LIGHT MILLICHARGED PARTICLES AND LARGE SCALE COSMIC MAGNETIC FIELDS

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Observations: $B_{gal} \sim$ a few μG coherence scale is several kiloparsec.
Intergalactic fields: $B \sim 10^{-9}$ G, coherence scale hundreds kegaparsecs.

Origin of large scale, galactic and intergalactic magnetic fields is unknown.

Suggested mechanisms of generation of large scale magnetic fields:

Conventional physics.

Either too weak field strength or too short coherence length or both.

New physics.

Generation of B in the very early universe, or at a later stage, during or around recombination, $z = 1000$, or close to the present day.

Creation during inflation: suppressed by conformal invariance of QED; can be broken either by conformal anomaly or by a new interaction, e.g. by $RA_\mu A^\mu$-term, it also breaks gauge invariance.
B with a large coherence length can be created, but very weak.
Postinflationary early universe models all lead to too small coherence scales.
E.g. phase transitions might lead to very large B but at tiny scales.

Generation of B at BBN:

$t > 1$ sec, $T < 1$ MeV.

Short coherence scale, $l_c < 100$ pc.

In the case of large and inhomogeneous lepton asymmetry B could be generated at such scales and by chaotic field line reconnection (like Brownian motion) might extend to galactic, but not intergalactic scales.

In all the cases huge, sometimes even unrealistic, dynamo amplification by galactic rotation is necessary.
This could help to amplify galactic magnetic fields from originally weak seed fields, but not intergalactic B.

Creation of seed fields at recombination epoch, and later during large scale structure formation. B can be generated by vortex currents, but vorticity perturbations are absent in the primordial density perturbations. However, vorticity may be created by the photon diffusion in the second order of the usual scalar perturbations (Z. Berezhiani, AD, 2003; Matarrese et al 2004).

Millicharged DM can generate galactic and intergalactic magnetic fields (Z.Berezhiani, AD, I.Tkachev). Consider first a protogalaxy rotating in the background of CMB photons. The pressure exerted by photons on electrons is by far larger than that exerted on protons, $F \sim \sigma \sim 1/m^2$. So circular electric current, proportional to the rotational velocity, v_{rot}, must be induced. The acceleration is even smaller, since $a \sim F/m \sim 1/m^3$.

Force acting on electrons:

$$\vec{F} \sim \vec{v}\sigma_{e\gamma} n_\gamma \omega_\gamma.$$

Conductivity, κ is determined by the *ep* scattering. The collision time is

$$\tau_{ep} = \frac{m_e^2 \langle v_e^2 \rangle}{4\pi\alpha^2 \langle 1/v_e \rangle n_e L_e} \simeq \frac{m_e^{1/2} T_e^{3/2}}{4\pi\alpha^2 n_e L_e},$$

where $L_e \sim 10$ and $\langle \mathrm{v_e^2} \rangle = \mathrm{T_e/m_e}$. So

$$\kappa = \frac{e^2 n_e \tau_{ep}}{2m_e} \simeq \frac{T_e^{3/2}}{8\pi\alpha L_e m_e^{1/2}}.$$

Note, that the conductivity does not depend on the density of charge carriers, n_e, unless the latter is so small that the resistance is dominated by neutral particles.

Thus the difference between rotational velocities of e and p is $\Delta v_e = \tau_{ep} F/2m_e$ and the current $j = e n_e \Delta v_e$. Naively estimating B by the Biot-Savart law as $B \sim 4\pi j R$ where R is the galaxy radius, we find that for a typical galaxy with $R \sim 10$ kpc $v_{\mathrm{rot}} \sim 100$ km/s: $B \sim \mu$G, very close to the observed value without any dynamo.
HOWEVER THIS IS WRONG! Time to reach stationary (Bio-Savart) limit is longer than the cosmological time.

MHD equation modified by presence of external force:

$$\partial_t \vec{B} = \vec{\nabla} \times \vec{F}/e + \vec{\nabla} \times (\vec{v} \times \vec{B}) + (4\pi\kappa)^{-1}(\Delta \vec{B} - \partial_t^2 \vec{B}).$$

In the limit of high conductivity, the second term in the equation, the advection term, can lead to dynamo amplification of magnetic seed fields once the value of the latter is non-zero.

Assuming $B = 0$ at $t = 0$, we find that the source term induces:

$$\vec{B}(t) = \int_0^t dt\, \vec{\nabla} \times \vec{F}/e$$

The largest value of the magnetic seed is generated around the hydrogen recombination and photon decoupling, $z_{\rm rec} \sim 10^3$, or $t_{\rm rec} \sim 5 \times 10^5$ yr. Earlier the plasma was strongly coupled and the relative motion of electrons and protons was negligible.

The seed field generated at this epoch with coherence length $\lambda \sim 1$ kpc, corresponding to the present scale of a typical galaxy ~ 1 Mpc, is

$$B_\lambda \sim \Omega_\lambda t_{\rm rec} B_F(t_{\rm rec}) \lesssim 10^{-20}\, G,$$

where $\Omega_\lambda = |\vec{\nabla}\times\vec{v}|_\lambda \lesssim 10^3 (\delta T/T)^2/\lambda$. However such seed is still too weak. The seeds with the coherence length $\sim$ a few kpc and $B_{\rm seed} > 10^{-15}$ G are needed to fit the observations.

Now: new DM particles, X, instead of CMB photons. The generated current is proportional to the cross-section of Xe-elastic scattering, σ_{Xe}, to n_X/n_e, and to $p_X = m_X v_{rot}$. Therefore, to produce stronger than CMB force on electrons, σ_{Xe} should be large. This is possible if X have long range interaction, so σ_{Xe} is strongly enhanced at low momentum transfer. So we consider millicharged particles with the mass from a few keV to several MeV.

Bounds on X-particle charge, $e' = \epsilon e$:

If $m_X < m_e$, from ortho-positronium invisible decays follows $\epsilon < 3.4 \cdot 10^{-5}$.
For $m_X = 1$ MeV: $\epsilon < 4.1 \times 10^{-4}$.
For $m_X = 100$ MeV $\epsilon < 5.8 \times 10^{-4}$.
We assume that $m_X > 10$ keV to avoid strong limits on e' from the stellar evolution.
BBN bounds can be relaxed if the lepton asymmetry is non-zero.

If X-particles were thermally produced, their abundance would be (Zeldovich):

$$\Omega_X h^2 \approx 0.023\; x_f\, g_{*f}^{-1/2} \left(\frac{v\sigma_{\rm ann}}{1\ {\rm pb}}\right)^{-1},$$

where

$$x_f \equiv \frac{m_X}{T_f} = 10 + \ln\frac{g_X\, x_f^{1/2} m_X}{g_{*f}\, MeV},$$

where g_X is the number of the spin states of X-particle and g_{*f} is the effective number of particle species in the plasma at $T = T_f$.

If $m_X < m_e$, X-particles can annihilate only into photons with

$$v\sigma(X\bar{X} \to 2\gamma) = \frac{\pi\alpha'^2}{m_X^2},$$

where $\alpha' = e'^2/4\pi = \epsilon^2\alpha$. Thus

$$\Omega_X h^2 \approx 150 \left(\frac{10^{-5} m}{\epsilon^2\,\mathrm{keV}}\right)^2 .$$

Hence X's would be overproduced if $\epsilon < 3.4 \cdot 10^{-5}$. Additional annihilation into $\bar{\nu}\nu$ or dark photons could help.
Moreover CMB demands $\Omega_X h^2 < 0.007$ (Dubovsky, Gorbunov, Rubtsov).

If $m_X > m_e$, then $X\bar{X} \to e^+e^-$ and:

$$v\sigma(X\bar{X} \to e^+e^-) = \frac{\pi\alpha\alpha'}{m_X^2}.$$

Correspondingly:

$$\Omega_X h^2 = 0.012 \left(\frac{10^{-5} m}{\epsilon\,\mathrm{MeV}}\right)^2.$$

Hence, e.g. for $m_X = 10$ MeV and $\epsilon = 3 \cdot 10^{-5}$, X-particles can make all DM. Nevertheless Ω_X wlll be taken as free parameter.

Force from X-particles on electrons:

$$F = \sigma_{eX}\, v_{rel}\, n_X\, m_X\, v_{rot},$$

where

$$v_{rel}\sigma_{eX} = \frac{4\pi\alpha\alpha' L}{m_X^2 v_{rel}^3},$$

$$m_X n_X = 10\,\Omega_X h^2 \kappa(z)(1+z)^3\,\mathrm{keV/cm^3},$$

where $\kappa(z)$ is the dark matter over-density in galactic halo with respect to its mean density at redshift z.

DM of X-particles and LLS formation.

Light X's. Prior to recombination $\tau_{Xe} < t_U$ and X's are frozen in $e\gamma$-liquid. After recombination and till reionization they behave as usual WDM. After reionization τ_{Xe} again becomes smaller than the cosmological time and thus the rotating ordinary matter in a protogalaxy would transfer a part of angular momentum to X-particles and involve it in its turbulent motion.

Estimate of field generated by light X.

We use the obtained above equations but integrate till reionization, $z = 6$ and thus $t_u = 1$ Gyr, $R = 100$ kpc and $\kappa = 100$, $v_{rot} = 10$ km/sec and impose the limit $\Omega_x h^2 = 0.007$ to find:

$$B = \frac{\epsilon_5^2}{m_{keV}^2} \cdot 10^{-11}\, G.$$

B can rise by factor 100, becoming 10^{-9} G, when the protogalaxy shrinks from 100 kpc to 10 kpc, by far larger then the minimal necessary strength of the seed.

Heavier X: $m_X > m_e$, so larger charge is allowed, $\epsilon > 10^{-4}$. X-particles can make all dark matter. After reionization, electron scatterings would not force X-particles into galaxy rotation and thus the effective integration time can be larger and magnetic fields as large as 10^{-9} G can be generated.

Concluson.

Existence of millicharged particles with mass in keV - MeV range allows to:

1. Explain the origin of galactic and intergalactic magnetic fields.
2. Introduce DM with time dependent interaction with normal matter.
3. To be tested in direct experiment.
4. To solve or smooth down problems of galactic satellites, angular momentum, and cusps in galactic centres.

THE END

Problems with CDM.

1. Missing satellites: CDM predicts an order of magnitude more galactic satellites than observed.

2. Destruction of galactic disk: Even if the number of the satellites is reduced by star formation winds, many smaller tightly bound DM systems would survive and destroy galactic disk by gravitational heating.

3. Central cusps: expected singularity in galactic centers, $\rho_{DM} \sim r^{-\kappa}$, $\kappa = 1 - 2$, while flat profiles are observed.

4. Excessive angular momentum: CDM predicts much smaller galactic angular momentum than observed. In "millicharged" scenario, electrons loose much more of their momentum than baryons.

Dynamical friction

$$\frac{d}{dt}\vec{v}_{BH} \approx -4\pi\, G_N^2\, M_{BH}\, \rho_b \frac{\vec{v}_{BH}}{v_{BH}^3} F(X)$$

where $X \equiv v_{BH}/(\sqrt{2}\sigma)$, ρ_b is the density of the background particles, σ^2 is the their mean square and

$$F(v_{BH}) = \mathrm{erf}(X) - \frac{2X\,\exp(-X^2)}{\sqrt{\pi}}$$

tends to unity for $v_{BH} \gg \sigma$ and tends to $v_{BH}^3/(2\sqrt{2\pi}\sigma^3)$ for $v_{BH} \ll \sigma$.