Letter

Dark matter and generation of galactic magnetic fields

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Abstract A new scenario for creation of galactic magnetic fields is proposed which is operative at the cosmological epoch of the galaxy formation, and which relies on unconventional properties of dark matter. Namely, it requires existence of feeble but long range interaction between the dark matter particles and electrons. In particular, millicharged dark matter particles or mirror particles with the photon kinetic mixing to the usual photon can be considered. We show that in rotating protogalaxies circular electric currents can be generated by the interactions of free electrons with dark matter particles in the halo, while the impact of such interactions on galactic protons is considerably weaker. The induced currents may be strong enough to create the observed magnetic fields on the galaxy scales with the help of moderate dynamo amplification. In addition, the angular momentum transfer from the rotating gas to dark matter component could change the dark matter profile and formation of cusps at galactic centers would be inhibited. The global motion of the ionized gas could produce sufficiently large magnetic fields also in filaments and galaxy clusters.

The origin of large-scale magnetic fields remains one of very deep cosmological mysteries. Magnetic fields are detected in galaxies of all types and they constitute a very important component of the galactic dynamics since they are relevant for compression of the gas clouds, influence star formation process, and determine the spectrum of the galactic cosmic rays. The Milky Way, for example, possesses the magnetic field of a few μG over the plane of its disc, with a coherence length of a few kpc. Similar magnetic fields have been detected in other disc galaxies and also in high redshift protogalactic structures. However, cosmic magnetism is not related only to galaxies: observations point to the presence of magnetic fields in galaxy clusters, though with weaker strength but on much larger scales. A detailed description of the observational data can be found e.g. in reviews [1–4].

It is widely accepted that the magnetic fields observed in disk galaxies are enhanced by galactic dynamo due to combined effect of differential rotation and helical turbulence. However, this paradigm in itself is incomplete since per sè dynamo mechanism principally cannot explain the origin of the initial magnetic fields acting as seeds. It can only amplify the magnetic field if its initial value was non-zero (for reviews, see Refs. [5–7]). No compelling mechanism for formation of large-scale seed fields has been found yet. Usually the problem is that the strength of the seed fields is too weak and their coherence length is too short, so huge galactic dynamo is necessary for amplifying it up to observed values. The task of creation of intergalactic magnetic fields is much more severe. The problem is that the dynamo mechanism is not efficient on intergalactic scales.

In a wide range of models the seed magnetic fields are generated in the very early universe, at different cosmological epochs ranging from inflation to big bang nucleosynthesis (for reviews, see e.g. Refs. [8–13]). The considered mechanisms are based, generically, on a new physics outside of the standard cosmological and particle physics frameworks. Some of these mechanisms could provide strong enough seeds to be dynamo-amplified up to the observed galactic fields, but their coherence length is by far smaller than the typical galactic scale. Chaotic field line reconnection could stretch up the coherence length but at the expense of a strong decrease of the magnitude.

Magnetic seeds can be generated also at later cosmological stages, from the recombination epoch to the period of

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star formation. The suggested mechanisms rely on the conventional astrophysics and cosmology and might give rise to reasonably strong magnetic seeds with large coherence scales. They employ the Biermann battery effect [14] or the turbulence generated at the radiation decoupling era and difference between the drag forces exerted on electrons and protons by the cosmic microwave background (CMB) radiation [15–18]. Non-zero vorticities induced at the recombination and radiation decoupling epoch by the photon diffusion in second order in the temperature/density fluctuations [17, 18] may generate the seeds of future galactic magnetic fields $\sim 10^{-20}$ G which in principle could be amplified by galactic dynamo up to the observed magnitude $\sim 10^{-6}$ G.

Dynamo mechanism can lead to an exponential increase of the galactic magnetic fields till they reach the saturation value, B_{eq}, of about a few μG. Saturation takes place when equipartition between the magnetic and turbulent energy densities is achieved, i.e. $\rho_B = B^2/8\pi$ becomes equal to $\sim \rho v^2$, where ρ is the typical matter density of the protogalaxy and v is the turbulent velocity in the system. After this moment the further growth of magnetic fields is halted by the dynamical back reaction of magnetic stress on the turbulence. Curiously, the energy density of magnetic field $\rho_B = B^2/8\pi$ is equal to the CMB density $\rho_{CMB} = 2 \times 10^{-51}$ GeV^4 when $B = 3$ μG.

In order to reach the saturation value during cosmological time t, the seed fields at the time of the galaxy formation t_{gal} must be big enough, $B_{seed} > B_{eq} \exp[-(t - t_{gal})/\tau_{dyn}]$, where $\tau_{dyn} \sim 0.2-0.5$ Gyr is a typical e-folding time in the dynamo regime. Its precise value strongly depends on the characteristics of the turbulent plasma in the protogalaxy as well as on the angular velocity profile, but the above estimate seems to be reasonable. Hence, for the Universe age $t \simeq 14$ Gyr, the galactic dynamo could amplify magnetic fields up to $B_{eq} \sim 10^{-6}$ G starting from $B_{seed} \sim 10^{-20}$ G or even less. Nevertheless, the situation cannot be considered satisfactory. There is a mounting evidence that magnetic fields in and around normal galaxies were already of the order of μG in galaxies at large cosmological redshifts $z \sim 1-2$, which are too young for an efficient galactic dynamo, since at this time the Universe was only about one-third of its present age [19, 20]. This observation significantly reduces the number of available e-foldings and thus requires much stronger magnetic seeds. E.g. for a galaxy formed at $z = 6$ or $t_{gal} = 1$ Gyr, in order to reach $B_{eq} \sim 10^{-6}$ G at the cosmological time $t \approx 4.4$ Gyr (corresponding to redshift $z = 1.5$), the seed fields at least of the order of 10^{-15} G are required even if the e-folding time is taken as $\tau_{dyn} = 0.2$ Gyr.

In addition, all disk galaxies, whenever appropriate observations are available, show that the regular (mean) component of the magnetic fields is nearly the same as the random (RMS) component which indicates that the coherence

length of the seeds should be comparable to the galaxy scale [5–7]. Summarizing these observations, it seems difficult to avoid the conclusion that the magnetic seeds at epoch of galaxy formation must be rather large, $B_{seed} > 10^{-15}$ G, with the coherence scale at least of the order of 1 kpc.

Note also that the radio observations of magnetic fields in the edge-on spiral galaxies suggest that mostly the dominant component of the magnetic field is parallel to the disk plane [21]. However, for some galaxies magnetic fields have strong vertical components extending far away from the disk plane [22], which may indicate that the dynamo had worked for a relatively short time and large poloidal component of the magnetic field was maintained.

In this paper we propose a new mechanism which leads to generation of rather strong magnetic seeds during the process of the galaxy formation. This mechanism has interesting implications for the nature of dark matter. In a sense this mechanism is a generalization of our previous work [17] to the epoch when galaxies or protogalaxies were already created and the vorticity perturbations evolved up to significantly high values. At this stage circular electric currents could be generated in rotating protogalaxies due to different drag forces exerted on protons and electrons by the CMB radiation. However, the seed magnetic fields generated in this way are uncomfortably low even for galaxies, to say nothing of the galactic clusters. The situation can be significantly improved if there exist relatively light dark matter particles which have some feeble but long range interaction with electrons. In this case, the friction force, produced by the dark matter particle interactions with the electron–proton plasma in the galactic halo, which is directed opposite to the galaxy rotation, causes a drag of electrons relative to ions, while the latter, along with the neutral atoms and molecules, rotate as a whole galaxy. Hence a circular electric current would be induced. This is an essence of our proposal. In the most optimistic case even the intergalactic magnetic fields of the proper strength can be generated with a moderate dynamo application. Thus, if such particles exist, the long standing problem of generation of galactic and intergalactic magnetic fields can be settled down.

As we know, galaxies start to form at cosmological redshift $z \sim 10$ or so, which corresponds to the cosmological time $t_z \simeq (2/3)H_0^{-1}[\Omega_m(1 + z)^3]^{-1/2} \sim 0.5$ Gyr, though most of the large galaxies are formed at much lower redshifts. The high density regions where primordial fluctuations have grown sufficiently large, start to collapse once their self-gravity begins to dominate over the cosmological expansion. The thermal bremsstrahlung cooling and dissipative contraction, recombination, fragmentation in molecular hydrogen clouds, and finally star production lead to creation of galaxies. Tidal torques acting between density fluctuations lead to galaxy rotation. On the other hand, observations show that the universe was reionized around the

same epoch, in the redshift interval $z \sim 10-6$, presumably by the ultraviolet emission from the first generation of massive stars and/or quasars.

For a simple order of magnitude estimate let us consider a protogalaxy as a cloud of partially ionized matter which rotates in the isotropic sea of the CMB photons with temperature $T = (1 + z)T_0$, where $T_0 = 2.73$ K. Let us denote the fraction of the ionized matter as ξ, so the number density of free electrons (ions) is $n_e = \xi n_B$, where n_B is the number density of baryons in the cloud. For simplicity, we assume that all ions are protons, neglecting contribution of helium. Apart from the regular rotational velocity v_{rot}, electrons and protons have chaotic thermal velocities, $v_{e,p} \sim (T_{e,p}/m_{e,p})^{1/2}$. Usually one takes $T_p = T_e$.

The CMB photons interact with electrons with the Thomson cross section $\sigma_{e\gamma} = 8\pi\alpha^2/3m_e^2 = 6.65 \times 10^{-25}$ cm^2, where m_e is the electron mass and $\alpha = e^2 = 1/137$ (we use the CGS system of units). Thus, the regular part of the drag force induced by the CMB on the electron in plasma with a local flow velocity $\boldsymbol{v}$ is

$$\boldsymbol{F} = e\boldsymbol{v}B_F \tag{1}$$

where factor B_F can be estimated as

$$\begin{aligned} B_F &= \sigma_{e\gamma}n_\gamma\omega_\gamma/e = 3.4 \times 10^{-30}(1+z)^4 \text{ eV}^2/e \\ &= 5.8 \times 10^{-28}(1+z)^4 \text{ G}. \end{aligned} \tag{2}$$

Here n_γ and ω_γ are, respectively, the number density of the CMB photons and their mean energy at the cosmological epoch corresponding to redshift z. The CMB pressure on protons is completely negligible since the respective cross section is smaller than $\sigma_{e\gamma}$ by the factor $(m_p/m_e)^2$. Therefore, in the rotating protogalaxy the friction force created by the CMB pressure causes a relative drag of electrons in the direction opposite to the galaxy rotation, while the ions rotate as a whole galaxy. Hence, circular currents must be induced, remarkably without charge displacement and local violation of the electric neutrality.

An important parameter governing the magnitude of this current is the electric conductivity, which in turn is determined by the Coulomb scattering among the electrons and ions (protons). Namely, the CMB pressure induces coherent (de)acceleration of electrons with respect to protons but the coherence is destroyed by their chaotic collisions due to their thermal motion. The characteristic collision time, τ_{ep}, due to the Coulomb scattering between e and p can be estimated as

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

where $L_e \sim 10$ is the electron Coulomb logarithm. In the above equation, we have taken the line-of-sight thermal av-

erage as $\langle v_e^2 \rangle = T_e/m_e$. Therefore, for the electric conductivity of the plasma we have

$$\sigma = \frac{e^2 n_e \tau_{ep}}{2m_e} \simeq \frac{T_e^{3/2}/m_e^{1/2}}{8\pi\alpha L_e} \sim 10^{12} \text{ s}^{-1} \left(\frac{T_e}{10^4 \text{ K}}\right)^{3/2} \tag{4}$$

Note that it does not depend on the density of charge carriers, n_e, i.e. on the ionization degree ξ, unless the latter is so small that the resistance is dominated by neutral atoms.

Due to the radiation drag force (1) electrons slow down with respect to ions, while the latter keeps on rotating with velocity v_{rot} practically non-attenuated. For the difference between the mean rotational velocities of ions and electrons we find $\Delta v_e = \tau_{ep}F/2m_e \ll v_{rot}$ which induces circular electric currents with density $j = en_e\Delta v_e = \sigma F/e = \sigma v_{rot}B_F$. One could naively estimate the magnetic field generated by the CMB induced current in a rotating galaxy via the Biot–Savart law as $B \sim 4\pi j R = \mathcal{R}_M B_F$, where R is the galaxy radius and $\mathcal{R}_M \equiv 4\pi\sigma v_{rot}R$, i.e.

$$\mathcal{R}_M \simeq \frac{4 \times 10^{22}}{L_e} \left(\frac{R v_{rot}}{10^3 \text{ kpc·km/s}}\right)\left(\frac{T_e}{10^4 \text{ K}}\right)^{3/2}. \tag{5}$$

For a typical galaxy with $R \sim 10$ kpc and rotational velocity $v_{rot} \sim 100$ km/s this would result in quite large magnetic field. In view of Eqs. (2) and (5), the magnitude of $B \sim \mathcal{R}_M B_F$ can reach 1 μG, which is practically the observed value of magnetic fields in galaxies.

However, the Biot–Savart law is valid only when the stationary regime is reached, while the system under scrutiny is far from that. The time to reach the stationary situation is much longer than the cosmological time. To see that let us consider the Maxwell equations in the cosmological plasma and modification of the MHD equations in presence of extra non-potential forces related to a dark matter interaction with electrons. Namely, let us consider the electric current $\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{F}/e)$, where $\boldsymbol{F}$ is the external force acting on electrons, see Eq. (1). In our case it is the drag force induced by the interaction with the CMB (or with dark matter halo, see below). Finding electric field $\boldsymbol{E}$ from this equation and substituting it into equation $\partial_t \boldsymbol{B} = -\nabla \times \boldsymbol{E}$, we obtain $\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{F}/e - \boldsymbol{J}/\sigma)$. Substituting the above expression for $\boldsymbol{J}$ and using $\nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B}$ and $\nabla \cdot \boldsymbol{B} = 0$, we come to

$$\partial_t \boldsymbol{B} = \nabla \times \boldsymbol{F}/e + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{1}{4\pi\sigma}\left(\Delta\boldsymbol{B} + \partial_t^2\boldsymbol{B}\right), \tag{6}$$

which is in fact the MHD equation in the presence of external source term $\nabla \times \boldsymbol{F}/e = B_F\nabla \times \boldsymbol{v} + (\nabla B_F) \times \boldsymbol{v}$. In the limit of high conductivity, the second term in the MHD equation, the so called advection term, leads to a dynamo effect on the magnetic seed fields once the value of the latter is non-zero. It is well-known, however, that in absence of the source term, the MHD equations cannot give rise to non-zero magnetic field if $\boldsymbol{B} = 0$ initially.

In our case, assuming $\boldsymbol{B} = 0$ at $t = 0$, we find that the source term (2) induces a non-zero magnetic seed field which initially grows roughly as

$$\boldsymbol{B}(t) = \int_0^t dt \, \boldsymbol{\nabla} \times \boldsymbol{F}/e = \int_0^t dt \, \boldsymbol{\nabla} \times (B_F \boldsymbol{v}). \tag{7}$$

However, taking into account that $B_F(t) \propto (1+z)^4 \propto t^{-8/3}$, see Eq. (2), we find that the biggest value for the magnetic seeds can be obtained around the cosmological epoch of hydrogen recombination and photon decoupling, $z \sim 1000$, or $t \sim 5 \times 10^5$ yr. At earlier times, the plasma is strongly coupled and the relative motion of the electrons with respect to protons is negligible, hence the lower limit of the integration is irrelevant. The mean value of vorticity at the characteristic spatial scale λ is $\Omega_\lambda = |\boldsymbol{\nabla} \times \boldsymbol{v}|_\lambda \le 10^3 (\delta T/T)^2/\lambda$, as calculated in Ref. [17]. Then one can estimate of a seed field generated at this epoch, say with the coherence length λ of few kpc which corresponds to the present day comoving scale of a typical galaxy ~ 1 Mpc, as $B_\lambda \sim \Omega_\lambda t_{\rm rec} B_F(t_{\rm rec}) \le 10^{-20}$ G, in agreement with the results of Refs. [17, 18]. However, as was emphasized earlier, such magnitude of the seeds is still too small. The seed fields with the coherence length ~ 1 kpc and $B_{\rm seed} > 10^{-15}$ G are needed to conform to observations of coherent magnetic fields $\sim$ μG at high redshift galaxies [19, 20].

In what follows we consider the formation of galactic magnetic fields by some hypothetical dark matter particles, X, forming extended halos around the galaxies. We note that drag force exerted on electrons by X particles is given again by Eq. (1) but with B_F proportional to their number density in the halo, to their average momentum, and of to the cross section of their elastic scattering on electrons. Therefore, to produce sufficient pressure on electrons, larger than that of CMB, the latter cross section must be large enough at low momentum transfer. This is feasible if these X particles have long range interaction with normal matter. As a natural example, we consider millicharged particles in the mass range from several keV to several GeV.

Millicharged particles, which can be either bosons or fermions, have tiny electric charges $e' = \varepsilon e$, where e is the electron charge and $\varepsilon \ll 1$, which are bounded by direct laboratory limits as well as by cosmological and astrophysical observations. These bounds strongly depend on the masses of X-particles. If X-particles are lighter than electron, $m_X < m_e$, a strong laboratory limit comes from the bounds on the invisible decay of ortho-positronium into $X\bar{X}$, according to which $e' < 3.4 \cdot 10^{-5} e$ [23]. For $m_X < 1$ keV, a stronger bound, $e' < 10^{-5} e$ was obtained in Ref. [24] but we shall not consider so small masses here. For $m_X > m_e$ the direct bounds were obtained in Ref. [25]. For $m_X = 1$ MeV these bounds give $e'/e < 4.1 \times 10^{-5}$ while for larger masses they become weaker, as e.g. $e'/e < 5.8 \times 10^{-4}$ for $m_X = 100$ MeV. For X-particles heavier than 100 MeV,

even $e' \sim 10^{-2} e$ is allowed whereas for $m_X > 1$ GeV, e' can be as large as $e/10$. More bounds on the mass/coupling of millicharged particles, derived from astrophysics and cosmology can be found in Refs. [26–28]. In the following we assume that $m_X > 10$ keV, in order to avoid strong limits on e' from stellar evolution.

The presence of light millicharged particles, with $m_X < 1$ MeV or so, during the epoch of big bang nucleosynthesis (BBN) influences standard cosmological picture in several respects. In particular, the expansion rate of the Universe and baryon-to-photon ratio can be significantly altered during BBN and this may be dangerous [27, 28]. The impact of such particles on BBN is discussed in our paper [38], with the conclusion that the model is not ruled out especially if the lepton asymmetry is non-zero.

For a simple consistent model for the millicharged X particles, one may consider a hidden gauge sector of particles, which, among other possible gauge factors, contains $U(1)$ gauge group and respective 'photon' field A'_μ interacting with X particles. This paraphoton A'_μ may have a kinetic mixing, $(\varepsilon/2) F'_{\mu\nu} F^{\mu\nu}$, to ordinary photon A_μ [29]. The prototype model is given e.g. by asymmetric mirror world, a shadow sector of the particles having strong and electroweak interactions similar to the ordinary particles, but with the electroweak and QCD scales v'_W and Λ' being different from the ordinary ones [30–33]. Lightest stable particles of this sector are e' and p' with opposite electric-like charges of a shadow $U(1)'$ gauge group. They resemble our electron and proton and their stability is guaranteed by conservation of respective 'baryon' number. Thus, such parallel matter would be dark matter for us. Kinetic mixing of shadow and ordinary $U(1)$ gauge factors makes shadow electron e' and proton p' to be millicharged (with electric charges $\sim \varepsilon$) with respect to our photon and gives rise to effective long range interactions between the ordinary and dark particles.[1] Kinetic mixing parameter ε can be considered as a (field-dependent) dynamical degree of freedom, with interesting implications for the time variability of the fine structure constant α [37].

For additional simplification, we can assume that the direct product $U(1) \times U(1)'$ of two gauge factors is spontaneously broken down to some diagonal $U(1)_{\rm em}$ representing the true massless photon eigenstate γ while another mass eigenstate γ' becomes heavy. This true photon may predominantly interact with ordinary particles with the coupling

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[1] Mirror world with microphysics exactly identical to the Standard Model also provides a viable dark matter (see a review [34, 35] and references therein). However, in this case the positronium oscillation limit on the photon–mirror photon kinetic mixing is very strong, $\varepsilon < 4 \times 10^{-7}$ [23] and there are cosmological limits two orders of magnitude more restrictive [36]. In the case of asymmetric mirror sector [30–33], with $m'_e > m_e$, the positronium limits are irrelevant, and the cosmological limits are also more flexible [36].

constant e, but it would see shadow particles as having electric charges $e' = \varepsilon e$. Clearly, such a theory has no anomalies. Another possibility is to leave the shadow photon massless as well, directly in spirit of Ref. [29].

These two cases have different cosmological implications. Namely, if X particles emerge from a shadow world with massless γ', then $X\bar{X} \to \gamma'\gamma'$ annihilation must be essential and the frozen cosmological number density of X-particles (i.e. mirror 'electrons' e') most probably would be determined by their charge asymmetry [30–35] as is a natural case of asymmetric dark matter. Such particles could recombine with their counterparts of the opposite sign of their mirror electric charge (mirror 'protons' p'), so after their recombination the density of charged mirror particles may be rather small. Rich spectrum of other possibilities will be considered elsewhere.

In the subsequent estimates we assume that γ' is heavy and hence X-particles have no relevant self-interactions, except for only feeble interactions with the normal matter induced by their millicharges with respect to our photon γ. In this case they practically do not recombine because their binding energy is tiny and the Bohr radius is huge.

The processes like $e^+e^- \to X\bar{X}$ induced via the photon kinetic mixing bring X particles into equilibrium with ordinary matter below temperatures $T \sim \varepsilon^2\alpha^2 M_{Pl}$. Then, once they were thermally produced in the early universe, their present abundance is given by the expression [39, 40]:

$$\Omega_X h^2 \approx 0.023 x_f g_{*f}^{-1/2} \left(\frac{v\sigma_{\mathrm{ann}}}{1\,\mathrm{pb}}\right)^{-1}, \tag{8}$$

where σ_{ann} is the $X\bar{X}$ annihilation cross section, and $x_f \equiv m_X/T_f = 10 + \ln(g_X/g_{*f}) + \ln m_{\mathrm{MeV}} + 0.5\ln x_f$ is the X-particle mass ratio to the annihilation freezing temperature, with g_X being the number of the degrees of freedom of X-particle, g_{*f} being the effective number of degrees of freedom of all particles in the plasma at T_f, and $m_{\mathrm{MeV}} = m_X/\mathrm{MeV}$. Typically $x_f \sim 10$; it varies between $5-20$ for X-particle masses in keV–GeV range.

Let us first consider the case when X-particles are lighter than electrons, $m_X < m_e$. Then they can annihilate only into photons, with the cross section

$$v\sigma(X\bar{X} \to 2\gamma) = \frac{\pi\alpha'^2}{m_X^2} = \frac{\varepsilon_5^4}{m_{\mathrm{keV}}^2} \times 6.5 \times 10^{-4}\,\mathrm{pb}, \tag{9}$$

where $m_{\mathrm{keV}} = m_X/\mathrm{keV}$, $\alpha' = e'^2/4\pi = \varepsilon^2\alpha$ and $\varepsilon_5 = 10^5\varepsilon$. Therefore, for X particles in the mass range of several keV, their cosmological energy density would be

$$\Omega_X h^2 \approx 150 \times \left(\frac{m_{\mathrm{keV}}}{\varepsilon_5^2}\right)^2. \tag{10}$$

Therefore, for $m_X > 10$ keV the dark matter density would be overproduced unless $\varepsilon_5 > 20$ or so, which contradicts

to the positronium bound $\varepsilon_5 < 3.4$ [23].[2] However, one can envisage an additional annihilation channel into some lighter species of dark sector (e.g. into mirror neutrinos $\nu'\bar{\nu}'$ [30–33]) which could diminish $\Omega_X h^2$ down to acceptable values. On the other hand, bounds imposed by the CMB anisotropies do not allow light X-particles to constitute the dominant part of dark matter, and they may provide only its rather small fraction, with a conservative bound $\Omega_X h^2 < 0.007$ [41]. Hence, the presence of some other form of dark matter is also needed. In what follows, we take the fraction Ω_X with respect to the total mass density of dark matter as a free parameter.

The origin of the above bound is the following. The collision time of X-particles with respect to eX-scattering in the primeval plasma is given by Eq. (3), where one has to substitute $m_X < m_e$ instead of m_e, $v_X > v_e$ instead of v_e, and $\alpha\alpha'$ instead of α^2:

$$\tau_{eX} = \frac{m_X^2 v_X^3}{4\pi\alpha\alpha' n_e L}. \tag{11}$$

The number density of free electrons is $n_e = \xi n_B = 2.5 \times 10^{-7}\xi(z)(1+z)^3$ cm^{-3}, where $\xi(z)$ is the ionization degree at redshift z and $\eta = n_B/n_\gamma = 6 \times 10^{-10}$ is the baryon-to-photon ratio. Just before the hydrogen recombination, $T > 0.2$ eV or $z > 1100$, when $\xi = 1$, the chaotic velocity of X-particles is $v_X \sim (T/m_X)^{1/2}$, and the Xe-collision time, $\tau_{eX} \simeq 1.6 \times 10^9\,(m_{\mathrm{keV}}^{1/2}/\varepsilon_5^2)(1100/z)^{3/2}$ s, is shorter than the cosmological time, $t = 2H^{-1}/3 = 1.6 \times 10^{13}(1100/z)^{3/2}$ s, unless parameter ε is very small ($\tau_{eX}/t \simeq (10^{-4}/\xi)(m_{\mathrm{keV}}^{1/2}/\varepsilon_5^2) < 1$).

So, prior to recombination X-particles are strongly coupled to electrons and through them to photons, and thus cannot participate in the structure formation. After recombination, when ξ drops down to 10^{-3}, the collision time rises up and becomes bigger than the cosmological time, so X-particles decouple from the usual matter and do not follow the bulk motion of the baryon matter. At this stage X-particles behave as a warm dark matter component and participate in the large-scale structure formation along with the rest of dark matter. The bound $\Omega_X h^2 < 0.007$ was obtained in Ref. [41] on the basis of the early WMAP results. Today, in light of high precision data acquired by the Planck Collaboration, this bound should become more stringent and deserves an independent study.

Let us return to the question of magnetic field generation in the process of galaxy formation and consider a partially ionized baryon cloud of typical galactic mass $M \sim 10^{11}\,M_\odot$. At e.g. $z \sim 6$ such an object, undergoing

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[2] One can assume, however, that ε is changing with time. In particular, its initial value can be larger than 2×10^{-4} in early epochs, effective for annihilation of X-particles, while it drops below the positronium limit today [37].

contraction due to thermal cooling, would have radial size $R \sim 100$ kpc, the baryon overdensity $\kappa_B \sim 10^2$, and temperature $T_e \sim 10^3$ K, hence $v_e = (T_e/m_e)^{1/2} \sim 10^{-3}c$. As for X-particles, they would be distributed in halo as a dark matter component, with typical virial velocity v_X.

The drag force exerted by X-particles on electrons is given again by Eq. (1), but with factor B_F proportional to the number density of X-particles, to their momentum, and to their elastic scattering cross section on electrons:

$$B_F = \sigma_{eX} n_X m_X v_{\text{rel}}/e \qquad (12)$$

with v_{rel} being the relative velocity between the electrons and X particles. Namely, $v_{\text{rel}} \simeq v_X$, if $v_X > v_e$. In the opposite case one has to substitute v_X by v_e. We have

$$v_{\text{rel}}\sigma_{eX} = \frac{4\pi\alpha\alpha' L}{m_X^2 v_{\text{rel}}^3} \simeq \frac{2 \times 10^{-8} \varepsilon_5^2}{m_{\text{keV}}^2 v_{100}^3} \text{ eV}^{-2}, \qquad (13)$$

where $L \sim 10$ is the corresponding Coulomb logarithm and $v_{100} = (v_{\text{rel}}/100 \text{ km/s})$. The mass density of X-particles is equal to

$$m_X n_X \approx \Omega_X h^2 (1+z)^3 \kappa \times 10^{-10} \text{ eV}^4, \qquad (14)$$

where $\kappa(z)$ is the dark matter overdensity in the galactic halo with respect to its mean cosmological density at redshift z. Thus, we obtain

$$B_F \simeq \frac{\varepsilon_5^2}{m_{\text{keV}}^2} \frac{\Omega_X h^2 \kappa (1+z)^3}{v_{100}^3} \times 4 \times 10^{-16} \text{ G} \qquad (15)$$

(cf. Eq. (2)). Let us note again that B_F practically does not depend on the ionization degree of matter unless it becomes so small that the resistance is dominated by neutral particles. So, this estimate is valid for the post-recombination residual ionization degree $\xi \sim 10^{-3}$.

Now, before evaluating the strength of the magnetic field generated by dark matter in the galactic halos, let us discuss the following. In the case of the current generated by the CMB photons we have taken into consideration that the (proto)galactic matter rotates, while the CMB photons do not. It should be verified if the same assumption is valid for X-particles. The collision time of X-particles with electrons and protons, given by Eq. (11), at the galaxy formation epoch reads

$$\tau_{eX} \approx \frac{m_{\text{keV}}^2 v_{100}^3}{\varepsilon_5^2 \kappa_B \xi (1+z)^3} \times 2 \times 10^{14} \text{ s} \qquad (16)$$

Therefore, taking $m_X \sim 10$ keV and $\varepsilon \sim 10^{-5}$, we see that for the galaxy forming at redshift $z \simeq 6$ (i.e. $t \simeq 1$ Gyr), with $\kappa_B \sim 10^2$ for the baryon overdensity, we get $\tau_{eX} \geq t$, if $\xi \leq 10^{-2}$. Therefore, at this epoch the bulk motion of X component could be again independent from that of the normal matter. For later epochs, with further increasing κ_B and

ξ, we have $\tau_{eX} < t$, so the X particles would be dragged by the rotation of the normal matter.[3]

Now we can estimate the magnitude of the magnetic field generated via the X-particle pressure on the electrons in the process of galaxy formation. For the collapsing protogalaxy, where B_F is not decreasing in time, the integral (7) is saturated on the upper limit, therefore the integration time can be formally as large as the age of the Universe. However, the Universe was completely reionized at $z \sim 6$ and this would diminish relative velocities among normal matter and X particles because of their mutual interactions (cf. (16)). Thus, to avoid the discussion of the corresponding subtleties let us integrate up to redshift $z = 6$, when the cosmological age was about 1 Gyr. Therefore, integrating Eq. (7) with B_F given by (15) up to $t = 1$ Gyr, taking $R \sim 100$ kpc, $\kappa \sim 10^2$, $v_{100} \sim 1$, and the rotational velocity $v_{\text{rot}} \sim 10$ km/s and taking into account the limit $\Omega_X h^2 < 0.007$, one can estimate the value of the galactic magnetic seed at $t = 1$ Gyr as

$$B \sim B_F v_{\text{rot}} \frac{t}{R} \sim \frac{\varepsilon_5^2}{m_{\text{keV}}^2} \times 10^{-14} \text{ G}. \qquad (17)$$

Thus, taking $m_X = 10$ keV and $\varepsilon_5 = 3$, one can achieve $B \sim 10^{-15}$ G. In addition, accounting for the adiabatic rise of magnetic field by a factor of 100 when the protogalaxy shrinks from the original 100 kpc down to contemporary galactic size 10 kpc, can finally get a galactic magnetic seed $\sim 10^{-13}$ G without great difficulties. This estimate exceeds the minimal necessary value for the galactic magnetic seeds by several orders of magnitude.[4]

The situation is quite different when X particles are heavier than electrons. If $m_X > m_e$, the dominant annihilation channel becomes $X\bar{X} \to e^+ e^-$, with cross section

$$v\sigma\left(X\bar{X} \to e^+ e^-\right) = \frac{\pi\alpha\alpha'}{m_X^2} = \frac{\varepsilon_5^2}{m_{\text{MeV}}^2} \times 6.5 \text{ pb.} \qquad (18)$$

Hence, assuming no coannihilations, cosmological abundance of X-particles reads

$$\Omega_X h^2 = 0.012 \times \left(\frac{m_{\text{MeV}}}{\varepsilon_5}\right)^2. \qquad (19)$$

Namely, one can obtain $\Omega_X h^2 \simeq 0.12$ e.g. taking $m_X \simeq 10$ MeV and $\varepsilon \simeq 3 \times 10^{-5}$, or $m_X \simeq 1$ GeV and $\varepsilon \simeq 3 \times 10^{-3}$,

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[3]Presumably, gradual reionization of the Universe started at $z \simeq 10$ whereas at $z < 6$ it was already completely ionized. Notice that for $m_X \sim 100$ keV, we get $\tau_{eX} \geq 1$ Gyr even if $\xi = 1$.

[4]Let us remark that in our scenario the definition of the seed field is somewhat ambiguous as far as the dynamo mechanism, related to the advection term in Eq. (6) is also at work. Magnetic Reynolds number $\mathcal{R}_M = 4\pi\sigma v\lambda$ is much larger than 1. Therefore, once the source term generates non-zero magnetic fields oriented towards local voriticities, this term becomes relevant whereas the diffusion term (the last term in Eq. (6)) can be ignored. Notice that $\nabla \times (v \times B)$ becomes comparable to the source term $\nabla \times (B_F v)$ when $B \sim B_F$.

in agreement with the experimental bounds of Ref. [25].[5] In the case when $m_X \gg m_e$, dark matter of the universe could consist entirely of X-particles since the CMB bounds of Ref. [41] are not applicable. Nevertheless, we still keep $\Omega_X h^2$ as a free parameter, assuming that there might exist other components of dark matter. In view of Eq. (19), to avoid overproducing of dark matter, we must require that $\varepsilon_5/m_{\mathrm{MeV}} > 0.3$ or so. However, if there are some additional annihilation channels, this constraint can be also circumvented. In any case, in the process of the galaxy formation the density distribution of X particles should have the typical profile of halo formed by dark matter.

Now, once $m_X > m_e$ one must substitute m_e instead of m_X in Eq. (13):

$$v_{\mathrm{rel}}\sigma_{eX} = \frac{4\pi\alpha\alpha' L}{m_e^2 v_{\mathrm{rel}}^3} \simeq \frac{\varepsilon_5^2}{v_{100}^3} \times 10^{-13} \text{ eV}^{-2} \qquad (20)$$

and the drag factor B_F (12) now becomes

$$B_F \simeq \frac{\varepsilon_5^2}{m_{\mathrm{MeV}}} \frac{\Omega_X h^2 \kappa(1+z)^3}{v_{100}^3} \times 10^{-21} \text{ G}. \qquad (21)$$

Taking into account Eq. (19), this can be rewritten as[6]

$$B_F \simeq m_{\mathrm{MeV}} \frac{\kappa(1+z)^3}{v_{100}^3} \times 10^{-23} \text{ G}. \qquad (22)$$

Now, X-particles, being heavy enough, can saturate the total dark matter density of the Universe, i.e. $\Omega_X h^2 \approx 0.12$ is allowed, which according to (19) yields $(\varepsilon_5/m_{\mathrm{MeV}})^2 \simeq 0.1$. In addition, in this case, electron motion would not be involved into the galaxy rotation after reionization, and thus the effective integration time in Eq. (7) can be taken larger than 1 Gyr when the Universe was completely reionized. Namely, integrating up to $t \simeq 2$ Gyr, assuming that for this time the shape of galaxy was already practically settled to its present form, with say $R \simeq 10$ kpc, $v_{\mathrm{rot}} \simeq 100$ km/s and overdensity $\kappa \sim 10^5$, one can achieve for the galactic seed fields

$$B \sim B_F v_{\mathrm{rot}} \frac{t}{R} \sim m_{\mathrm{MeV}} \times 10^{-15} \text{ G}. \qquad (23)$$

Therefore, for $m_X \simeq 1$ MeV, one can obtain the galactic seed field $\sim 10^{-15}$ G in a natural way, whereas for $m_X \simeq 1$ GeV, the seed magnitude can be as large as 10^{-12} G. Larger masses require larger values of ε, with interesting implications for the experimental search of millicharged particles as well as for low threshold experiments on direct search of dark matter.

The following features are also worth mentioning. During evolution of the protogalaxy the scattering of electrons and protons on X-particles can become strong. In particular, after reionization of the Universe ($\xi = 1$) the collision time of X particles with protons

$$\begin{aligned} \tau_{pX} &\approx \frac{m_{\mathrm{MeV}}^2 v_{100}^3}{\varepsilon_5^2 \kappa_B \xi (1+z)^3} \times 2 \times 10^{20} \text{ s} \\ &\approx \frac{\Omega_X h^2}{0.12} \frac{v_{100}^3}{\kappa_B(1+z)^3} \times 2 \times 10^{21} \text{ s} \end{aligned} \qquad (24)$$

becomes less than the cosmological time as soon as the effective baryon overdensity κ_B becomes large enough.[7] This would lead to a partial transfer of angular momentum from the rotating ordinary matter to dark component in the inner dense regions of galaxies, avoiding thus the formation of the cusp and providing more shallow inner profiles of dark matter halos. However, in the external part of the halos, outside the galactic disk where the baryon density is small, the collision time must be large and hence the halos should maintain their normal density distribution. In addition, co-rotation of dark matter in the Galaxy at the position of the sun may have interesting implications for direct experimental search of dark matter.

Another interesting possibility is related to the annihilation of X-particles with the mass in the range of a few MeV in the galactic center, $X\bar{X} \to e^+e^-$, which can be the origin of the 511 keV line observed by INTEGRAL/SPI [42, 43]. Indeed, the rate of e^+e^- production in the Galaxy is $\int \langle v_{\mathrm{rel}}\sigma(X\bar{X} \to e^+e^-)(\boldsymbol{r})\rangle n_X(\boldsymbol{r})\,dV$, where $n_X(\boldsymbol{r})$ the number density of dark X particles at the position $\boldsymbol{r}$ in the Galaxy. According to dedicated studies [44, 45], the observed flux of 511 keV photons can be explained by dark matter annihilation in a dark matter halo with a mild enough inner profile provided that

$$\left(\frac{\Omega_X h^2}{m_{\mathrm{MeV}}}\right)^2 \frac{v\sigma(X\bar{X} \to e^+e^-)}{1 \text{ pb}} \simeq (0.5\text{--}1.5) \times 10^{-5}. \qquad (25)$$

Taking into account Eqs. (18) and (19), we find that dependence on m_X disappear from condition (25) and thus it is reduced to $1/\varepsilon_5^2 = 0.005\text{--}0.016$, or $\varepsilon = (0.8\text{--}1.4) \times 10^{-4}$. These values for the millicharge of X particle are compatible with the experimental limits [25], respectively, for $m_X > 5\text{--}10$ MeV. On the other hand, for e.g. $\varepsilon = 8 \times 10^{-5}$, X particles could constitute the dark matter density, $\Omega_X h^2 \simeq 0.12$, if $m_X \sim 25$ MeV or so (cf. (19)). For lighter X particles we have $\Omega_X h^2 < 0.12$ and thus the presence of some other type of dark matter would be required.

Until now we did not discuss whether our mechanism could generate also the intergalactic magnetic fields, namely

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[5]One could take $m_X \simeq 10$ GeV and $\varepsilon \simeq 0.03$, also in agreement with the bounds of Ref. [25]. However, that heavy X particles with so large couplings could be excluded, or are already excluded, by the existing experiments on direct search of dark matter.

[6]Let us remind the reader, however, that Eq. (19) is not valid if X particles have additional annihilation channels.

[7]We use here Eq. (19). Then τ_{pX} does not depend on m_X and ε, but only on the cosmological density of X particles, $\Omega_X h^2$.

the ones observed in galaxy clusters. As we know, the normal matter in clusters is presented dominantly in the form of hot gas, and the fraction of the luminous matter (galaxies and stars) is smaller. The global motion of the ionized gas relative to dark X matter and induced drag of electrons could produce magnetic fields also in filaments and galaxy clusters. This process can be somewhat less efficient than in galaxies, due to smaller overdensity of dark matter and weaker adiabatic amplification. Applying naively the same estimate as (23) for magnetic seeds in clusters but with $R \sim 1$ Mpc, one can achieve magnetic seeds $\sim 10^{-14}$ G. One has to keep in mind, however, but the whole picture can be more complicated, e.g. smaller scale peculiar turbulent motion of the intergalactic gas should be taken into account which could result in larger values of B at the cluster scales than those based on the simplified estimates presented above. This question requires a special investigation.

Concluding, we suggested a new scenario for generation of galactic magnetic fields which is based on dark matter interaction with the normal matter in the process of the galaxy formation. The necessary interaction can be induced by pressure of millicharged dark matter particles on electrons. In this case, circular electric currents can be generated due to rotation of free electrons together with the bulk of normal matter in the galaxy, colliding with dark matter particles virialized in the halo. The impact of such collisions on galactic protons is considerably weaker due to their larger mass. The induced currents may be strong enough to create the observed magnetic fields on the galaxy scales with the help of very moderate dynamo amplification. In particular, this can naturally explain the recent observational data which suggest that the environments of galaxies were significantly magnetized at high redshifts, with magnetic fields that were at least as strong already after a few Gyr of the cosmological time, as they are today.

The millicharged dark matter particles may also have interesting implications for the properties of galaxies. Namely, in the dense inner regions of galaxies, the angular momentum transfer from the rotating gas to dark matter component could involve the latter into its rotation which would change the dark matter inner profile and prevent the formation of cusps at galactic centers. In addition, the observed intensity and shape of 511 keV shining from the galactic core can be explained by $X\bar{X} \to e^{+}e^{-}$ annihilation provided that X particles have masses in the range of 5–10 MeV, and, respectively, millicharges in the range $(0.8-1.3) \times 10^{-4}$.

We conclude that it is quite possible that the mechanism proposed in this work may simultaneously explain both galactic and intergalactic magnetic fields by a single hypothesis of existence of millicharged dark matter particles. The suggested mechanism has interesting implications for direct experimental search of dark matter as well as for a laboratory search of millicharged particles. Cosmological consequences of existence of mirror or mirror-like dark sectors [30–35], which possess dark massless paraphoton and can form a sort of atomic dark matter, will be discussed elsewhere.

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