fields.

They are also potentially produced in other structures like cosmic strings that may carry phenomenal fields. This depends on whether these objects exist atb alland if their parameters are such that superconductivity obtains.

Observational methods

- Synchroton radiation,
- Zeeman effect
- Faraday effect
- Zeeman polarization effect

  Faraday rotation correlators

What is sure………………

Theoretical and observational problems and status on galactic, cluster, supercluster and intergalactic fields

There is very good evidence for the presence of magnetic fields in nearby galaxies.

There is 2 sigma evidence for μG fields for galaxies up to almost z=3.

There is good evidence for fields in intergalactic media of clusters. These only exist for z to about 2.

For superclusters the evidence is flimsy and beyond speculative.

The complexitiy of galactic and extragalactic fields

Observations of galactic and extragalactic magnetic fields can be summarized as follows:

• Magnetic fields with strength ~ 10μG are found in spiral galaxies whenever the pertinent observations are made.

These fields invariably include a large-scale component whose coherence length is comparable to the size of the visible disk. There are also small-scale tangled fields with energy densities approximately equal to that of the coherent component. The magnetic field of a spiral galaxy often exhibits patterns or symmetries with respect to both the galaxy's spin axis and equatorial plane. About 70 are measured with a narow

More on galactic and cluster fields

- • Magnetic fields are ubiquitous in elliptical galaxies, though in contrast with the fields found in spirals, they appear to be random with a coherence length much smaller than the galactic scale. Magnetic fields have also been observed in barred and irregular galaxies.
- • Microgauss magnetic fields have been observed in the intracluster medium of a number of rich clusters.
- The coherence length of these fields is comparable to the scale of the cluster galaxies.
- • There is compelling evidence for galactic-scalemagnetic fields in a redshift $z \simeq 0.4$ spiral. In addition, microgauss
- fields have been detected in radio galaxies at $z > 2$
- Magnetic fields may also exist in damped Lyα systems at cosmological redshifts.

Cluster magnetic field empirical formula

$$B_{ICM} \sim 2\ \mu\text{G} \left(\frac{L}{10kpc}\right)^{-\frac{1}{2}} (h_{50})^{-1}$$

L is the reversal distance and h the reduced Hubble constant.

Some examples of cluster observations

where L is the reversal field length and h_{50} is the reduced Hubble constant. Typical values of L are $10 - 100$ kpc which correspond to field amplitudes of $1 - 10$ μG. The concrete case of the Coma cluster [4] can be fitted with a core magnetic field $B \sim 8.3 h_{100}^{\frac{1}{2}}$ G tangled at scales of about 1 kpc. A particular example of clusters with a strong field is the Hydra A cluster for which the RMs imply a 6 μG field coherent over 100 kpc superimposed with a tangled field of strength ~ 30 μG [5]. A rich set of high resolution images of radio sources embedded in galaxy clusters shows evidence of strong magnetic fields in the cluster central regions [6]. The typical central field strength $\sim 10 - 30$ μG with peak values as large as ~ 70 μG. It is noticeable that for such large fields the magnetic pressure exceeds the gas pressure derived from X-ray data suggesting that magnetic fields may play a significant role in

Theoretical questions

a) how strong are these fields and what is their spatial extent?

b) Are these fields homogenous?

c) How old are these fields?

d) How were the fields generated?

Existing and potential fields

type	strength	extension	observed
laboratory	10^5 G	meters	yes
stars	10^5 G	10^3 km	yes
Neutron stars	10^{13}G	km	yes
galaxies	μ G	kiloparsecs	yes
Galaxy clusters	$.1\mu$G	megaparsecs	yes
superclusters	$.1\mu$G	megaparsecs	yes
Superconductive cosmic	10^{20}G	kiloparsecs	no

An example of a cosmological field

Our Milky Way is fairly well mapped. Using Faraday rotation measurements one establishes that the field is in the plane of the galactic disk and directed along the spiral arm. The field is basically toroidal and of strength 2μG, though it varies by factors of 3. The toroidal field is a vector sum of a radial and azimuthal one. There are other Components as well: a poloidal one a the center. The parity of the toroidal field is also important. If this could be well established, a dynamo mechanism could be ruled out if the field is not axially symmetric.

There could be reversals as well and one seems established though several are claimed. A view is seen in the next slide.

The Milky way field

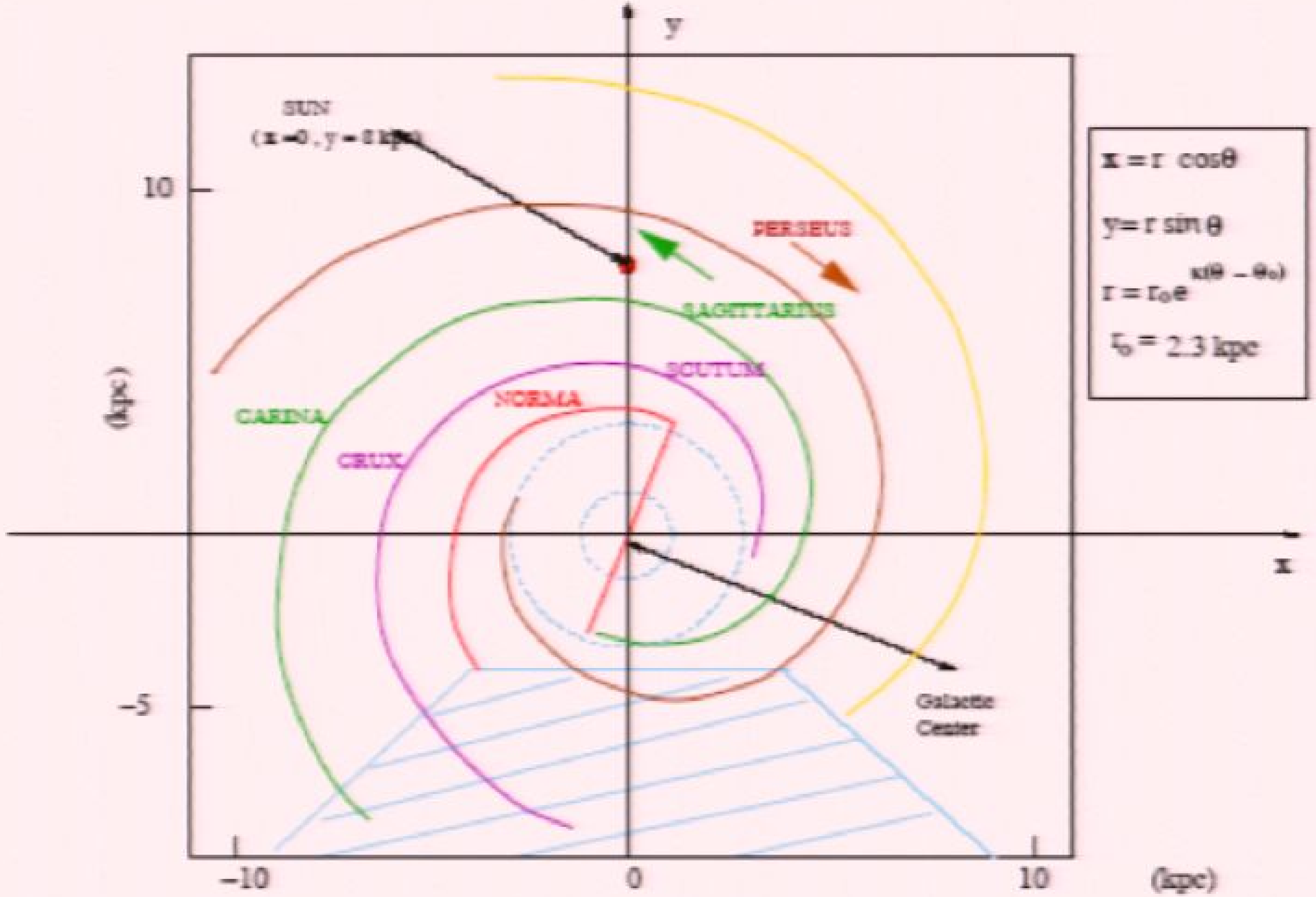

Figure 3: The map of the MW is illustrated. Following [45] the origin of the two-dimensional coordinate system are in the Galactic center. The two large arrows indicate one of the possible (3 or 5) field reversals observed so far. The field reversal indicated in this figure is the less controversial one.

Are intergalactic fields generated by stars?

How are these fields generated? Are fields in all these systems of same origin? The energy stored in the field of the Milky Way is:

$$E^B = \frac{4}{3}\pi R^3{}_{gal}\rho_B \approx 10\, M_{solar}$$

The magnetic energy of a neutron star is:

$$E_{ns}{}^B = 10^{-11} M_{solar}(\frac{B}{10^{13}\ G})^2$$

And for a white dwarf with radius 10^9 cm the energy is

$$E_{wd} = 10^{-10} M_{solar}(\frac{B}{10^9 G})^2$$

10^{10} white dwarfs carrying B = 10^{10}G or 10^{12} neutron stars with fields 10^{13}G should exist to create the field assuming perfect efficiency. Since the galaxy has 2.10^{11} stars it seems quite difficult. Therefore the galactic field is probably NOT generated by stars

Recent measurements on superclustersclusters

:omparison of the mean values of absolute SRM in areas I, II, and
+II+III, and in areas IV and V.

:ky Area Galaxy Density Range SRM mean

rad m−2]

ll 14.3 ± 2.0

Iercules Area I, 50 sources Ng < 7. 14.8

)○ 6 l 6 70○, 30○ 6 b 670○) 7. 6 Ng 610. 15.9

Ig > 10. 12.9

ll 10.0 ± 1.8

Iercules Comparison Area II Ng < 7. 8.7

70○ 6l 6120○ or l > 330○, 30○ 6b 670○), 30 sources Ng >7. 10.9

ll 10.2 ± 0.8

Iercules Comparison Zone, Area I+II+III, 154 sources Ng < 7. 11.4

)○ 6l 6 360○, 30○ 6 b 6 70○) 7. 6 Ng 610. 8.7

Ig > 10. 10.5

ll 56.8 ± 8.6

'erseus-Pisces Area IV, 45 sources Ng < 7. 65.7

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Fields in clusters and beyond

Measurements are dependent on assumptions like the electron column between us and the source and other backgrounds. There is limited agreement that in clusters and superclusters the field is about $.1\mu$G and in the Universe perhaps between 10^{-9} to 10^{-11} G, though this is not established. The Faraday rotation and synclotron radiation requires knowledge of the local electron density. Sometimes the electron density can b e measured independently.

$$RM(z_s) \equiv \frac{\Delta(\kappa)}{\Delta(\lambda^2)} = 8.1 \times 10^5 \int_0^{z_s} n_e B_{\|}(z)(1+z)^{-2} dl(z) \quad \frac{\text{rad}}{\text{m}^2}$$

where $B_{\|}$ is the field strength along the line of sight and

$$dl(z) = 10^{-6} H_0^{-1}(1+z)(1+\Omega z)^{-\frac{1}{2}} dz \ \text{Mpc} .$$

conductivity

The reaction $p + e \leftrightarrow H + \gamma$ determines the number of leftover electrons in the competition between the Hubble expansion and the reaction strength.
Using this information we obtain for the conductivity

$$\sigma = \frac{ne^2}{m_e n_\gamma \sigma_T} \simeq 10^{11} \Omega_0 h \ \ s^{-1}.$$

leading to a diffusion length

$$L_{\rm diff} \simeq 2 \times 10^{13} \text{ cm} \simeq 1 \text{ A.U.}$$

which shows that fields are constant at cosmological scales.

This flux conservation leads to the equation

$$B(t) = B(t_i) \left(\frac{a(t_i)}{a(t)} \right)^2 .$$

How and when were these fields created?

The two options:

1. Primordial

2. small seeds enhanced by a dynamo mechanism

How these fields originated?

We have seen that fields of extension of kpar exist.
We also know that fields are complicated,with en tangled components but a remarkably constant piece of μG strength.
The question of age is still open and depends of the generating mechanism. Nothing is known about it. However
We have some limits at different periods that we will discuss.
Again these limits make assumptions: if coupling constants varied with time or extra dimensions are present the analysis may change. We know though that, for example, that the electromagnetic coupling was almost the same, to a few percent, already at nucleosynthesis time.We will not discuss in detail the question of generation of these fields. Just a few remarks on the wide range of models.
We will express these limits as the predicted or allowed field

Dynamo mechanism

$$\frac{\partial \rho_{\rm m}}{\partial t} + \vec{\nabla} \cdot (\rho_{\rm m} \vec{v}) = 0,$$
$$\frac{\partial \rho_{\rm q}}{\partial t} + \vec{\nabla} \cdot \vec{j} = 0.$$
$$\rho_{\rm m} \left[\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \vec{\nabla} \right] \vec{v} = \rho_{\rm q} \vec{E} + \vec{J} \times \vec{B} - \vec{\nabla} P,$$
$$\vec{E} + \vec{v} \times \vec{B} = \frac{1}{\sigma} \vec{J} + \frac{1}{en} (\vec{J} \times \vec{B} - \vec{\nabla} P_{\rm e}).$$

supplemented by the Maxwell's equations

$$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_{\rm q}, \qquad \vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0,$$
$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}$$

- during the 30 rotations performed by the galaxy since the protogalactic collapse, the magnetic field should be amplified by about 30 e-folds;
- if the large scale magnetic field of the galaxy is, today, $\mathcal{O}(\mu G)$ the magnetic field at the onset of galactic rotation might have been even 30 e-folds smaller, i.e. $\mathcal{O}(10^{-19} G)$;
- assuming perfect flux freezing during the gravitational collapse of the protogalaxy (i.e. $\sigma \to \infty$) the magnetic field at the onset of gravitational collapse should be $\mathcal{O}(10^{-23})$ G over a typical scale of 1 Mpc.

The inflationary models

These models are appealing because the acausal generation of the field can naturally explain the universality of the strength at all scales. However, it is difficult to get enough strength to explain todays fields.

In the same spirit people have tried to generate a photon mass in the inflation period but it is not clear if it has been achieved.

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What do we know about B(t)

The next question is:

How old and extensive are known magnetic fields?

We have information that can constrain fields at

a)Nucleosynthesis

b)recombination time

c) z from 3 - 6

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A side remark: particle physics in large fields

f magnetic fields would exist with intensity $B = m_\pi^2$ many nteresting things would happen:

Hadronic masses would change significantly, chiral breaking will take a different form.

For weak fields there could be effects on the photon mass, see below.

There are some subtle points concerning the particle masses and moments in the presence of high fields, for example the electron magnetic moment saturates

$$M = \begin{cases} -\frac{\alpha}{2\pi}\frac{eB}{2m_e}\left[1 - \frac{8}{3}\frac{eB}{m_e^2}\left(\log\frac{m_e^2}{2eB} - \frac{13}{24}\right)\right] & B \ll B_c \\ \frac{\alpha}{4\pi} m_e \left(\log\frac{2eB}{m_e^2}\right)^2 . & B \gg B_c \end{cases}$$

And the proton neutron mass difference becomes

$$Q(B) = 0.12\mu_N B - m_n + m_p + f(B) \ .$$

Which implies that for a high enough B the proton becomes heavier than the neutron

f(B) is a function of the B field that determines the change of colour forces due to the magnetic field.

Magnetic fields and nucleosynthesis

Which factors control if B is present at nucleosynthesis given he tight limits on the abundances?

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Which factors control if B is present at nucleosynthesis given the tight limits on the abundances?

- Changes in the neutron decay rate
- Changes in energy density of the electron positron pairs
- Changes in the expansion rate of the Universe
- Changes in the thermodynamics of the electrons

- Many subdominant effects like the changes of particle masses (proton becomes heavier than neutron for fields 10^{20} Gauss or higher!) are unimportant. Once more the fields even in magnetstars are too low to test these phenomena.

Chirality breaking

- In very strong magnetic fields (B> 1.5 10^{18} G the strong interaction group SU(2)xSU(2) differently.
- Instead of the neutral component getting an expectation value it is the π^+ that gets one. As a consequence the magneetic field gets screened.

Weak interactions

The weak reactions that control the n-p equilibrium are:

$$n + e^+ \leftrightarrow p + \overline{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n \leftrightarrow p + e^- + \overline{\nu}_e \, .$$

And the rate for B=0 is given by standard electroweak theory:

$$\Gamma_{n\to p}(B=0) = \frac{1}{\tau}\int_1^\infty d\epsilon \, \frac{\epsilon\sqrt{\epsilon^2-1}}{1+e^{\frac{m_e\epsilon}{T}}}\left[\frac{(q+\epsilon)^2 e^{\frac{(\epsilon+q)m_e}{T_\nu}}}{1+e^{\frac{(\epsilon+q)m_e}{T_\nu}}} + \frac{(\epsilon-q)^2 e^{\frac{\epsilon m_e}{T}}}{1+e^{\frac{(\epsilon-q)m_e}{T_\nu}}}\right]$$

where q and ϵ are respectively the neutron-proton mass difference and the electron, or positron, energy, both expressed in units of the electron mass

Explicit calculation outline

n the presence of a field the electron orbits for B>B_c become quantized

$$E_n(B) = \left[p_z^2 + |e|B(2n+1+s) + {m_e}^2\right]^{\frac{1}{2}}$$

And the decay rate becomes

$$\Gamma_{n\to p}(\gamma) = \frac{\gamma}{\tau}\sum_{n=0}^{\infty}(2-\delta_{n0}) \times \int_{\sqrt{1+2(n+1)\gamma}}^{\infty} d\epsilon \frac{\epsilon}{\sqrt{(\epsilon-\kappa)^2 - 1 - 2(n+1)\gamma}}$$

$$\times \frac{1}{1+e^{\frac{m_e\epsilon}{T}}}\left[\frac{(\epsilon+q)^2 e^{\frac{m_e(\epsilon+q)}{T_\nu}}}{1+e^{\frac{m_e(\epsilon+q)}{T_\nu}}} + \frac{(\epsilon-q)^2 e^{\frac{m_e\epsilon}{T}}}{1+e^{\frac{m_e(\epsilon-q)}{T_\nu}}}\right] ($$

with

$$B_c \equiv eB/m_e^2 = 4.4 \times 10^{13}$$

and

$$\gamma \equiv B/B_c$$

This contribution reads:

Effect on the Universe geometry

The ratio n/p freezes when $\Gamma_{n\to p}(T_F) = H(T_F)$.

The expansion rate is determined by

$$H \equiv \frac{\dot{a}}{a} = \left(\frac{8\pi G \rho_{tot}}{3}\right)^{1/2} .$$

and the density by

$$\rho(T,B) = \rho_{em}(T,B) + \rho_\nu + \rho_B(B)$$

where the first term is the stored electromagnetic energy , the second the neutrino energy and the third is the magnetic energy given by

$$\rho_B(T) = \frac{B^2(T)}{8\pi} . \longrightarrow \rho_B(T) \propto T^4 ,$$

Effect on the electron thermodynamics

$$n_e(B) = \frac{eB}{(2\pi)^2}\sum_{n=0}^{\infty}(2-\delta_{n0})\int_{-\infty}^{+\infty} f_{FD}(T)dp_z$$
$$\rho_e(B) = \frac{eB}{(2\pi)^2}\sum_{n=0}^{\infty}(2-\delta_{n0})\int_{-\infty}^{+\infty} E_n f_{FD}(T)dp_z$$

The time temperature dependence is changed by the magnetic field

$$\frac{dT}{dt} = -3H\frac{\rho_{em}+p_{em}}{d\rho_{em}/dT} ,$$

where $\rho_{em} \equiv \rho_e + \rho_\gamma$ and $p_{em} \equiv p_\gamma + p_e$ are the energy density and the pressure

For small values of the ratio eB/T^2, the most relevant effect of the mag-
ietic field enters in the derivative $d\rho_{em}/dT_\gamma$ that is smaller than the free field
alue. This effect can be interpreted as a delay in the electron-positron an-
ihilation time induced by the magnetic field. This will give rise to a slower
ntropy transfer from the electron-positron pairs to the photons, then to a
lower reheating of the heat bath. In fact, due to the enlarged phase-space
f the lowest Landau level of electrons and positrons, the equilibrium of the
rocess $e^+e^- \leftrightarrow \gamma$ is shifted towards its left side. Below we will discuss as
his effect has a clear signature on the deuterium and ^{3}He predicted abun-
lances. Another point of interest is that the delay in the e^+e^- annihilation
auses a slight decrease in the T_ν/T ratio with respect to the canonical value,

Effect on electron thermodynamics

In the presence of a magnetic field

$$
\begin{aligned}
n_e(B) &= \frac{eB}{(2\pi)^2}\sum_{n=0}^{\infty}(2-\delta_{n0})\int_{-\infty}^{+\infty} f_{FD}(T)dp_z \\
\rho_e(B) &= \frac{eB}{(2\pi)^2}\sum_{n=0}^{\infty}(2-\delta_{n0})\int_{-\infty}^{+\infty} E_n f_{FD}(T)dp_z \\
p_e(B) &= \frac{eB}{(2\pi)^2}\sum_{n=0}^{+\infty}(2-\delta_{n0})\int_{-\infty}^{+\infty} \frac{E_n^2-m_e^2}{3E_n} f_{FD}(T)dp_z
\end{aligned}
$$

where

$$
f_{FD}(T) \equiv \frac{1}{1+e^{\beta E_n(p_z)}}
$$

The result is:

Treating these equations numerically one shows that for small T the electron density grows linearly for $B > B_c$.
The analysis gets complicated but the net result but two consequences result out of running the nucleosynthesis code

1. The growth of $e^+ e^-$ in the presence of B results in a faster expansion of the Universe.
2. The time temperature relation is also changed because of the equation

$$\frac{dT}{dt} = -3H \frac{\rho_{em} + p_{em}}{d\rho_{em}/dT} ,$$

Effectively it delays electron positron annihilation.

The model dependent path to a limit

3BN however proves scales related to the horizon radius at hat time (100 pc) while at galaxy or proto galaxy generation ime it is 10 Mpc. If fields are tangled on scales smaller than his one must make some random walk over the volume or p can then vary from 1 to 2.

$$\langle B(L,t)\rangle_{\mathrm{rms}} = B_0 \left(\frac{a_0}{a(t)}\right)^2 \left(\frac{L_0}{L}\right)^p ,$$

f we assume L_0 to be 100 pc and p=1, then B at this time can be 10^{-10} G

These results define the scales one is probing. CMBR for Example tests much larger scales.

However fields seen today can be primordial,and by expansion thy could be 10^{-6} G

Effects of a magnetic field at recombination time

The isotropy of the CMBR limits the possible size of a field,in fact

$$\frac{\Delta T}{T} = \frac{T_x - T_z}{T_{\rm rec}} = 1 - \exp\left(\int_{t_{\rm rec}}^{t_0} (\alpha - \beta) dt\right)$$
$$\approx \int_{t_{\rm rec}}^{t_0} (\beta - \alpha) dt = -\frac{1}{2}\int_{t_{\rm rec}}^{t_0} \sigma d\ln t \, . \qquad \sigma \equiv \alpha - \beta \, .$$

Where a and b are defined by the axially symmetric metric

$$\text{define } \alpha = \frac{\dot a}{a}; \quad \beta = \frac{\dot b}{b}; \text{ and}$$

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2) - b^2(t) dz^2 \, .$$

A magnetic field today of strength 10^{-9} to 10^{-10} G would produce an anisotropy $\delta T/T \lesssim 10^{-6}$.

A more refined analysis gives $B(t_0) < 3.5 \times 10^{-9} f^{1/2} (\Omega_0 h_{50}^2)^{1/2}$ G

The effect of B on the acoustic peaks

The equations for the acoustic peaks distribution functions are changed in the presence of a magnetic field to

$$\dot{\delta} + \frac{\nabla \cdot \mathbf{v_1}}{a} = 0 \ ,$$

where a is the scale factor.

$$\dot{\mathbf{v}}_1 + \frac{\dot{a}}{a}\mathbf{v}_1 + \frac{c_S^2}{a}\nabla\delta + \frac{\nabla\phi_1}{a} + \frac{\hat{\mathbf{B}}_0 \times \left(\dot{\mathbf{v}}_1 \times \hat{\mathbf{B}}_0\right)}{4\pi a^4} + \frac{\hat{\mathbf{B}}_0 \times \left(\nabla \times \hat{\mathbf{B}}_1\right)}{4\pi \rho_0 a^5} = 0 \ ,$$

$$\partial_t \hat{\mathbf{B}}_1 = \frac{\nabla \times \left(\mathbf{v_1} \times \hat{\mathbf{B}}_0\right)}{a} \ ,$$

$$\nabla^2 \phi_1 = 4\pi G \rho_0 \left(\delta + \frac{\hat{\mathbf{B}}_0 \cdot \hat{\mathbf{B}}_1}{4\pi \rho_0 a^4}\right)$$

and

$$\nabla \cdot \hat{\mathbf{B}}_1 = 0 \ ,$$

where $\hat{\mathrm{B}} \equiv \mathrm{B}a^2$ and $\delta = \dfrac{\rho_1}{\rho_0}$, ϕ_1 and v_1 are small perturbations on the background density, gravitational potential and velocity respectively. c_S is the sound velocity.

Validity conditions

Ihe subscript 1 refers to the small deviations from the field B_0
Ihe terms that are relevant are

$$+ \frac{\hat{\mathbf{B}}_0 \times \left(\dot{\mathbf{v}}_1 \times \hat{\mathbf{B}}_0\right)}{4\pi a^4} + \frac{\hat{\mathbf{B}}_0 \times \left(\nabla \times \hat{\mathbf{B}}_1\right)}{4\pi \rho_0 a^5}$$

Ihe first term is due to the displacement current contribution to the rotor, the second is the magnetic force of the current lensity.
Ihese equations are derived under several assumptions:
Linear regime, one neglects viscosity and heat conductivity ind assumes that the field homogeneous on scales larger than

Possible effects of a magnetic field

In the presence of the magnetic field several waves can exist:

a)fast magnetosonic waves,characterized by

$c_+^2 \sim c_S^2 + v_A^2 \sin^2\theta$, and where θ is the angle between k and B_0.

$$v_A \equiv \frac{B_0}{\sqrt{4\pi(\rho+p)}} \ll c_S \ ,$$

b) Slow magnetosonic waves:

$$c_-^2 \sim v_A^2 \cos^2\theta \ .$$

c) Alfven waves.

These propagate with c_ velocity but are purely rotational and do not involve density fluctuations.

Magnetosonic wave effects can be calculated as shown below.

The sound velocity changes...

$$\dot{\delta}_b + V_b - 3\dot{\phi} = 0, \tag{2.20}$$

$$\dot{V}_b + \frac{\dot{a}}{a}V_b - c_b^2 k^2 \delta_b + k^2\psi + \frac{a n_e \sigma_T (V_b - V_\gamma)}{R} - \frac{1}{4\pi \hat{\rho}_b a}\mathbf{k}\cdot\left(\hat{\mathrm{B}}_0 \times (\mathbf{k}\times \hat{\mathrm{B}}_1)\right) = 0\ , \tag{2.21}$$

for the baryon component of the plasma and

$$\dot{\delta}_\gamma + \frac{4}{3}V_\gamma - 4\dot{\phi} = 0 \tag{2.22}$$

$$\dot{V}_\gamma - k^2(\frac{1}{4}\delta_\gamma - \sigma_\gamma) - k^2\psi - a n_e \sigma_T (V_b - V_\gamma) = 0\ , \tag{2.23}$$

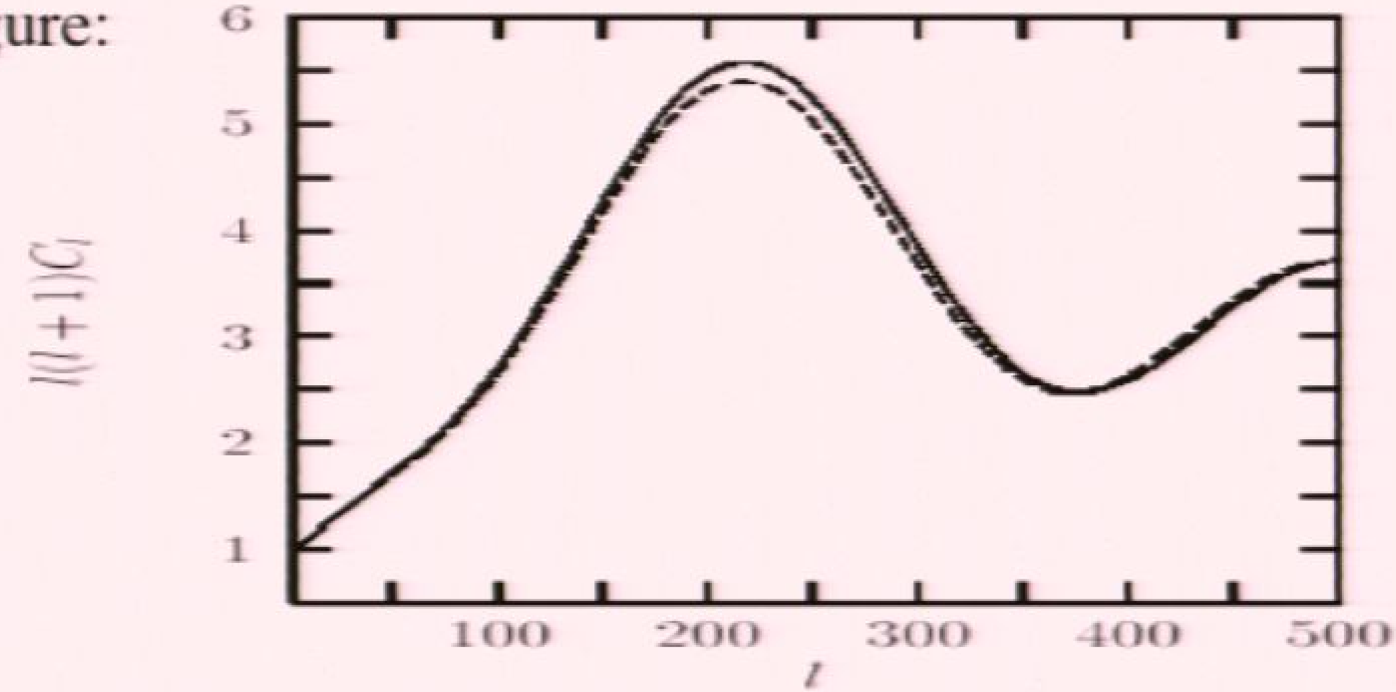
for the photon component. In the above $V = i\mathbf{k}\cdot\mathbf{v}$, $R = \dfrac{p_b + \rho_b}{p_\gamma + \rho_\gamma} = \dfrac{3\rho_b}{4\rho_\gamma}$ and c_b is the baryon sound velocity in the absence of interactions with the photon gas. As it is evident from the previous equations, the coupling between the baryon and the photons fluids is supplied by Thomson scattering with cross section σ_T.

Effectively the solution is

$$c_b^2 \longrightarrow c_b^2 + v_A^2 \sin^2\theta\ .$$

There is a hope via WMAP to see effects

Summing and averaging over the observation angle and the magnetic field direction we obtain the results of the accompanying Figure:



effect of a field $B_0 = 2 \times 10^{-7}$ G on the first acoustic peak.

Figure 2.1: The effect of a cosmic magnetic field on the multipole moments. The solid line shows the prediction of a standard CDM cosmology ($\Omega = 1, h = 0.5$, $\Omega_B = 0.05$) with an $n = 1$ primordial spectrum of adiabatic fluctuations. The dashed line shows the effect of adding a magnetic field equivalent to 2×10^{-7} Gauss today. From Ref.[58]

Effects concerning polarization

$$\langle \varphi_{12}^2 \rangle^{1/2} = 1.1^\circ \left(1 - \frac{\nu_1^2}{\nu_2^2}\right) \left(\frac{B_0}{10^{-9}\,\mathrm{G}}\right) \left(\frac{30\,\mathrm{GHz}}{\nu_1}\right)^2$$

The rotation angle between photons of frequencies 1 and 2 is given By the above formula. So fields of strength 10^{-9} can be observed. These predictions are precisely at the upper limit of possible fields and will put further bounds on these fields.

An important application of galactic and cosmic fields:
the photon mass

Is the photon mass 0?

What is the connection of the
observed mass with magnetic fields?

Gauge invariance..

t is a basic concept of field theory that gauge invariance protects the photon mass to remain 0 always. Another consequence of this principle s that the potential A is not locally observable (Bohm Aharonov is lifferent,one does observe an integral of the potential).

Iowever things are not that simple. Though we live in a world most probably consistent with general relativity we do live in a preferred frame ingled out by the Universe expansion. This is a bit strange.

Are there caveats on the general gauge conditions?

For a massive photon the Maxwell equations get replaced by the Proca equation. The potential becomes observable!

a) What is the experimental situation?

b) Possible origins of a photon mass

1. Thermodynamic considerations
2. Thermal mass

The experimental situation

There are old methods and recent measurements.

1.De Broglie used the observation of light from a binary after occultation. Any change of colour would imply a photon mass. He obtained from the absence of any effect

$M_{ph} < 10^{-44}$ gr (1940) $= 10^{-11}$ ev

2.Coulomb law null effect

3.Davies et al used the mapping by Pioneer-10 of Jupiter s magnetic field to put a limit on the mass.

4.Lakes used a remarkable galactic effect to get (slightly improved later) the best present limit. However, there are problems of interpretation

The Coulomb experiment

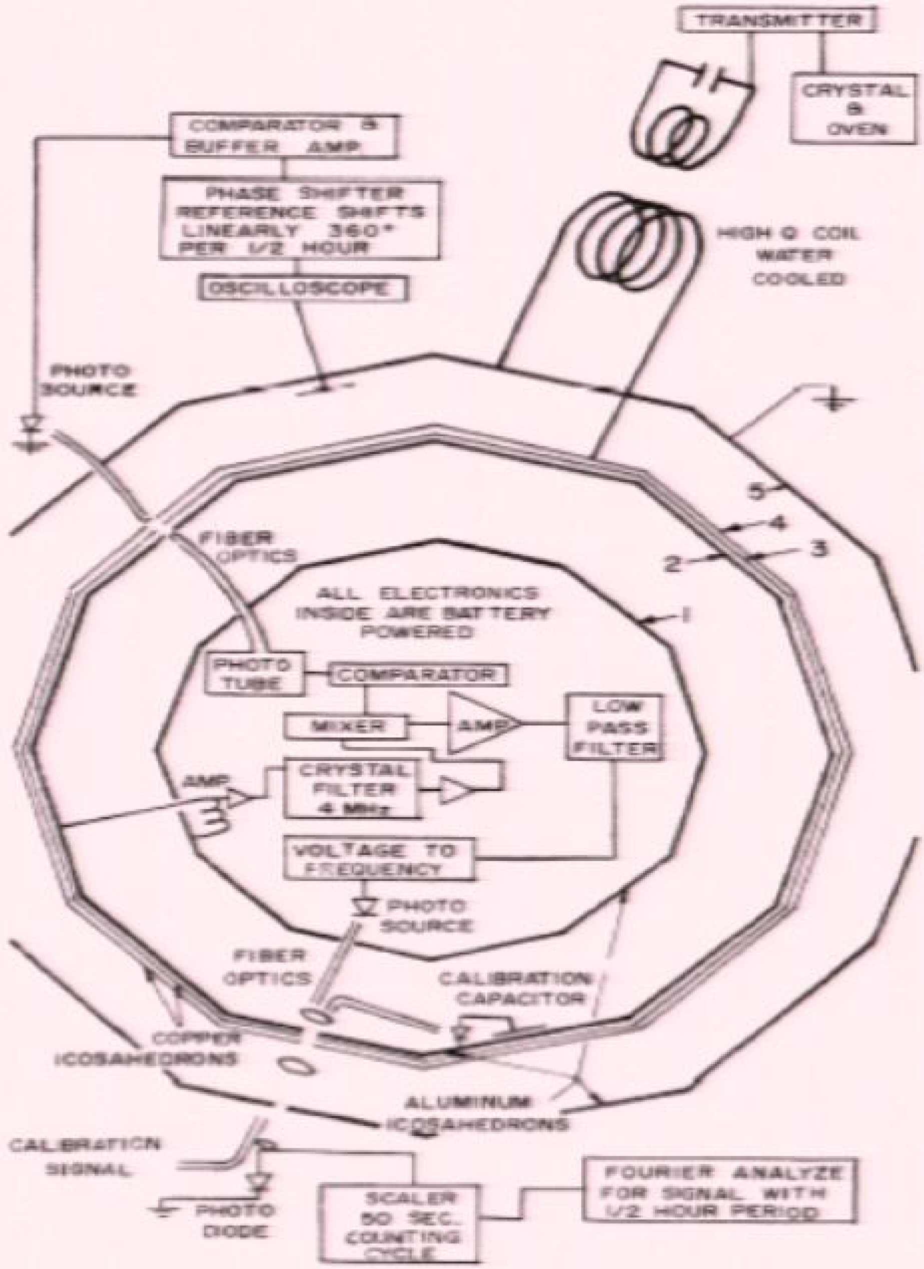


FIG. 1. Schematic drawing of the apparatus. A 4-MHz voltage is applied between shells 4 and 5. A signal of less than 10^{-12} V could have been detected be-

The calculation goes as:

If the photon is massless, the electric field in between the shielded spheres must vanish, provided there is no charge on the inner surface.

If the photon is massive Maxwells equations are replaced by the Proca equations:

$$(\Box + \mu^2) A_\nu = (4\pi/c) J_\nu,$$

where $\mu = m_0 c/\hbar$. In three-dimension Gauss's law becomes

$$\nabla \cdot \vec{E} = 4\pi\rho - \mu^2 \varphi.$$

If we apply to the external sphere a potential

$$V = V_0 e^{iwt}$$

The new Gauss law becomes:

$$\int [\nabla \cdot \vec{E} - 4\pi\rho + \mu^2 V_0 e^{i\omega t}] d^3x = 0.$$

The photon mass limit becomes:

The field is now also radial:

$$\vec{\mathbf{E}}(r) = (qr^{-2} - \tfrac{1}{3}\mu^2 V_0 e^{i\omega t} r)\hat{r},$$

where q is the total charge on the inner shell.

The result is

a) If we parametrize the deviation of the law as :

$$\frac{1}{r^{2+q}} \quad then \quad q = \quad (2.7 \pm 3.1)10^{-16}$$

b) or as a mass

$$\mu^2 = (1.04 \ \text{-} +1.2)10^{-19} \ \text{cm}^{-2}$$

Results of Coulomb or laboratory tests of Coulombs law

	Coulomb's Law violation of form r^{2+q} q	$\mu^2 = (\frac{m_o c}{\hbar})^2$	Photon rest mass m_o
Cavendish (1773)	2×10^{-2}		
Coulomb (1785)	4×10^{-2}		
Maxwell (1873)	4.9×10^{-5}		
Plimpton and Lawton (1936)	2.0×10^{-9}	$1.0 \times 10^{-12}\,cm^{-2}$	$\leq 3.4 \times 10^{-44}\,g$
Cochran and Franken (1967)	9.2×10^{-12}	$7.3 \times 10^{-15}\,cm^{-2}$	$\leq 3 \times 10^{-45}\,g$
Bartlett, Goldhagen, Phillips (1970)	1.3×10^{-13}	$1 \times 10^{-16}\,cm^{-2}$	$\leq 3 \times 10^{-46}\,g$
Williams, Faller, Hill	$(2.7 \pm 3.1) \times 10^{-16}$	$(1.04 \pm 1.2) \times 10^{-19}\,cm^{-2}$	$\leq 1.6 \times 10^{-47}\,g$
Schroedinger (1943)		$3 \times 10^{-19}\,cm^{-2}$	$\sim 2 \times 10^{-47}\,g$
Gintsburg (1953)	Test of Ampere's Law from Geo-	$5 \times 10^{-20}\,cm^{-2}$	$\leq 8 \times 10^{-48}\,g$

The galactic experiment of Lakes

Lakes had a remarkable idea. Given the smallness of the mass its Compton wave length is phenomenal. Assume a mass and again:

$$\text{div}\,\mathbf{E} = 4\pi\rho - \mu_\gamma^2 V\,,$$

$$\text{curl}\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}\,,$$

$$\text{div}\,\mathbf{B} = 0\,,$$

$$\text{curl}\,\mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} - \mu_\gamma^2 \mathbf{A}\,.$$

The experiment looks for a contribution to the energy $\mu^2 A^2$

One looks for the product of a local dipole field and the ambient field

$$\mu_\gamma^2 |\mathbf{A}_{\text{ambient}}| = \frac{G \frac{1}{L} \frac{\pi d^4}{32} \frac{\phi}{2}}{k\left[\frac{1}{4}(w-u)^2 nhI \ln\left(\frac{w}{w-u}\right)\right]}$$

$\times \sin(\theta\ )$

The apparatus

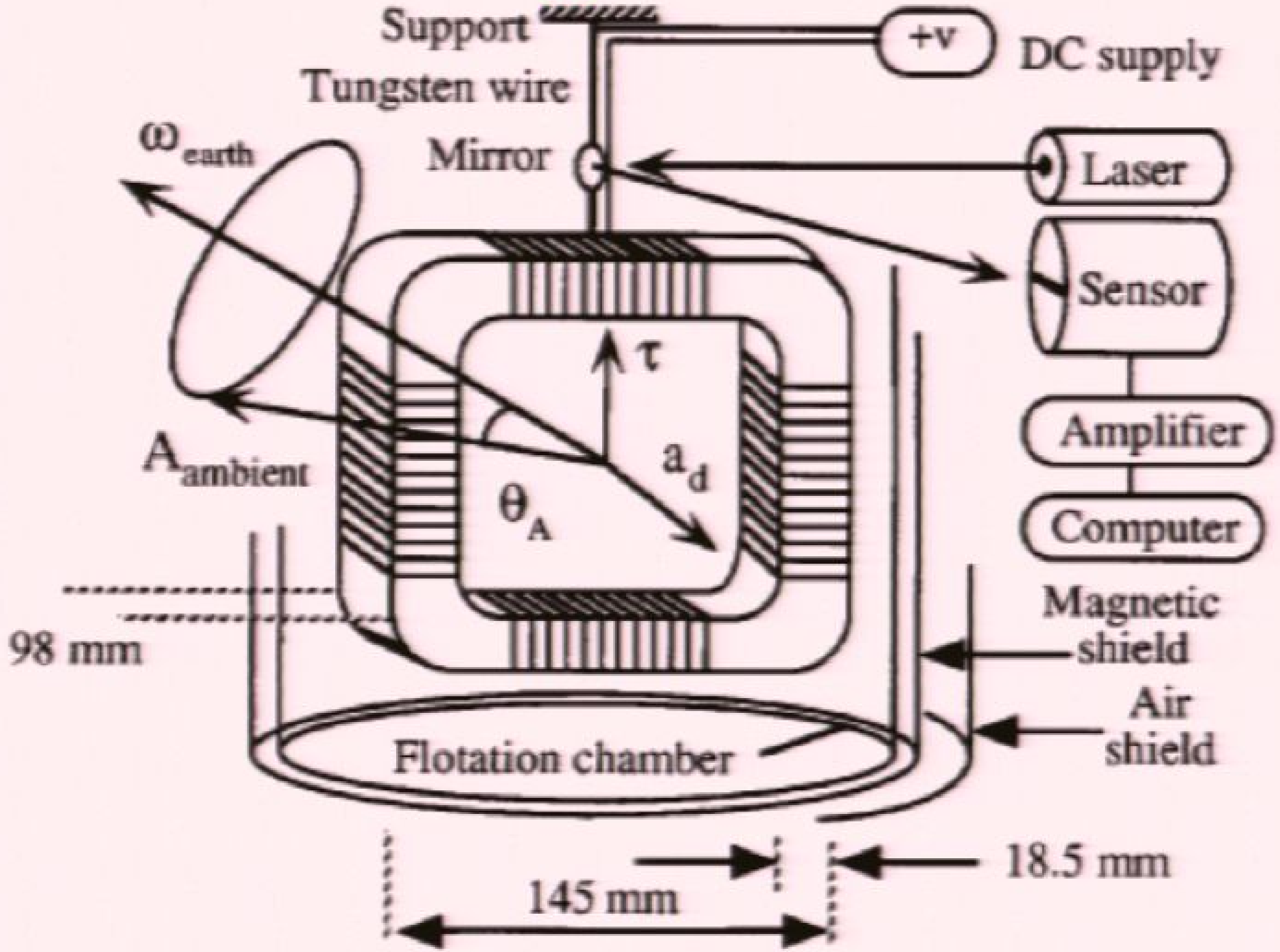


FIG. 1. A toroid carries an electric current giving rise to a dipole field $\mathbf{a}_d$ in magnetic vector potential. If $\mu_\gamma > 0$, this interacts with the ambient vector potential $\mathbf{A}_{\rm ambient}$ to produce a torque τ on the toroid, which varies with time according to

Possible contributions to the ambient field

1) 200 Tm due to the earth magnetic field. 1 T = 10^4 G.

2) 10 Tm due do the Sun dipole magnetic field.

3) Galactic fields have a strength μG and a spatial extension about 600 parsecs without reversal giving A ≈ 2 10^9 Tm

4) For the Coma cluster with B=.2μ and extension 1300 kiloparsecs we obtain A ≈ 10^{12}Tm

5) For other clusters 10^{13} Tm.

6) Finally for cosmological fields of Universe size since the upper limit for B is 10^{-9} G, A can be 10^{17} Tm.

Limits on the photon mass

[T]he best data from true tabletop experiments [2,6] of [d]eviations from Coulomb's law give $\mu_\gamma^{-1} > 3 \times 10^7$ m. [T]he present results are a factor $\approx 6 \times 10^2$ more sensitive. [A] tabletop limit based on a low-temperature null test [21] [o]f Ampère's law gives $\mu_\gamma^{-1} > 4 \times 10^5$ m. The present [r]esults are a factor $>10^4$ more sensitive. We are in a [g]alaxy, and potentials from cluster or intercluster fields [m]ight be partly neutralized by galactic potentials. If we, [t]hen, conservatively use galactic fields prior to a reversal, $\mu_\gamma^{-1} > 1 \times 10^9$ m, a figure still superior to that derived [f]rom the Jovian field. If, however, $A \approx 4 \times 10^{13}$ T m [(]due to the lower value of intercluster filament fields), [t]hen $\mu_\gamma^{-1} > 2 \times 10^{11}$ m.

This is equivalent to about 10^{-17} ev

The thermodynamic paradox

t was noticed by Schrodinger that something was peculiar about he photon thermodynamics.

The Stefan Wien law has a factor 2 because of the polarization legrees of freedom but no mass factor. Therefore, if there is a hird degree of freedom, and for that the photon must be massive, he Proca equations allow now for a longitudinal component. It ooks like the factor 2 changes discontinuouly to 3!

Transverse and longitudinal waves behave differently.

Consider a plane wave $e^{i(ßt-k.x)}$ then $ß^2 + k^2 = \mu^2_{ph}$

For a transverse wave E,H and k are mutually orthogonal.

A and E are parallel, V = 0, and $E = i\, ß/\mu\ A$; $H/E = k/ß < 1$

For a longitudinal wave E is parallel to k, H = 0, A is parallel to E and $E = -\, i\, \mu/ß\ A$ and $V = k/ß\ A$.

The energy is given by $1/8\pi\,(E^2 + H^2 + A^2 + V^2)$

and the Poynting vector $1/4\pi(B\wedge E + AV)$

n a perfect conductor there is no oscillatory H and $E = 0$. Only the
ector potential can survive.
As a consequence (not obvious) an incident transverse wave
s almost perfectly reflected and transmits a longitudinal wave
f order $(\mu/ß)^2$ while a longitudinal one does likewise: no mixing.
So for a cavity of volume Ω the mean collision time is $\Omega^{1/3}/c$
nd the loss per second $\Omega^{-1/3}\, c\, (\mu/ß)^2$ and an equilibration time
or infrared radiation $t > \Omega^{1/3}\, 3.10^{17}$ sec (don't wait!)

But in fact the photon is massive!

We live, in as in GR in a preferred system. The physical vacuum is a thermal one. Remember we are at T=2.7. In general:

$M_{ph} = m_{ph}(T=0) + \phi\, T^2$

where ø is a function of the relevant interaction.

The thermal photon mass, since the first term vanishes in principle, must be calculated. Sher and Primack fell in the trap and said that since the temperature of the Universe is 10^{-5} ev the photon mass should be of that order!

The thermal propagator of a particle is

$$\frac{i}{k^2-\mu^2}+\frac{2\pi}{e^{E/kT}-1}\delta(k^2-\mu^2)$$

Where μ is the propagating particle in the thermal bath

Thermal mass is VERY small!

Notice that the temperature factor refers to particles on shell to lowest order. Therefore the virtual photons of a static field cannot couple to lowest order.

In higher orders it is possible via electron positron pairs. These contributions are suppressed by a factor $e^{-m/kT}$ where m is the electron mass. The contribution to the mass is

$$e^2 m_e^{\ 2} \left(\frac{m_e}{kT}\right) e^{-m_e/kT}$$

The thermal mass is a phenomenally small number.

oca theory, Eq. 2, can be extended to the Higgs theory, by promoting m_A into s
field $\phi = m_A/g$, with the self-Lagrangian

$$\frac{1}{2}(\partial_\mu \phi)^2 - \frac{\lambda^2}{2}(\phi^2 - \eta^2)^2.$$

, ϕ can be thought of as the modulus of a complex Higgs field, $H = \phi e^{i\psi}$, and ψ
(Goldstone boson), which becomes a longitudinal photon. The static energy i
ce of the electric field is

$$\mathcal{E} = \int d^3x \left(\frac{B^2}{2} + \frac{g^2}{2}\phi^2 \left(\mathbf{A} - \frac{1}{g}\nabla\psi \right)^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{\lambda^2}{2}(\phi^2 - \eta^2)^2 \right).$$

wo important parameters of the theory are the mass of the photon $m_A = g\eta$, an
of the Higgs particle $m_\phi = \lambda\eta$. With frozen $\phi = \eta$, the theory simply reduc
theory with the energy

$$\mathcal{E} = \int d^3x \left(\frac{B^2}{2} + \frac{g^2}{2}\eta^2 \vec{\mathbf{A}}^2 \right),$$

Yamaguchi's argument

f the galaxy is in the Proca regime there is an argument due to Yamaguchi that gives a strong limit to the photon mass.

$$p_{\text{magnetic}} = \frac{\mathrm{B}^2}{24\pi} - \frac{m^2 \tilde{\mathrm{A}}^2}{24\pi}.$$

The magnetic pressure must be balanced by the kinetic pressure and the plasma pressure. Assuming equipartition which holds if Conventional QED is correct it follows that the energy $B^2/8\pi$ Is compared to the other terms. Therefore $m^2 \tilde{\mathbf{A}}^2 \lesssim \mathbf{B}^2,$

and

$\tilde{A} \sim RB$ we obtain

$$m \lesssim R^{-1} \lesssim 10^{-26}\ \text{eV}.$$

The SKA project

1991 Concept

1994

International Working Group formed

1997 Start of design and prototyping

2000 Signing of first Memorandum of Agreement

2005 Signing of extended Memorandum of Agreement

2006 Selection of reference design

Selection of short-list of acceptable sites

2008 External review of the SKA design

2008-10 System design

2009-10 Decisions on funding, governance, and site

2011 Start of construction of Phase 1 (10% SKA)

2014 Early science with Phase 1 - the first 10% of the array

2015-20 Complete construction of full array

Potential SKA capabilities

5.1. Galaxies in the Foreground of Bright Extended Radio Sources

At intermediate redshifts, we expect galaxies to be $< 1'$ in extent, too small to be adequately probed by the RM grid of compact background sources discussed in §3. However, there are many distant *extended* polarized sources (e.g., many of the quasars and radio galaxies in the 3C catalogue), which provide ideal background illumination for probing Faraday rotation in galaxies which happen to lie along the same line of sight. These experiments can deliver maps of magnetic field structures in galaxies more than 100 times more distant than discussed in §4.1 above, and thus provide information on the evolution of magnetic fields as a function of cosmic epoch. Currently this technique has been applicable in just a few fortuitous cases, such as for NGC 1310 seen projected against a lobe of Fornax A (Figure 4; [14,35]), and for an absorption line line system at $z = 0.395$ seen against PKS 1229–021 [29]. With the greater sensitivity of the SKA, many such systems lying in front of bright polarized radio sources can be targeted. These objects are less evolved counterparts to the nearby galaxies discussed in §4.1; comparison of the two populations will demonstrate how present day magnetic fields emerge. For example, the $z = 0.395$ system discussed by Kronberg et al. [29] appears to be a spiral galaxy with a bisymmetric magnetic field geometry and a magnetic field strength of $\sim 1 - 4\ \mu$G, surprisingly similar to results from nearby galaxies. Clearly a significant expansion of the sample of such systems can provide strong

Conclusions

1.Magnetic fields of great extension (kparc or more) exist.

2. The origin of these fields in intergalactic cluster space and larger regions seem to exist, and their uniformity seems to indicate primordial origin, though it is not sure.

3. Fields compatible with the values seen today could exist at nucleosynthesis and recombination time. The CMBR ones may be observable with Planck via peak distorsion or polarization effects. This is the most promising place to look for early fields.

Conclusions continuation

5. If magnetic fields exist and their galactic value and beyond are different, the photon mass would be different in these two environments. This however depends on the mechanism generating the photon mass.

6. The origin of magnetic fields, their age and extension are open problems.

Two complementary comprehensive reviews are:
Grasso and H. Rubinstein
M. Giovannini
They are complemenary, the second studying in detail the

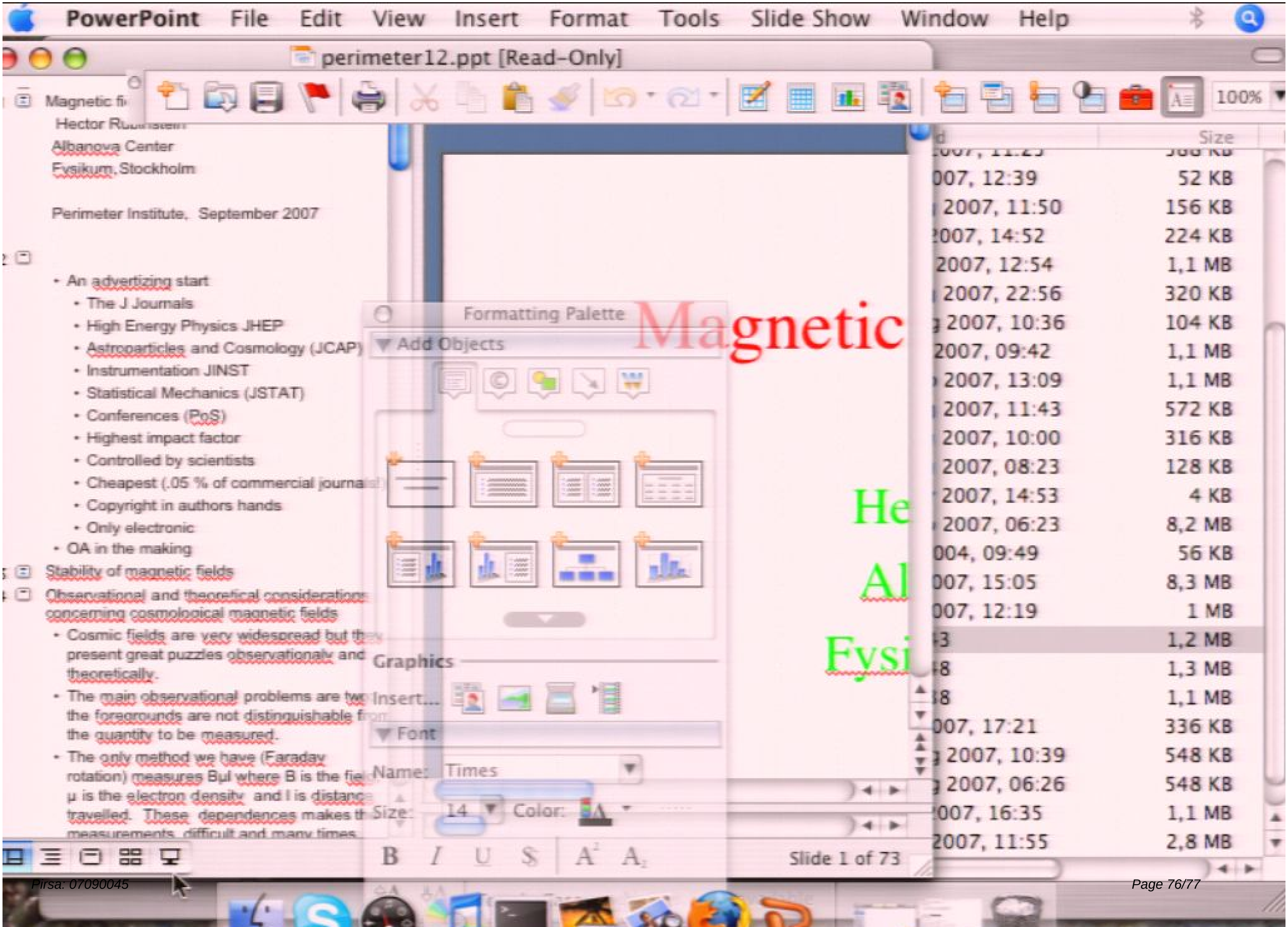
More conditions..

)) Avoidance of screening by magnetic charges if they exist.
Absence of magnetic monopoles is the key(Parker limit).

:) Near perfect conductivity to avoid diffusion.

How is conductivity estimated? One must find the relevant charged particles and calculate the evolution of the magnetic field in the presence of the conductivity coefficient.
The appropriate equation for the time evolution is:

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla \times (\mathrm{v} \times \mathrm{B}) + \frac{1}{4\pi\sigma}\nabla^2 \mathrm{B} \,,$$



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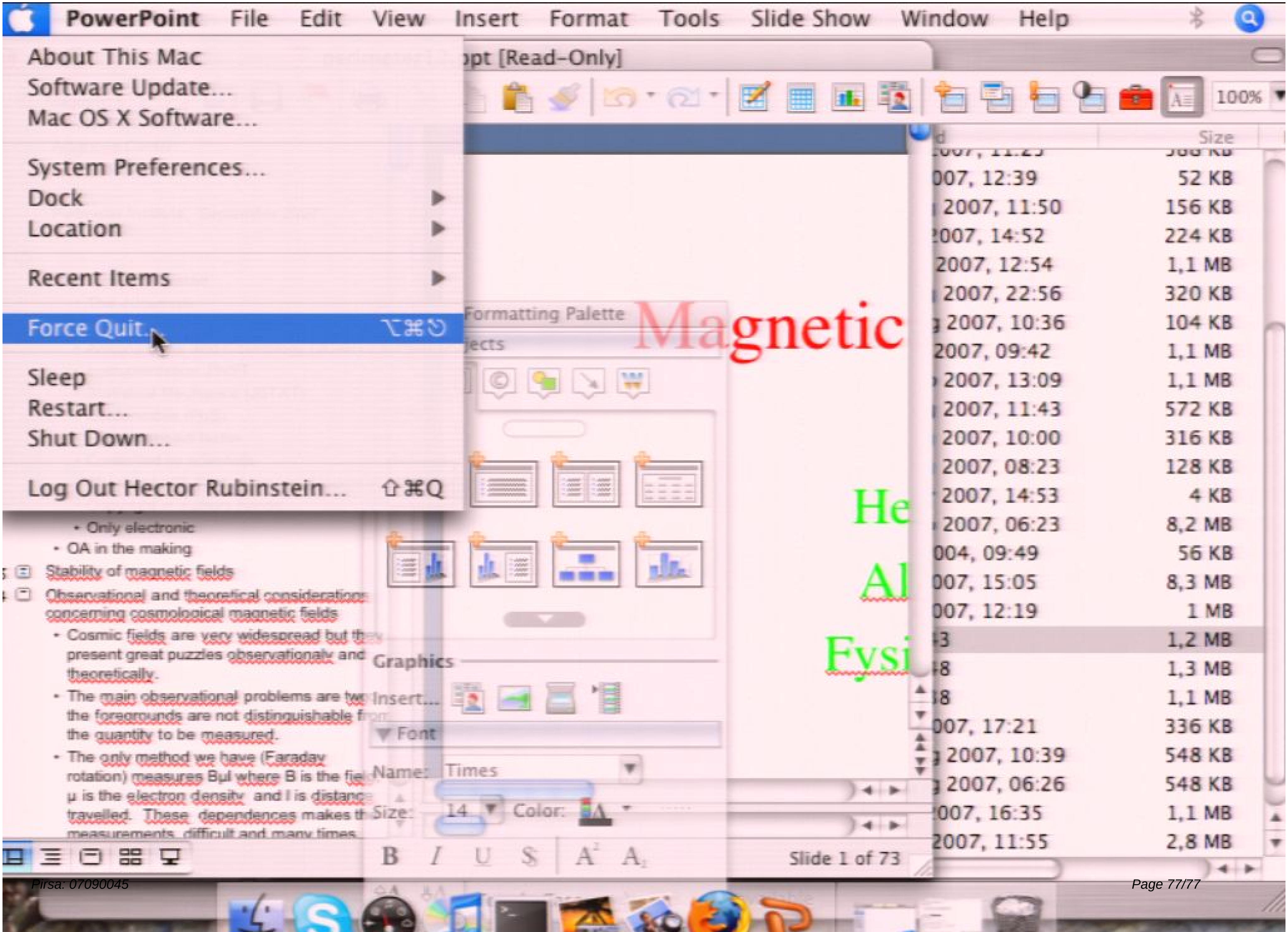
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OA in the making
Stability of magnetic fields
Observational and theoretical considerations concerning cosmological magnetic fields
Cosmic fields are very widespread but they present great puzzles observationally and theoretically.
The main observational problems are tw the foregrounds are not distinguishable fr the quantity to be measured.
The only method we have (Faraday rotation) measures Bμl where B is the fie μ is the electron density and l is distanc travelled. These dependences makes th measurements difficult and many times