Magnetizing the Cosmic Web during Reionization

Mathieu Langer [1,*,†] and **Jean-Baptiste Durrive [2,*,†,‡]**

[1] Institut d'Astrophysique Spatiale, CNRS/Université Paris-Sud, Université Paris-Saclay, bâtiment 121, 91405 Orsay, France

[2] Department of Physics and Astrophysics, Nagoya University, Nagoya 464-8602, Japan

[*] Correspondence: mathieu.langer@ias.u-psud.fr (M.L.); jdurrive@irap.omp.eu (J.-B.D.)

[†] These authors contributed equally to this work.

[‡] Current address: Institut de Recherche en Astrophysique et Planétologie (IRAP), CNRS, Université de Toulouse, 9 Avenue du Colonel Roche, BP 44346, CEDEX 4, 31028 Toulouse, France.

check for
updates

Abstract: Increasing evidence suggests that cosmological sheets, filaments, and voids may be substantially magnetized today. The origin of magnetic fields in the intergalactic medium (IGM) is, however, currently uncertain. It seems well known that non-standard extensions to the physics of the standard model can provide mechanisms susceptible of magnetizing the universe at large. Perhaps less well known is the fact that standard, classical physics of matter–radiation interactions actually possesses the same potential. We discuss a magnetogenesis mechanism based on the exchange of momentum between hard photons and electrons in an inhomogeneous IGM. Operating in the neighborhood of ionizing sources during the epoch of reionization, this mechanism is capable of generating magnetic seeds of relevant strengths over scales comparable to the distance between ionizing sources. In addition, summing up the contributions of all ionizing sources and taking into account the distribution of gas inhomogeneities, we show that this mechanism leaves the IGM, at the end of reionization, with a level of magnetization that might account, when amplification mechanisms take over, for the magnetic fields strengths in the current cosmic web.

Keywords: magnetic fields; large-scale structure; Faraday tomography

1. Introduction

From planets to galaxies through stars and the interstellar medium, the existence of magnetic fields in astrophysical objects and environments has been detected by various, complementary techniques (see, e.g., [1–4]). On the scales of galaxy clusters too, there is growing evidence that the warm-hot, ionized gas of the intracluster medium is essentially always magnetized [5–7], typically up to the level of a few microgauss. Magnetic fields may well be present even on the yet larger scales of intergalactic filaments (∼10 nG typically) and cosmic voids (possibly $\geq 10^{-18}$ G) as hinted at by observations of distant blazars [8–12]. In a word, magnetic fields seem ubiquitous in the universe.

While their existence within collapsed cosmic structures may be explained, at least to some degree, by the action of a local mechanism that generates fields with, to the least, a non-vanishing dispersion on some scales, followed by a sequence of various dynamo actions (see, e.g., [13–16]), their origin on large, cosmological scales remains unclear. According to the current paradigm, they were first generated as weak seeds that were later amplified and reshaped, perhaps first on small scales in the post-recombination intergalactic medium (IGM) through collisionless plasma instabilities (e.g., [17]), and/or through adiabatic compression and various dynamo mechanisms during or after structure formation [18–20]. Had they been generated with strengths larger than a few nano-Gauss, magnetic fields would have noticeably affected subsequent structure formation [21–25].

However, the origin of the seed magnetic fields themselves, particularly on the largest scales, is unsettled, despite the many magnetogenesis mechanisms that have been proposed in the literature (see for instance [1,19,26–28] for reviews). Many of these (reviewed in [27–29]) rely on high energy, beyond the standard model physics possibly operating in the early universe. In the post-recombination universe, classical plasma physics can also generate magnetic field seeds through plasma instabilities (e.g., [30–35]), the Biermann [36] battery (e.g., [37–41]), or the momentum transfer of photons or protons to electrons (e.g., [42–50]). Whether all these mechanisms are suitable candidates for explaining the origin of the magnetic fields probably permeating the cosmic web is debated, and will hopefully be answered in the near future notably thanks to the current and forthcoming large radio telescopes (see [51] and pages 369–597 of [52]).

We summarize here the basic features and results of an astrophysical mechanism, based on the photoionization of the IGM, that is bound to have contributed to the magnetization of the cosmic web during the first billion years of the universe, in the epoch of reionization. Its principles have been explored in [47,53], and the resulting, average strength of the magnetic field that permeates the universe by the end of reionization has been estimated in [54].

2. Outline of the Physical Mechanism

In principle, the "recipe" for the generation of magnetic fields is rather simple. First, some mechanism must spatially separate positive and negative electric charge carriers. Second, this charge separation must be sustained, at least effectively, so that the medium becomes permeated with a large-scale electric field. Third, for it to be suitable for the induction of magnetic fields, by virtue of Faraday's law, this electric field must possess a curl. In the context of astrophysical plasmas, this rotational electric field enters the magnetic field induction equation as a source term,

$$\partial_t \vec{B} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) - c\vec{\nabla} \times \vec{E}_\text{s} \tag{1}$$

(magnetic field diffusion has been omitted here). The question of astrophysical magnetogenesis thus essentially boils down to identifying the propitious epochs and environments for such rotational electric fields to appear. The Biermann battery [36] is perhaps the best known mechanism that creates rotational electric fields such that

$$\vec{\nabla} \times \vec{E}_\text{s} = \frac{\vec{\nabla} n_e \times \vec{\nabla} p_e}{en_e^2} \tag{2}$$

where p_e and n_e are the electron pressure and number density, and e is the elementary charge. In the cosmological context, it has been explored by several authors [38,40,55,56] who demonstrated that magnetic fields of strengths of 10^{-20}–10^{-18} Gauss, depending on the characteristic gradient scales involved, are thus generated in regions where the cosmological plasma is baroclinic, typically within ionization fronts during cosmological reionization or in shocks and caustics associated with structure formation by gravitational collapse.

Magnetizing the entire IGM is a little bit trickier. Of course, setting aside inflationary mechanisms or primordial universe phase-transitions, one may invoke the possibility that magnetic fields were first created within galaxies and subsequently injected into the circum- and inter-galactic media by galactic winds and AGN jets [57–63]. The resulting volume filling factor of these processes remains, however, highly uncertain. In addition, the origin of the initial magnetic seed fields generated within galaxies remains to be specified in that scenario, as well as the efficiency of any amplification mechanism that is required to produce the strong enough fields that would be injected into the IGM.

Cosmological reionization has most likely contributed to the global magnetization of the entire IGM. The first step of charge separation occurs naturally in that epoch. In fact, before the end of reionization, two different regions can be identified. First, the immediate surroundings of ionizing sources (first stars and galaxies, possibly quasars) are essentially fully ionized by photons with energies just at the threshold of hydrogen (and helium I) ionization forming cosmological HII regions equivalent

to Strömgren spheres. Higher energy photons can, however, penetrate beyond the Strömgren edge of such bubbles into the otherwise essentially neutral IGM. There, occasionally, they hit neutral atoms and eject new electrons. As long as the ionizing source shines, the resulting charge separation gives birth to an electric field. Now, if the distribution of matter around ionizing sources were completely isotropic, the electric field would obviously be curl-free. Nevertheless, two circumstances ensure that local isotropy is broken (see Figure 1). First, the IGM is naturally inhomogeneous, if only because of the primordial density fluctuations initially present at all scales. As we discuss below, the most favorable inhomogeneities are only mildly nonlinear, but any overdensity (underdensity) locally enhances (lessens) the photoionization process, meaning that behind it the strength of the resulting electric field is smaller (larger) than it is along photons trajectories that miss density contrasts. Thus, the electric field varies *across* the photon radial trajectories and possesses a curl. Second, due to the presence of inhomogeneities, the HII bubbles themselves are strongly aspherical (see for instance [64,65]), which contributes to making the flux of hard photons that escape into the IGM anisotropic.
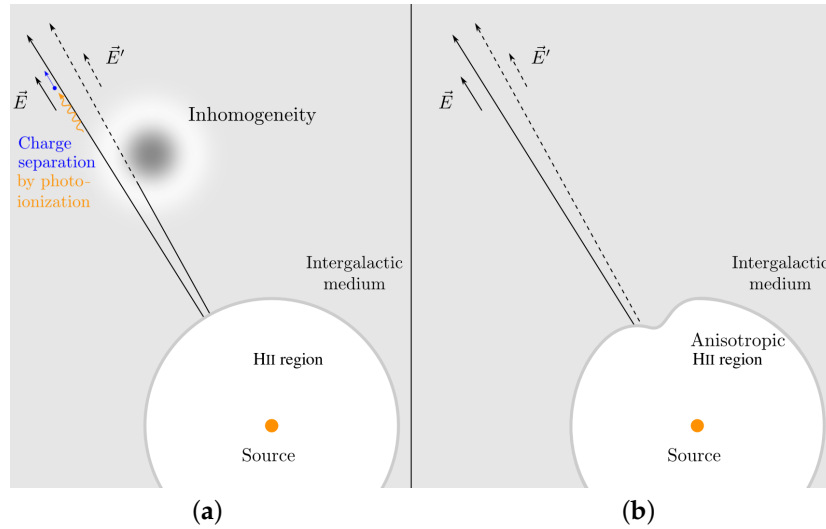

(a)　　　　　　　　　　　　　　　　　　　　　　　　**(b)**

Figure 1. Inhomogeneities at the origin of rotational electric fields. An ionizing source creates an HII bubble around itself. Photons above the hydrogen ionization threshold may propagate deeper into the IGM, where, occasionally, they hit neutral atoms and eject new electrons. This process occurs continuously, and the resulting charge separation induces an electric field. This electric field may possess a curl either (**a**) because of gas inhomogeneities present in the IGM or (**b**) because of anisotropies in the bubble boundary that both induce differences in adjacent photon paths.

In [53], we analyzed in detail the mechanism by which non-zero magnetic fields emerge in the neutral surroundings of ionizing sources during cosmological reionization. At the fundamental level, it relies on the momentum transfer between hard photons and initially bound electrons. It may in fact be described microscopically as a perturbation of the electron distribution function in the IGM. We then reduced the description to that of a single fluid at a macroscopic level and obtained a generalized Ohm's law whose curl leads to the induction Equation (1), where, this time, the source electric field contains an additional term such that

$$\vec{\nabla} \times \vec{E}_s = \frac{\vec{\nabla} n_e \times \vec{\nabla} p_e}{e n_e^2} + \vec{\nabla} \times \left(\frac{\dot{\vec{p}}}{e n_e} \right) \qquad (3)$$

where $\dot{\vec{p}} \equiv \dot{\vec{p}}(\vec{r})$ is the rate of electron momentum creation at position $\vec{r}$ in the IGM due to the higher energy photons. As we have shown in [53], this new source term depends notably on the neutral gas density, the spectrum of the ionizing source, the attenuation along the photon trajectories, and the distance from the edge of the HII bubble (a geometric dilution of photons). By the integration of

Equation (1), keeping only the photoionization source term of Equation (3), we were able to obtain the general expression for the magnetic field thus induced (not considering the role of the asphericity of ionized bubbles), and we examined, in a simple model of the cosmological reionization context, the typical spatial distribution and strengths of the magnetic fields obtained.

3. Resulting Magnetic Fields

Depending on their spectrum, luminosity, and lifetime, different sources generate different magnetic fields at different epochs. As illustrative numerical applications, we considered three different types of sources that presumably have contributed to reionization: clusters of Population III stars, primeval galaxies, and high redshift quasars. We modeled an inhomogeneity in the IGM by a Mexican hat density profile in which a central overdensity is compensated by a surrounding underdensity (see Figure 1a). The most favorable gas inhomogeneities in the IGM are mildly nonlinear, $\delta\rho/\rho\sim5$, corresponding to the density contrast of cosmic structures that are in the turn-around phase of their gravitational collapse. Much smaller inhomogeneities are not contrasted enough to make adjacent photon trajectories significantly different. Strongly nonlinear density contrasts are too opaque and possess much sharper, narrower boundaries that limit the extent of the areas over which rotational electric fields; hence, magnetic fields are induced. Finally, the strength of the magnetic field, growing linearly with time (see [47,53]), is shown in Figure 2 for each ionizing source type, assuming a source lifetime of 100 Myr.
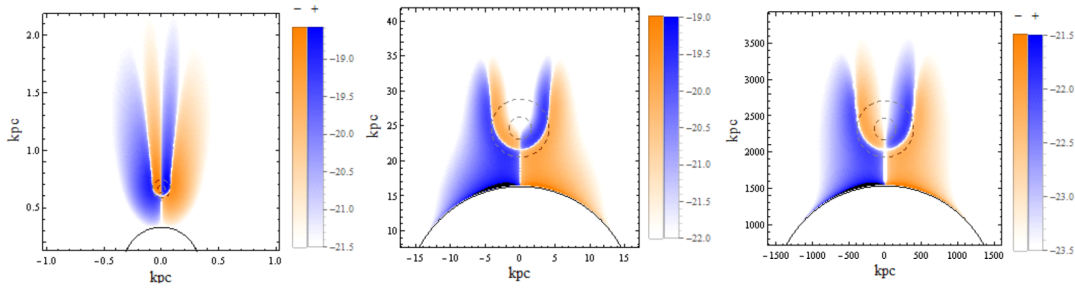

Figure 2. Strength and spatial configuration of the magnetic fields induced by the radiation of (**a**) Population III stars at $z\sim20$, (**b**) a primeval galaxy at $z\sim10$, and (**c**) a quasar at $z\sim10$. In each panel, the blue areas correspond to the magnetic field pointing toward the reader, orange in the opposite direction. This peculiar geometrical configuration of the fields simply reflects the axisymmetry of the matter distribution with respect to the ionizing source. Strengths are in Gauss in logarithmic scale. The solid line arc represents the edge of the HII region created by the ionizing source (not shown). Inner and outer dashed black circles delineate, respectively, the one sigma location of the overdensity and of the compensating underdensity (the latter being responsible for the reversal of the magnetic field). Note that the scales change from panel to panel.

Population III star clusters generate relatively stronger fields (up to $\sim10^{-18}$ G) on short distances (1–2 kpc). Assuming that they formed by molecular cooling in gas overdensities of mass $10^6 M_\odot$ [66], their half physical mean separation is roughly 10 kpc, estimated from the abundance of their $\sim3\sigma$ parent halos [67]. In addition, the size of their HII bubbles is of the order of a fraction of kpc. It thus seems that these sources magnetize essentially their immediate neighborhood, leaving an important fraction of the IGM unmagnetized. Luminous quasars, on the contrary, magnetize less (up to $\sim10^{-21}$ G) but over much larger distances (several Mpc). Considering that these sources, rare at $z = 10$, are hosted by 5σ halos, their half physical mean separation is of a couple of Mpc. Their HII bubbles have radii of the order of the Mpc, which means that these sources emit photons of large enough mean-free paths to contribute to globally magnetizing the IGM. Finally, primeval galaxies combine modestly high amplitudes (up to $\sim10^{-19}$ G) and reasonably large scales (tens of kpc). Assuming they are hosted in $10^8 M_\odot$ halos, their half physical mean separation is typically several tens of kpc, while the radius

of their HII bubbles is of the order of a few tens of kpc. We thus may conclude that such sources have probably magnetized the entire IGM before the end of reionization.

4. Average Magnetic Energy Density Seeded in the IGM

To support this conclusion, we estimated in [54] the level of global magnetization produced in the universe by the end of reionization by the mechanism outlined above. The final result naturally depends on the distribution of all ionizing sources, their spectral properties, the epochs at which they start shining, and the shape and distribution of density inhomogeneities in the IGM. In [53], we derived a very detailed formula giving the strength of the magnetic field generated within and around a given overdense cloud in the neighborhood of an ionizing source. The latter expression is rather involved but, fortunately, we were also able to identify the characteristic length scales of the problem useful for modeling simply the magnetized area around the given overdensity.

Building upon this, we employed in [54] the Press–Schechter (PS) formalism [68] to estimate the statistical distribution of ionizing sources and of overdensities around the sources. To be more precise, we considered dark matter (DM) halos that are massive enough to host luminous sources and DM overdensity regions that have not yet collapsed but that contain diffuse baryonic overdense clouds. Then, using an approximate expression for the magnetic field generated around overdensities, we estimated the magnetic field generated by all sources forming during the epoch of reionization. In fact, for simplicity, we concentrated only on the contribution of faint, primeval galaxies. Indeed, the latter are probably the dominant contributors to the reionization process itself, as has been suggested in the literature (see for instance [69] and references therein).

The details of our calculations are exposed in [54]. Here, we simply outline our approach, illustrated in Figure 3, which consists in the following steps.

1. First, along the lines outlined in Section 2, we considered an isolated source and a gas inhomogeneity in its vicinity. We then condensed all the details into a simpler and more tractable version of the results we obtained in [53]. We then derived an efficient expression for the magnetic energy density $E_m(D)$ associated with any cloud of mass m at a given distance D of the ionizing source.

2. Second, we summed up the contributions of all the clouds surrounding the source. For this, we needed to estimate the distribution of such baryonic clouds, which we did by considering their underlying DM halos. Using the PS formalism, we obtained that the source, contained in a DM halo of mass M, contributes to the magnetization of the IGM by injecting a magnetic energy density

$$E_M = \int_{r_s}^{r_s + \ell_{\nu_1}} \int_{m_{\min}}^{m_{\max}} E_m(D) \, \mathrm{d}^2 P(D, m | M) \tag{4}$$

where $\mathrm{d}^2 P(D, m | M)$ is the probability of finding a DM cloud of mass m within a spherical shell of volume $4\pi D^2 \mathrm{d}D$, at a distance D from the halo of mass M. As one can see from the boundaries of the first integral in Equation (4), we take into account only the clouds outside the HII bubbles (of radius r_s), but not too far from it, namely within an "interaction zone" set by the photoionization mean free path ℓ_{ν_1} beyond which the mechanism is no longer significantly efficient (orange dashed lines in Figure 3). The boundaries of the second integral, $m_{\min}$ and $m_{\max}$ for the mass of the clouds, are important parameters of this process, and we discuss in details how we chose them in [54].

3. Third, we considered the full cosmological context, as illustrated in the right panel of Figure 3. The energy density E_M generated around each source must be integrated over the distribution of DM halos containing the sources. However, ionized bubbles of individual sources start to overlap toward the end of the epoch of reionization. Since the mechanism outlined in Section 2 takes place only in the neutral IGM, the efficiency of magnetic field generation actually decreases as reionization proceeds. Hence, we weighed the contribution of all sources by a factor $1 - Q_i(z)$ (where $Q_i(z)$ is the volume filling factor of ionized bubbles at redshift z) when summing them

up in order to reduce the generated magnetic field energy as time increases according to the ionization of the IGM. We thus estimated the mean physical magnetic energy density generated by photoionizations during the epoch or reionization as

$$\frac{B_{\mathrm{P}}^2(z)}{8\pi} = (1+z)^4 \int_z^{z_0} \mathrm{d}z' \frac{1-Q_i}{H(1+z')^5} \int_{M_*}^{M_{\max}} \mathrm{d}M\, E_M\, g_{\mathrm{gl}} \frac{\mathrm{d}n_M}{\mathrm{d}M} \tag{5}$$

where $\frac{\mathrm{d}n_M}{\mathrm{d}M}$ is the mass function of the DM halos, with mass M, hosting the sources. We also used the PS formalism to compute the latter, and we discuss our choices for the values of the boundaries M_* and $M_{\max}$ in [54]. The parameter z_0 is the redshift at which the first sources form. We also introduced the rate g_{gl} at which sources in DM halos switch on, with a numerical value chosen in order for our model to be consistent with recent observational constraints on reionization (see [70]). Finally, the presence of the Hubble parameter H and of the $(1+z)$ factors reflects the expansion of the universe that dilutes the magnetic fields.
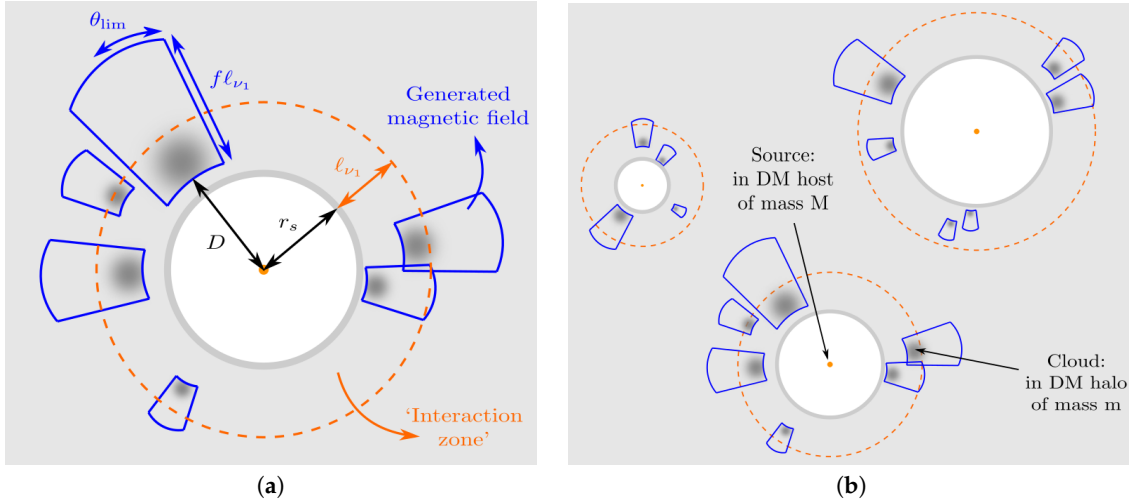

Figure 3. Illustration of the approach we followed for estimating the global magnetization level of the IGM. We first (**a**) evaluated the magnetic field generated around one source, surrounded by a distribution of clouds, and then (**b**) considered a distribution of sources. The orange dot represents an ionizing source. Gray spots represent small baryonic inhomogeneities in the IGM. Blue frames delineate the characteristic regions that are magnetized around such gas clouds.

In Figure 4, for illustration, we plot the comoving strength of the generated magnetic field $B_{\mathrm{c}} = B_{\mathrm{p}}/(1+z)^2$, as a function of redshift, in three different reionization histories, all consistent with the value of the Thomson optical depth to the cosmic microwave background measured by the Planck collaboration [70].

The global shape of the curves is naturally understood as follows. Above $z = 20$, there are no galaxies, and the magnetic field strength is equal to zero. As time passes, galaxies form and their radiation induces magnetic fields, i.e., a small fraction of their radiation energy is converted into magnetic energy that accumulates in the IGM. Once the universe is totally ionized, the mechanism outlined above stops, and a plateau is reached (in comoving units). Note that in physical units, the strength of the magnetic field permeating the universe by the end of reionization due to this process is a few 10^{-18} Gauss, which is a suitable seed value for any succeeding amplification by nonlinear processes.
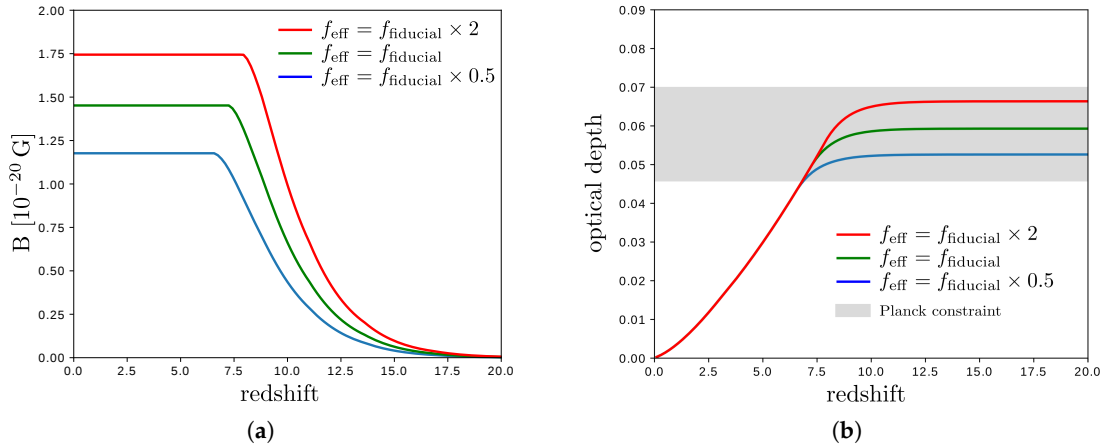
Figure 4. (**a**) Evolution with redshift of the mean comoving magnetic field strength accumulated in the IGM in different reionization histories. The green curve corresponds to the fiducial model assumed in [54] where $f_{\rm eff} \equiv f_* f_{\rm esc}$ is an effective reionization efficiency. It combines the fraction f_* of baryons converted into stars in the halos hosting the ionizing sources and the fraction $f_{\rm esc}$ of ionizing radiation that actually escapes into the IGM. The blue and red curves correspond, respectively, to reionization scenarios that are half and twice as efficient. All three considered reionization histories are in agreement with the Planck constraints ($\tau = 0.058 \pm 0.012$, [70]), as illustrated in panel (**b**), which shows the cumulative Thomson optical depth τ to the CMB.

5. Discussion

The model we summarized here is arguably simplistic in some aspects and can be improved in several ways. In particular, in the estimate of the average magnetization of the universe, we considered only gas overdensities, and neglected the contribution of underdense regions (see Section 2), which could, in principle, multiply the result obtained above by a factor of two. Similarly, we did not take into account the asphericity of the cosmological HII regions, which would probably be best investigated through numerical simulations.

Finally, we neglected a few time-dependent aspects in this first approach. Indeed, we assumed for instance that the HII regions surrounding the ionizing sources have reached their steady state. However, in the transitory phase during which they grow, hard photons reaching the neutral IGM are less diluted, so that the mechanism is more efficient andinitially closer to the photon sources. At the same time, it is slightly less efficient and further away from the sources, since photons above the hydrogen ionization threshold are more absorbed by the intervening matter. Whether taking this into account would increase or decrease the overall mean generated magnetic field is not obvious. Note, however, that nonlinearities develop in the cosmic velocity field as structure formation proceeds. They enter into play in Equation (1) basically when the seed magnetic field has reached its final strength at a given scale [47]. We also know from numerical simulations that strong turbulent motions arise naturally during the formation of the first galaxies [71,72]. In addition, mechanical feedback associated to the formation and evolution of large-scale structure after reionization injects turbulence into the IGM (e.g., [20,73–75]). Magnetic field amplification by shear and adiabatic contraction thus sets in early on, counterbalancing (and overwhelming) the effect of the dilution due to the expansion of the universe, at least within the nodes, filaments, and sheets of the cosmic web. The strength shown in Figure 4 is thus likely an underestimate of the actual magnetization level of these structures by the end of reionization. Within cosmic voids, collisionless plasma instabilities have the potential to amplify rapidly the magnetic seed fields [17] and bring them to, and maintain them above,the lower limits suggested by the observation of distant blazars and cited in the introduction.

As a final note, let us point out that the many magnetogenesis mechanisms proposed in the literature are not mutually exculsive. Quite on the contrary, several may contribute either

simultaneously or sequentially, sympatrically or allopatrically, to the magnetization of the IGM[1]. Disentangling their respective contributions may become possible in the near future thanks to synchrotron measurements and Faraday tomography (e.g., [77,78])—especially when compared to numerical simulations that are able to track the various contributions [79,80]—or even in the statistical properties of the neutral gas during the epoch of reionization [81,82].

Author Contributions: Conceptualization, M.L. and J.-B.D.; Formal Analysis, J.-B.D. and M.L.; Investigation, J.-B.D. and M.L.; Writing–Original Draft Preparation, M.L. and J.-B.D.; Writing–Review & Editing, M.L.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Widrow, L.M. Origin of galactic and extragalactic magnetic fields. *Rev. Mod. Phys.* **2002**, *74*, 775–823. [CrossRef]

2. Beck, R.; Wielebinski, R. Magnetic Fields in Galaxies. In *Planets, Stars and Stellar Systems—Volume 5: Galactic Structure and Stellar Populations*; Oswalt, T.D., Gilmore, G., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp. 641–723.

3. Vallée, J.P. Magnetic fields in the nearby Universe, as observed in solar and planetary realms, stars, and interstellar starforming nurseries. *New Astron. Rev.* **2011**, *55*, 23–90. [CrossRef]

4. Vallée, J.P. Magnetic fields in the galactic Universe, as observed in supershells, galaxies, intergalactic and cosmic realms. *New Astron. Rev.* **2011**, *55*, 91–154. [CrossRef]

5. Govoni, F.; Feretti, L. Magnetic Fields in Clusters of Galaxies. *Int. J. Mod. Phys. D* **2004**, *13*, 1549–1594. [CrossRef]

6. Feretti, L.; Giovannini, G.; Govoni, F.; Murgia, M. Clusters of galaxies: Observational properties of the diffuse radio emission. *Astron. Astrophys. Rev.* **2012**, *20*, 54. [CrossRef]

7. Han, J. Observing Interstellar and Intergalactic Magnetic Fields. *Annu. Rev. Astron. Astrophys.* **2017**, *55*, 111–157. [CrossRef]

8. Aleksić, J.; Antonelli, L.A.; Antoranz, P.; Backes, M.; Baixeras, C.; Barrio, J.A.; Bastieri, D.; Becerra González, J.; Bednarek, W.; Berdyugin, A.; et al. Search for an extended VHE γ-ray emission from Mrk 421 and Mrk 501 with the MAGIC Telescope. *Astron. Astrophys.* **2010**, *524*, A77. [CrossRef]

9. Neronov, A.; Vovk, I. Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars. *Science* **2010**, *328*, 73–75. [CrossRef] [PubMed]

10. Tavecchio, F.; Ghisellini, G.; Bonnoli, G.; Foschini, L. Extreme TeV blazars and the intergalactic magnetic field. *Mon. Not. R. Astron. Soc.* **2011**, *414*, 3566–3576. [CrossRef]

11. Finke, J.D.; Reyes, L.C.; Georganopoulos, M.; Reynolds, K.; Ajello, M.; Fegan, S.J.; McCann, K. Constraints on the Intergalactic Magnetic Field With Gamma-Ray Observations of Blazars. *Astrophys. J.* **2015**, *814*, 20. [CrossRef]

12. Ackermann, M.; Ajello, M.; Baldini, L.; Ballet, J.; Barbiellini, G.; Bastieri, D.; Bellazzini, R.; Bissaldi, E.; Blandford, R.D.; Bloom, E. D.; et al. The Search for Spatial Extension in High-latitude Sources Detected by the Fermi Large Area Telescope. *Astrophys. J. Suppl. Ser.* **2018**, *237*, 32. [CrossRef]

---

[1] Among the possible contributions is the resistive mechanism suggested in [76], in which *temperature* inhomogeneities of the IGM are responsible for spatial variations of the resistivity that induce rotational electric fields thanks to cosmic ray driven return currents.

13. Brandenburg, A.; Subramanian, K. Astrophysical magnetic fields and nonlinear dynamo theory. *Phys. Rep.* **2005**, *417*, 1–209. [CrossRef]

14. Schober, J.; Schleicher, D.R.G.; Klessen, R.S. Magnetic field amplification in young galaxies. *Astron. Astrophys.* **2013**, *560*, A87. [CrossRef]

15. Schober, J.; Schleicher, D.R.G.; Federrath, C.; Bovino, S.; Klessen, R.S. Saturation of the turbulent dynamo. *Phys. Rev. E* **2015**, *92*, 023010. [CrossRef] [PubMed]

16. Federrath, C. Magnetic field amplification in turbulent astrophysical plasmas. *J. Plasma Phys.* **2016**, *82*, 535820601. [CrossRef]

17. Falceta-Gonçalves, D.; Kowal, G. Fast Magnetic Field Amplification in the Early Universe: Growth of Collisionless Plasma Instabilities in Turbulent Media. *Astrophys. J.* **2015**, *808*, 65. [CrossRef]

18. Arshakian, T.G.; Beck, R.; Krause, M.; Sokoloff, D. Evolution of magnetic fields in galaxies and future observational tests with the Square Kilometre Array. *Astron. Astrophys.* **2009**, *494*, 21–32. [CrossRef]

19. Ryu, D.; Schleicher, D.R.G.; Treumann, R.A.; Tsagas, C.G.; Widrow, L.M. Magnetic Fields in the Large-Scale Structure of the Universe. *Space Sci. Rev.* **2012**, *166*, 1–35. [CrossRef]

20. Donnert, J.; Vazza, F.; Brüggen, M.; ZuHone, J. Magnetic Field Amplification in Galaxy Clusters and Its Simulation. *Space Sci. Rev.* **2018**, *214*, 122. [CrossRef]

21. Wasserman, I. On the origins of galaxies, galactic angular momenta, and galactic magnetic fields. *Astrophys. J.* **1978**, *224*, 337–343. [CrossRef]

22. Kim, E.J.; Olinto, A.V.; Rosner, R. Generation of Density Perturbations by Primordial Magnetic Fields. *Astrophys. J.* **1996**, *468*, 28. [CrossRef]

23. Tashiro, H.; Sugiyama, N. Early reionization with primordial magnetic fields. *Mon. Not. R. Astron. Soc.* **2006**, *368*, 965–970. [CrossRef]

24. Marinacci, F.; Vogelsberger, M. Effects of simulated cosmological magnetic fields on the galaxy population. *Mon. Not. R. Astron. Soc. Lett.* **2016**, *456*, L69–L73. [CrossRef]

25. Varalakshmi, C.; Nigam, R. Corrections to halo model in presence of primordial magnetic field. *Astrophys. Space Sci.* **2017**, *362*, 16. [CrossRef]

26. Kulsrud, R.M.; Zweibel, E.G. On the origin of cosmic magnetic fields. *Rep. Prog. Phys.* **2008**, *71*, 046901. [CrossRef]

27. Widrow, L.M.; Ryu, D.; Schleicher, D.R.G.; Subramanian, K.; Tsagas, C.G.; Treumann, R.A. The First Magnetic Fields. *Space Sci. Rev.* **2012**, *166*, 37–70. [CrossRef]

28. Durrer, R.; Neronov, A. Cosmological magnetic fields: Their generation, evolution and observation. *Astron. Astrophys. Rev.* **2013**, *21*, 62. [CrossRef]

29. Subramanian, K. The origin, evolution and signatures of primordial magnetic fields. *Rep. Prog. Phys.* **2016**, *79*, 076901. [CrossRef] [PubMed]

30. Gruzinov, A. Gamma-Ray Burst Phenomenology, Shock Dynamo, and the First Magnetic Fields. *Astrophys. J.* **2001**, *563*, L15–L18. [CrossRef]

31. Schlickeiser, R.; Shukla, P.K. Cosmological Magnetic Field Generation by the Weibel Instability. *Astrophys. J.* **2003**, *599*, L57–L60. [CrossRef]

32. Medvedev, M.V.; Silva, L.O.; Kamionkowski, M. Cluster Magnetic Fields from Large-Scale Structure and Galaxy Cluster Shocks. *Astrophys. J.* **2006**, *642*, L1–L4. [CrossRef]

33. Lazar, M.; Schlickeiser, R.; Wielebinski, R.; Poedts, S. Cosmological Effects of Weibel-type Instabilities. *Astrophys. J.* **2009**, *693*, 1133–1141. [CrossRef]

34. Bret, A. Weibel, Two-Stream, Filamentation, Oblique, Bell, Buneman... Which one grows faster? *Astrophys. J.* **2009**, *699*, 990–1003. [CrossRef]

35. Schlickeiser, R. Cosmic Magnetization: From Spontaneously Emitted Aperiodic Turbulent to Ordered Equipartition Fields. *Phys. Rev. Lett.* **2012**, *109*, 261101. [CrossRef] [PubMed]

36. Biermann, L. Über den Ursprung der Magnetfelder auf Sternen und im interstellaren Raum (mit einem Anhang von A. Schlüter). *Zeitschrift Naturforschung Teil A* **1950**, *5*, 65–71.

37. Pudritz, R.E.; Silk, J. The origin of magnetic fields and primordial stars in protogalaxies. *Astrophys. J.* **1989**, *342*, 650–659. [CrossRef]

38. Subramanian, K.; Narasimha, D.; Chitre, S.M. Thermal generation of cosmological seed magnetic fields in ionization fronts. *Mon. Not. R. Astron. Soc.* **1994**, *271*, L15–L18. [CrossRef]

39. Ryu, D.; Kang, H.; Biermann, P.L. Cosmic Magnetic Fields in Large Scale Filaments and Sheets. *Astron. Astrophys.* **1998**, *335*, 19–25.

40. Gnedin, N.Y.; Ferrara, A.; Zweibel, E.G. Generation of the Primordial Magnetic Fields during Cosmological Reionization. *Astrophys. J.* **2000**, *539*, 505–516. [CrossRef]

41. Naoz, S.; Narayan, R. Generation of Primordial Magnetic Fields on Linear Overdensity Scales. *Phys. Rev. Lett.* **2013**, *111*, 051303. [CrossRef] [PubMed]

42. Harrison, E.R. Generation of Magnetic Fields in the Radiation Era. *Mon. Not. R. Astron. Soc.* **1970**, *147*, 279–286. [CrossRef]

43. Mishustin, I.N.; Ruzmaikin, A.A. Occurrence of 'Priming' Magnetic Fields During The Formation of Protogalaxies. *Sov. Phys. JETP* **1972**, *34*, 233–235.

44. Harrison, E.R. Origin of Magnetic Fields in the Early Universe. *Phys. Rev. Lett.* **1973**, *30*, 188–190. [CrossRef]

45. Birk, G.T.; Wiechen, H.; Lesch, H. Generation of magnetic seed fields in self-gravitating protogalactic clouds. *Astron. Astrophys.* **2002**, *393*, 685–691. [CrossRef]

46. Langer, M.; Puget, J.L.; Aghanim, N. Cosmological magnetogenesis driven by radiation pressure. *Phys. Rev. D* **2003**, *67*, 043505. [CrossRef]

47. Langer, M.; Aghanim, N.; Puget, J.L. Magnetic fields from reionization. *Astron. Astrophys.* **2005**, *443*, 367–372. [CrossRef]

48. Fenu, E.; Pitrou, C.; Maartens, R. The seed magnetic field generated during recombination. *Mon. Not. R. Astron. Soc.* **2011**, *414*, 2354–2366. [CrossRef]

49. Saga, S.; Ichiki, K.; Takahashi, K.; Sugiyama, N. Magnetic field spectrum at cosmological recombination revisited. *Phys. Rev. D* **2015**, *91*, 123510. [CrossRef]

50. Hutschenreuter, S.; Dorn, S.; Jasche, J.; Vazza, F.; Paoletti, D.; Lavaux, G.; Enßlin, T.A. The primordial magnetic field in our cosmic backyard. *Class. Quantum Gravity* **2018**, *35*, 154001. [CrossRef]

51. Beck, R. Future Observations of Cosmic Magnetic Fields with LOFAR, SKA and Its Precursors. In *Magnetic Fields in Diffuse Media*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 3–17.

52. Bourke, T.L.; Braun, R.; Fender, R.; Govoni, F.; Green, J.; Hoare, M.; Jarvis, M.; Johnston-Hollitt, M.; Keane, E.; Koopmans, L.; et al. *Advancing Astrophysics with the Square Kilometre Array*; Dolman Scott Ltd.: Thatcham, UK, 2015; Volume 1.

53. Durrive, J.B.; Langer, M. Intergalactic magnetogenesis at Cosmic Dawn by photoionization. *Mon. Not. R. Astron. Soc.* **2015**, *453*, 345–356. [CrossRef]

54. Durrive, J.B.; Tashiro, H.; Langer, M.; Sugiyama, N. Mean energy density of photogenerated magnetic fields throughout the Epoch of Reionization. *Mon. Not. R. Astron. Soc.* **2017**, *472*, 1649–1658. [CrossRef]

55. Kulsrud, R.M.; Cen, R.; Ostriker, J.P.; Ryu, D. The Protogalactic Origin for Cosmic Magnetic Fields. *Astrophys. J.* **1997**, *480*, 481–491. [CrossRef]

56. Hanayama, H.; Takahashi, K.; Kotake, K.; Oguri, M.; Ichiki, K.; Ohno, H. Biermann mechanism in primordial supernova remnants and seed magnetic fields. *Astrophys. J.* **2005**, *633*, 941–945. [CrossRef]

57. Rees, M.J. The origin and cosmogonic implications of seed magnetic fields. *R. Astron. Soc. Q. J.* **1987**, *28*, 197–206.

58. Daly, R.A.; Loeb, A. A possible origin of galactic magnetic fields. *Astrophys. J.* **1990**, *364*, 451. [CrossRef]

59. Kronberg, P.P. Extragalactic magnetic fields. *Rep. Prog. Phys.* **1994**, *57*, 325–382. [CrossRef]

60. Kronberg, P.P.; Lesch, H.; Hopp, U. Magnetization of the Intergalactic Medium by Primeval Galaxies. *Astrophys. J.* **1999**, *511*, 56–64. [CrossRef]

61. Furlanetto, S.R.; Loeb, A. Intergalactic Magnetic Fields from Quasar Outflows. *Astrophys. J.* **2001**, *556*, 619–634. [CrossRef]

62. Hanasz, M.; Lesch, H.; Naab, T.; Gawryszczak, A.; Kowalik, K.; Wóltański, D. Cosmic Rays Can Drive Strong Outflows from Gas-rich High-redshift Disk Galaxies. *Astrophys. J.* **2013**, *777*, L38. [CrossRef]

63. Beck, A.M.; Hanasz, M.; Lesch, H.; Remus, R.S.; Stasyszyn, F.A. On the magnetic fields in voids. *Mon. Not. R. Astron. Soc.* **2013**, *429*, L60–L64. [CrossRef]

64. Ciardi, B.; Ferrara, A.; Marri, S.; Raimondo, G. Cosmological reionization around the first stars: Monte Carlo radiative transfer. *Mon. Not. R. Astron. Soc.* **2001**, *324*, 381–388. [CrossRef]

65. Pawlik, A.H.; Rahmati, A.; Schaye, J.; Jeon, M.; Dalla Vecchia, C. The Aurora radiation-hydrodynamical simulations of reionization: calibration and first results. *Mon. Not. R. Astron. Soc.* **2017**, *466*, 960–973. [CrossRef]

66. Barkana, R.; Loeb, A. In the beginning: The first sources of light and the reionization of the universe. *Phys. Rep.* **2001**, *349*, 125–238. [CrossRef]

67. Mo, H.J.; White, S.D.M. The abundance and clustering of dark haloes in the standard ΛCDM cosmogony. *Mon. Not. R. Astron. Soc.* **2002**, *336*, 112–118. [CrossRef]

68. Press, W.H.; Schechter, P. Formation of Galaxies and Clusters of Galaxies by Self-Similar Gravitational Condensation. *Astrophys. J.* **1974**, *187*, 425. [CrossRef]

69. McQuinn, M. The Evolution of the Intergalactic Medium. *Annu. Rev. Astron. Astrophys.* **2016**, *54*, 313–362. [CrossRef]

70. Lewis, A.; Munshi, D.; Adam, R.; Aghanim, N.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Ballardin, M.; Banday, A.J.; Planck Collaboration. Planck intermediate results. XLVII. Planck constraints on reionization history. *Astron. Astrophys.* **2016**, *596*, A108. [CrossRef]

71. Greif, T.H.; Johnson, J.L.; Klessen, R.S.; Bromm, V. The first galaxies: assembly, cooling and the onset of turbulence. *Mon. Not. R. Astron. Soc.* **2008**, *387*, 1021–1036. [CrossRef]

72. Sur, S.; Federrath, C.; Schleicher, D.R.G.; Banerjee, R.; Klessen, R.S. Magnetic field amplification during gravitational collapse—Influence of turbulence, rotation and gravitational compression. *Mon. Not. R. Astron. Soc.* **2012**, *423*, 3148–3162. [CrossRef]

73. Rauch, M.; Sargent, W.L.W.; Barlow, T.A. Small-Scale Structure at High Redshift. II. Physical Properties of the C IV Absorbing Clouds. *Astrophys. J.* **2001**, *554*, 823–840. [CrossRef]

74. Ryu, D.; Kang, H.; Cho, J.; Das, S. Turbulence and magnetic fields in the large-scale structure of the universe. *Science* **2008**, *320*, 909–912. [CrossRef] [PubMed]

75. Ravi, V.; Shannon, R.M.; Bailes, M.; Bannister, K.; Bhandari, S.; Bhat, N.D.R.; Burke-Spolaor, S.; Caleb, M.; Flynn, C.; Jameson, A.; et al. The magnetic field and turbulence of the cosmic web measured using a brilliant fast radio burst. *Science* **2016**, *354*, 1249–1252. [CrossRef] [PubMed]

76. Miniati, F.; Bell, A.R. Resistive Magnetic Field Generation at Cosmic Dawn. *Astrophys. J.* **2011**, *729*, 73. [CrossRef]

77. Akahori, T.; Kumazaki, K.; Takahashi, K.; Ryu, D. Exploring the intergalactic magnetic field by means of Faraday tomography. *Astron. Soc. Jpn.* **2014**, *66*, 65. [CrossRef]

78. Akahori, T.; Nakanishi, H.; Sofue, Y.; Fujita, Y.; Ichiki, K.; Ideguchi, S.; Kameya, O.; Kudoh, T.; Kudoh, Y.; Machida, Mami; et al. Cosmic magnetism in centimeter- and meter-wavelength radio astronomy. *Astron. Soc. Jpn.* **2018**, *70*, R21–R244. [CrossRef]

79. Vazza, F.; Brüggen, M.; Gheller, C.; Hackstein, S.; Wittor, D.; Hinz, P.M. Simulations of extragalactic magnetic fields and of their observables. *Class. Quantum Gravity* **2017**, *34*, 234001. [CrossRef]

80. Katz, H.; Martin-Alvarez, S.; Devriendt, J.; Slyz, A.; Kimm, T. Magnetogenesis at Cosmic Dawn: Tracing the Origins of Cosmic Magnetic Fields. *arXiv* **2018**, arXiv:1810.08619.

81. Venumadhav, T.; Oklopčić, A.; Gluscevic, V.; Mishra, A.; Hirata, C.M. New probe of magnetic fields in the prereionization epoch. I. Formalism. *Phys. Rev. D* **2017**, *95*, 083010. [CrossRef]

82. Gluscevic, V.; Venumadhav, T.; Fang, X.; Hirata, C.; Oklopčić, A.; Mishra, A. New probe of magnetic fields in the pre-reionization epoch. II. Detectability. *Phys. Rev. D* **2017**, *95*, 083011. [CrossRef]