Radiation pressure driven large scale magnetic field generation

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Outline

- Origin of large scale magnetic fields
  - Observations
  - The need of weak magnetic seeds
  - Available models & related problems
- New magnetogenesis scenario
  - Basics
  - Order of magnitude
  - Power spectrum
- Comparison with “usual” models
- Summary & prospects

Introduction

Observations

Magnetic fields are everywhere

- Galaxies : $B \sim 10\ \mu$G

  (e.g.: Ehle *et al*. 1996)
- Galaxy clusters : $B \sim 1 - 30\ \mu$G

  (Clarke *et al*. 2001)
- On larger scales : $B \sim 10^{-7}$ - 10^{-6} G

  (Kronberg 2000)

Questions

Where do such fields come from ?

$\Rightarrow$ magnetic seeds

How and when are the seed fields generated ?

Proposed scenarios

- Before decoupling
  - Inflation (e.g.: Dimopoulos *et al.* 2002)
  - Phase transitions (e.g.: Sigl *et al.* 1996)

  $B \sim 10^{-65}$ - 10^{-9} G
- After decoupling

  plasma physics, battery effect

  (Biermann 1950 $\longrightarrow$ e.g.: Lesch & Chiba 1995
  Kulsrud *et al*. 1997)

  $B \sim 10^{-19}$ G

- Amplification by dynamo necessary...

  ...but controversial in some aspects

  - Small scale fields

    $\Rightarrow$ potential back-reaction problem

    (e.g. : Kulsrud & Anderson 1992)

    see, however, magnetic helicity escape process, e.g. Blackman & Field 2002

  - Amplification time scale

    $B \sim$ a few μG detected at $z \sim 2$ (Athreya *et al*. 1998)

    $\Rightarrow$ hardly consistent with weak seeds

    (e.g. Widrow 2002)

New magnetogenesis model

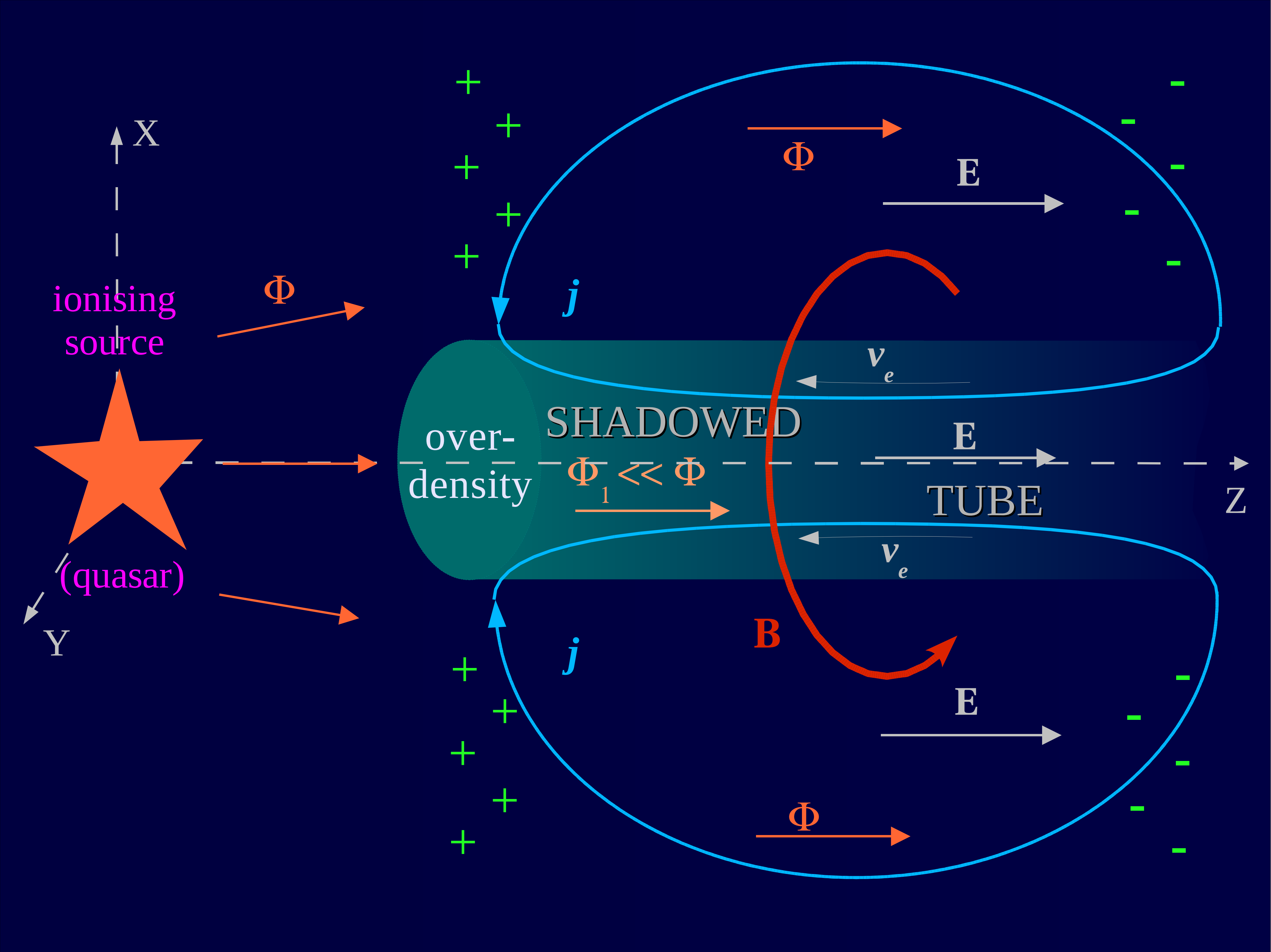
[Langer, Puget & Aghanim, *Phys. Rev.* D 67, 043505 (2003)]

- After decoupling
- At reionisation

  $z \sim 6$ - 7, quasar absorption lines
  (e.g. Becker *et al.* 2001)
- Ionising sources

  $\Rightarrow$ charge separation
- Density fluctuations

  $\Rightarrow$ flux inhomogeneity



X
Y
Z
ionising
source
(quasar)
Φ
over-
density
SHADOWED
TUBE
$\Phi_1 << \Phi$
E
j
B
v_e
+
-

Formalism

Physical assumptions

- Anisotropic flux (Φ // Oz)
- Inhomogeneous flux ($\Phi = [1+f]\Phi_0$)

  relative fluctuations $f(\boldsymbol{r}) \ll 1$

Maxwell equations

$$\nabla.\boldsymbol{E} = 4\pi\rho \qquad \nabla.\boldsymbol{B} = 0$$

$$\nabla\times\boldsymbol{E} = (1/c)\partial_t\boldsymbol{B} \qquad \nabla\times\boldsymbol{B} = (4\pi/c)\,\boldsymbol{j}+\partial_t\boldsymbol{E}$$

Generalised Ohm's law

$$\frac{m_e}{q_e n_e}\frac{d\boldsymbol{j}}{dt} = q_e\boldsymbol{E} + \frac{1}{q_e n_e}\frac{\boldsymbol{j}\times\boldsymbol{B}}{c} - \frac{m_e \nu_c}{q_e n_e}\boldsymbol{j} + \frac{h\nu_c}{c}\sigma_T\Phi$$

Lorentz' force

ohmic dissipation

radiation pressure

Other assumptions

- Steady state
- Invariance by translation along (Oz) axis

Cosmological magnetogenesis driven by radiation pressure

Results

- Analytic form

$$\nabla^2 \boldsymbol{B} = \frac{4\pi}{c} \frac{h\nu}{c} \sigma_T \nabla \times \left(\frac{e n_e}{m_e \nu_c} \Phi \right)$$

- Order of magnitude
- Magnetic field power spectrum

Order of magnitude of the generated magnetic seeds (1)

Saturated regime :

$$\frac{q_e n_e}{m_e \nu_c} = \frac{\sigma}{q_e} \qquad \text{with } \sigma \sim \sigma_0 \left(\frac{\nu_{ei}}{\omega_c}\right)^2, \ \omega_c = \frac{eB}{m_e c}$$

$$\sigma_0 \sim 1.35\ 10^{16}\ T^{3/2}\ \text{esu (non saturated)}$$

Ionising flux : $h\nu\Phi = f \dfrac{L}{4\pi D^2}$,

$$LD^{-2} \approx 6.4\ 10^{-11}(1+z)^3\ (L/10^{12}\ L_\odot)^{1/3}\ \text{W.m}^{-2} \quad \text{(photons for the reionisation)}$$

Order of magnitude estimation :

$$B \sim 3.14\ 10^{-2}\ f^{1/3} \left[\frac{T}{10^4\ \text{K}}\right]^{1/2} \left[\frac{R}{100\ \text{kpc}} \frac{LD^{-2}}{10^{-8}\ \text{W.m}^{-2}}\right]^{1/3} B_s^{2/3}\ \text{Gauss}$$

Order of magnitude of the generated magnetic seeds (2)

- $R \sim 1$ Mpc (source separation)
- $T \sim 10^4$ K (reionisation)
- $L \sim 10^{12}\ L_\odot$ (luminous quasar)
- $z \sim 7$
- $f \sim 10\%$

$\Big\}$ $B \sim 8.\ 10^{-12}$ **Gauss**

Amplification by adiabatic collapse

$$\Rightarrow \quad B_{gal} \sim \delta_c^{2/3}\ B \sim 2.7\ 10^{-10}\ \text{Gauss}$$

less time required for dynamo

only 4 orders of magnitude to gain

Magnetic field power spectrum (1)

- Shape

$$P_B(k) = |B_k|^2 \propto \frac{|f_k|^2}{k^2}$$

where $f(x,y) = \exp[-\tau_l(x,y)] - 1$

with $\tau_l(x,y) \propto \int_0^l \delta(\boldsymbol{r})\, dz$

$$P_B(k_\perp) \propto \frac{l^2}{|k_\perp|^2} \int d^2\boldsymbol{k}'_\perp \delta_D(\boldsymbol{k}_\perp - \boldsymbol{k}'_\perp) \int dk'_{||} |\delta_{k'}|^2 (2 \sin[k'_{||} l/2] / k'_{||} l)^2$$

Magnetic field power spectrum
(2)

- Shape

$$P_B(k) \leftrightarrow |\delta_k|^2 \propto k^n$$

at cluster scales : $P_B(k) \propto k^{-3}$

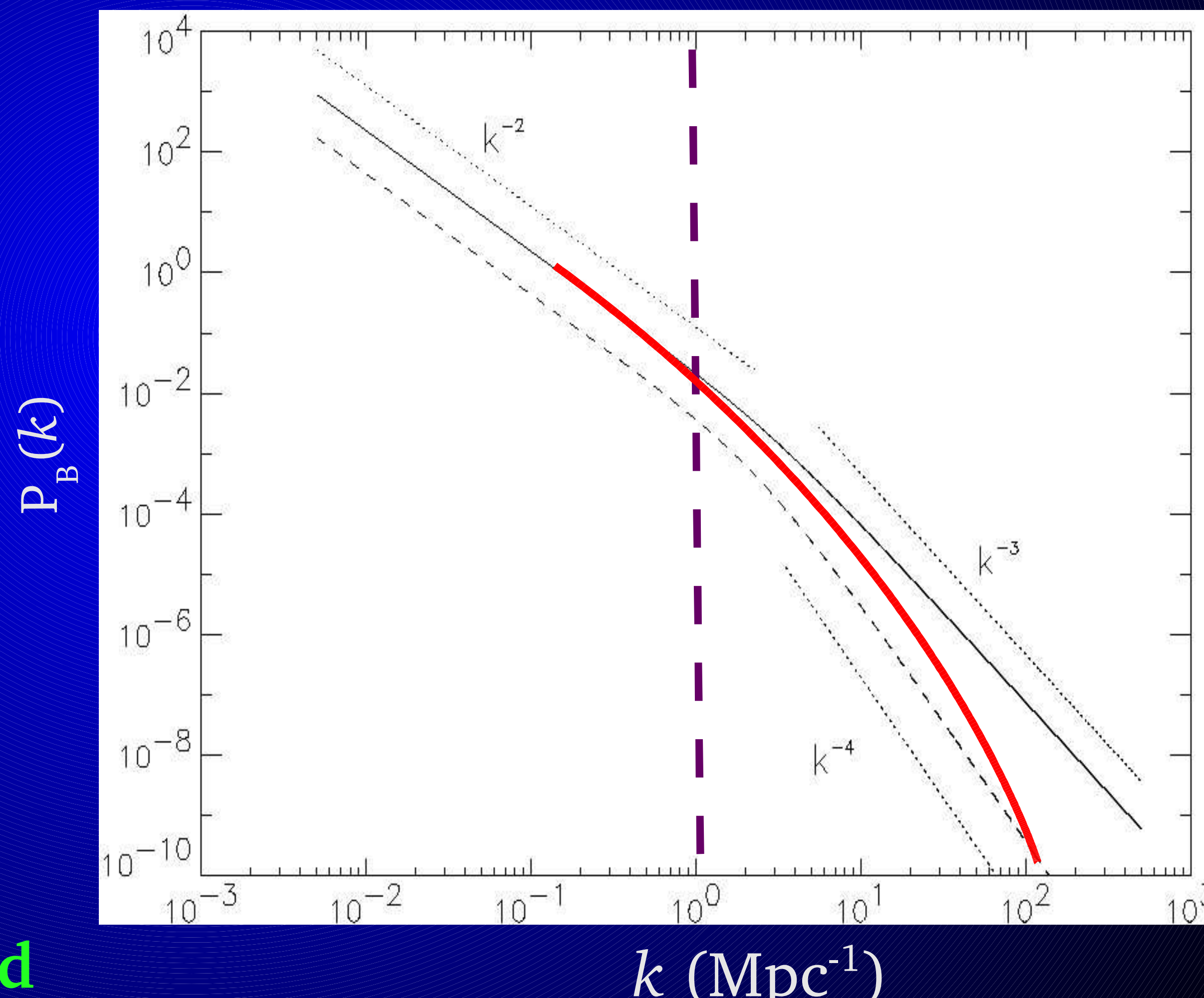
at galaxy scales : $P_B(k) \propto k^{-4}$

- Magnetic field generated

at large scales

- Small scale magnetic fields

are strongly suppressed



Comparison with previous models

- Other models
  - Weak fields, B ~ 10^{-19} Gauss
  - Mainly at small scales
- Battery effect :

  thermal pressure

  ⇒ acceleration $a_j^t \propto m_j^{-1}$

- Our model
  - Strong(er) fields, B ~ 8. 10^{-12} Gauss
  - Mainly at large scales
- Presented mechanism :

  radiation pressure

  ⇒ acceleration $a_j^r \propto m_j^{-3}$

Radiation pressure is more efficient by a factor

$$\frac{a_e^r/a_i^r}{a_e^t/a_i^t} = \left[\frac{m_p}{m_e}\right]^2 \sim 3.\ 10^6$$

Summary

- New magnetogenesis scenario
  - Strong magnetic fields

$$B \sim 8\ 10^{-6}\ \mu\text{G at } R \sim 100\ \text{kpc}$$

  - Magnetic power mostly on large scales

$$P_B(k) \propto k^{-4} \ \text{ on galactic scales}$$

most promising for seeds of galactic and extragalactic magnetic fields

- Prospects
  - Numerical simulations : Confront with more realistic conditions
  - Implications for structure formation : Energy budget (turbulent mhd), angular momentum loss, etc.