Primordial magnetic field constraints from the end of reionization

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ABSTRACT
Primordial magnetic fields generated in the early universe are subject of considerable investigation, and observational limits on their strength are required to constrain the theory. Due to their impact on the reionization process, the strength of primordial fields can be limited using the latest data on reionization and the observed UV-luminosity function of high-redshift galaxies. Given the steep faint-end slope of the luminosity function, faint galaxies contribute substantial ionizing photons, and the low-luminosity cutoff has an impact on the total budget thereof. Magnetic pressure from primordial fields affects such cutoff by preventing collapse in halos with mass below $10^{10}\, M_\odot \left( B_0/3\, \mu G \right)^3$, with $B_0$ the co-moving field strength. In this letter, the implications of these effects are consistently incorporated in a simplified model for reionization, and the uncertainties due to the cosmological parameters, the reionization parameters and the observed UV luminosity function are addressed. We show that the observed ionization degree at $z \sim 7$ leads to the strongest upper limit of $B_0 < 2 \times 10^{-3} \, \mu G$. Stronger limits could follow from measurements of high ionization degree at $z > 7$.

Key words: magnetic fields – galaxies: high-redshift – intergalactic medium – cosmology: theory – dark ages, reionization, first stars

1 INTRODUCTION
The origin of magnetic fields in the universe is subject of active study. Magnetic fields are a common feature of nearby and distant galaxies (Beck et al. 1996; Bernet et al. 2008; Murphy 2009), where they quickly build up due to small scale dynamo action (e.g. Schleicher et al. 2010; Sur et al. 2011; Federrath et al. 2011; Schober et al. 2011). Magnetic fields exist also in the intergalactic medium (IGM). In particular, galaxy clusters exhibit $\mu$G fields (Clarke et al. 2001), which require non-negligible initial seeds (Dubois & Teyssier 2003; Ryu et al. 2008; Miniati & Martin 2011). Also, tiny but significant magnetic fields appear to exist in cosmic voids, as recently suggested by gamma-ray experiments (Neronov & Vovk 2010; Tavecchio et al. 2010; Taylor et al. 2011 but see Broderick et al. (2011)). The generation of magnetic fields in cosmic environments is generally slower than in galaxies, owing to the longer dynamical timescales.

Various astrophysical mechanisms have been proposed for the origin of intergalactic magnetic fields (Miniati & Bell 2011; Schlickeiser & Shukla 2003; Bertone et al. 2003; Ando et al. 2010). In particular, Miniati & Bell (2011) make consistent predictions for the magnetic fields observed in the cosmic voids. Primordial models of magnetogenesis (e.g. Grasso & Rubinstein 2001) provide an alternative scenario. Unlike most astrophysical cases, their seeds are not-necessarily negligible. This is particularly so for some inflationary scenarios (Turner & Widrow 1988), electroweak phase transition (Baym et al. 1996), or QCD phase transition (Ohashi et al. 1989; Cheng & Olinto 1993; Sigl et al. 1993; Banerjee & Jedamzik 2003). Therefore several efforts to constrain primordial seeds have been made.

Probing magnetic fields at high redshift is however still challenging. A primordial magnetic field has an impact on the CMB anisotropies (e.g. Barrow et al. 1997; Subramanian 2006; Durrer 2007) and the latest analysis implies an upper limit on the co-moving field strength $B_0 < 3 \mu G$ at 95% CL (Yang et al. 2010), where $B_0 \equiv B(z)/(1+z)^2$. Constraints from Big Bang nucleosynthesis can also be obtained, with $B_0 \lesssim 1 \mu G$ (Grasso & Rubinstein 1996). Considerations of gravitational wave production seem to rule out magnetic field production during primordial phase transitions (Caprini et al. 2008). Finally, as pointed out in various works (e.g. Coles 1992; Kim et al. 2011; Schlickeiser & Shukla 2003; Bertone et al. 2003; Ando et al. 2010). In particular, Miniati & Bell (2011) make consistent predictions for the magnetic fields observed in the cosmic voids. Primordial models of magnetogenesis (e.g. Grasso & Rubinstein 2001) provide an alternative scenario. Unlike most astrophysical cases, their seeds are not-necessarily negligible. This is particularly so for some inflationary scenarios (Turner & Widrow 1988), electroweak phase transition (Baym et al. 1996), or QCD phase transition (Ohashi et al. 1989; Cheng & Olinto 1993; Sigl et al. 1993; Banerjee & Jedamzik 2003). Therefore several efforts to constrain primordial seeds have been made.

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In order to assess the impact of primordial magnetic fields by considering their impact on the reionization process. Our analysis is based on the latest data of the high redshift IGM. In particular, we use observed UV luminosity function at redshifts \( z \sim 4 - 8 \) (Bouwens et al. 2011) and the recent observations of a \( z = 7.085 \) quasar (Mortlock et al. 2011) which indicates a fraction of neutral hydrogen of \( 10^{-4} - 10^{-3} \) at \( z \sim 7 \) (Bolton et al. 2011). We find that \( B_0 \lesssim 2 - 3 \text{ nG} \), similar to findings from the latest CMB analysis (Yamazaki et al. 2010). More importantly, our constraint is complementary with the latter as it is based on different physical processes and refers to a different cosmological epoch. Throughout we use the cosmological parameters from WMAP7 (Komatsu et al. 2011).

2 TECHNICAL APPROACH

In order to solve the following equation for the evolution of the volume fraction of ionized hydrogen, \( Q_{\text{H II}} \) (Madau et al. 1999)

\[
\frac{dQ_{\text{H II}}}{dt} = -\frac{Q_{\text{H II}}}{t_{\text{rec}}} + \text{SFR}(z) f_{\text{esc}} 10^{53.2} \frac{n_{\text{H}}(0)}{n_{\text{H}}(0)},
\]

where \( n_{\text{H}}(0) \) is the comoving number density of neutral hydrogen and the other parameters are described below. For our reference model we assume the parameter values as in Bouwens et al. (2011), see also references therein, which reproduce the Thomson optical depth observed by WMAP7 within 1σ. However, for the cosmological parameters we use the more recent WMAP7 results (Komatsu et al. 2011). As discussed below, this makes a negligible difference. So, the adopted escape fraction of Lyman-continuum photons is \( f_{\text{esc}} = 0.2 \). The temperature of the reionized IGM is \( 2 \times 10^4 \, K \), leading to an hydrogen recombination timescale

\[
t_{\text{rec}} = 1.0 \, \text{Gyr} \left( \frac{1 + z}{7} \right)^{-3} C_3^{-1},
\]

where \( C_3 \) is the clumping factor normalized to a value of 3. Note that the recombination timescale would decrease by a factor of 2 for an IGM temperature of \( 10^4 \, K \). The factor \( 10^{53.2} \) in Eq. (1) is the production rate of Lyman-continuum photons per \( M_{\odot} \, \text{yr}^{-1} \) of forming stars, enhanced by 30% for metal-poor stars in galaxies in the early universe (Bouwens et al. 2011). The cosmic star formation rate, SFR, uncorrected for dust attenuation and in \( M_{\odot} \, \text{yr}^{-1} \), is

\[
\text{SFR} = \int_{-\infty}^{M_{\text{UV}}^{\text{max}}} \Phi(M_{\text{UV}}) \dot{\rho}_{\ast}(M_{\text{UV}}) \left( 10^{-0.4(M_{\text{UV}}-M_{\text{UV}}^{\ast})} \right),
\]

where \( \Phi(M_{\text{UV}}) \) is the Schechter function as a function of the UV magnitude, \( M_{\text{UV}} \), and \( M_{\text{UV}}^{\ast} \) its characteristic magnitude. As for the parameters entering the Schechter function (including \( M_{\text{UV}}^{\ast} \)) we use the observational values in Table 1 of Bouwens et al. (2011). The star formation rate (uncorrected for dust attenuation) for a galaxy with magnitude \( M_{\text{UV}} \) is obtained by manipulation of the expression in Madau et al. (1998) and reads

\[
\dot{\rho}_{\ast}(M_{\text{UV}}) = 5.43 \times 10^{-20} (M_{\text{UV}} + 20)^{-1/2} M_{\odot} \, \text{yr}^{-1}.
\]

Eq. (3) contains contributions up to a limiting magnitude, \( M_{\text{UV}}^{\text{max}} \). Bouwens et al. (2011) assumes \( M_{\text{UV}}^{\text{max}} = -10 \), corresponding to the mass scales where galaxy formation is suppressed due to inefficient gas cooling and/or feedback effects. Here we generalize this limit to include effects of magnetic pressure on the Jeans mass. For this purpose we use the filtering mass \( M_F \) (Gnedin & Hui 1998, Schleicher et al. 2008)

\[
M_F^{2/3} = \frac{3}{a} \int_0^a d a' M_{\ast}^{2/3}(a') \left[ 1 - \left( \frac{a'}{a} \right)^{1/2} \right] ,
\]

where, \( a_0 \) denotes the maximum of the thermal, \( M_\ast \), and magnetic Jeans masses, \( M_F^{\ast} \). These are, respectively

\[
M_F = 2 M_\odot \left( \frac{c_s}{0.2 \, \text{km/s}} \right)^3 \left( \frac{n}{1000 \, \text{cm}^{-3}} \right)^{-0.5}
\]

with \( c_s \) the sound speed and \( n \) the gas number density, and (Subramanian & Barrow 1998)

\[
M_{\ast}^{\text{max}} = 10^{10} M_\odot \left( \frac{B_0}{3 \, \text{nG}} \right)^3,
\]

with \( B_0 \) the co-moving field strength. Finally, to convert the filtering mass scale into a UV magnitude, we use the following relation inferred from Fig. 10 of Salvaterra et al. (2011) (which also consistently reproduces the above limiting magnitude in absence of magnetic field)

\[
M_{\text{UV}}(M_{\text{halo}}) = -20 - 3 \times \log_{10} \left( \frac{M_{\text{halo}}}{10^{10.75} M_\odot} \right).
\]

In addition to the volume fraction of ionized hydrogen, our calculation follows the time evolution of the temperature and ionization degree of the partially-ionized IGM, and the magnetic field strength. The full set of equations is given in Schleicher et al. (2008) and was implemented in the RECFAST code (Seager et al. 1999). In particular, the magnetic energy decreases with time due to adiabatic expansion and dissipation into heat through ambipolar diffusion. For strong fields this can change substantially the thermal and ionization history of the IGM, although full reionization cannot be achieved this way, as collisions induced by ambipolar diffusion become inefficient at high temperatures.

With the calculation results, the Thompson scattering optical depth is computed as

\[
\tau_e = \frac{n_{\text{H}}(0) c}{H_0} \int_{z=0}^{z_{\text{rec}}} x_{\text{eff}}(z) \sigma_T \frac{(1+z)^2}{\sqrt{\Omega_L + \Omega_m (1+z)^3}} \text{d}z,
\]

where \( \sigma_T \) is the Thompson scattering cross section and the effective ionization degree is

\[
x_{\text{eff}} = Q_{\text{H II}} + (1 - Q_{\text{H II}}) x_e
\]

1 http://www.astro.ubc.ca/people/scott/recfast.html
3 RESULTS

In the following, we set the upper limits on the comoving magnetic field strength, \( B_0 \), using the Thomson optical depth (a redshift-integrated quantity) as well as the observed ionization degree at \( z \approx 7 \). We discuss the uncertainties due to the cosmological parameters, the reionization pa-

contributed by both the fully ionized volume fraction as well as the partially ionized gas.
Fig. 1 shows the constraints on future progress on the high redshift IGM. We discuss the possibility of more stringent constraints from the cosmological parameters and the observed UV luminosity function. Finally, we discuss the possibility of more stringent constraints from future progress on the high redshift IGM.

3.1 Constraints from the Thompson optical depth

Fig. 1 shows the constraints on $B_0$ due to the observed optical depth, $\tau_e$, and its uncertainties. Starting from our reference case in the top panel, we see that for weak magnetic fields the optical depth is well within the 1σ range of WMAP7 results. As $B_0$ increases the low-luminosity cutoff of halos contributing ionizing photons is raised and at $B_0 \gtrsim nG$, $\tau_e$ starts to drop. It reaches a minimum at several nG and then, as collisional ionization resulting from heating due to ambipolar diffusion kicks in, $\tau_e$ increases again (however, values of several nG for $B_0$, would be inconsistent with CMB observations, e.g., Yamazaki et al. 2010). This is the qualitative trend in all panels of Fig. 1, 2 and 3.

The top panel also shows the effects of 3σ variations of the cosmological parameters, on $\tau_e$. For the purpose of the current discussion, higher values of $H_0$ and smaller values of $\Omega_M$ increase the value of $\tau_e$ and thus weaken the constrain on $B_0$. Thus, the constraint on $B_0$ is set by the highest curve, which says that the required field strength at the 95% CL limit is 3 nG. Note also that adopting a cosmology as in Bouwens et al. (2011) would have minor effects on our results.

In the mid panel we consider instead the effect due to uncertainties in the reionization parameters. Such uncertainties can in principle be very large. However, a large clumping factor $\sim 30$ is inconsistent with the observed ionization fraction (see Fig. 2) even in the limit of weak magnetic fields. Likewise, a very large escape fraction $f_{esc} \sim 50\%$ produce too high an ionization rate at $z \lesssim 6$ (Srbinovsky & Wyithe 2011; Miniati et al. 2004). With these considerations, a meaningful 95% CL upper limit of 2 nG is implied by our results.

Finally, in the bottom panel we consider the uncertainties due to 3σ observational errors in the parameters $\alpha$, $M_{UV}^*$ and $\Phi^*$, of the Schechter function. Here, it is large values of $\Phi^*$ or $M_{UV}^*$ that increase $\tau_e$, and therefore weaken our constraint. Thus, the highest curve on the plot shows that the computed value of $\tau_e$ remains within 2σ of the WMAP7 result for $B_0 \lesssim 3nG$. Note that the redshift evolution of the Schechter function parameters is also very uncertain, but we have verified that it does not lead to more significant uncertainties on the current constraints. We thus arrive at a 95% CL upper limit of $\sim 2 - 3$ nG on $B_0$.

3.2 Constraints from the ionization degree

Fig. 2 shows the constraints due to the observed ionization degree, $x_{eff}$, and its uncertainties. Following the analysis of Bolton et al. (2011), the IGM is assumed mostly ionized at $z \sim 7$. Note that for the present purposes the accurate value of the ionization degree is not crucial and even a 90% value would lead to very strong constraints independent of the specifically adopted CL. In our reference case (top panel), we find at $z = 7$ an ionization degree close to 1 for co-moving field strengths up to $\sim 1.5$ nG. For increasing field strengths, $x_{eff}$ drops rapidly, as the magnetic Jeans mass increases with $B_0$, significantly suppressing the production of ionizing photons. Thus considering all the uncertainties due to the cosmological parameters leads to $B_0 < 2nG$.

As already discussed for the optical depth, the uncertainties due to the reionization parameters are considerably higher (mid panel). However, cases with high clumping factors, low escape fractions or low IGM temperatures and even very high escape fraction (Srbinovsky & Wyithe 2010; Miniati et al. 2004) are inconsistent even in the limit of weak magnetic fields. For the remaining cases, the ionization degree drops rapidly for $B_0$ above a nG, and the most conservative upper limit corresponds again to $B_0 \lesssim 2nG$.

As for the uncertainties in the parameters of the Schechter function bottom panel of Fig. 2 shows that some extreme values can be ruled out because inconsistent with the ionization degree at $z = 7$, even with negligible $B_0$. However, the most important source of uncertainty for the upper limit on $B_0$ are those related to $M_{UV}^*$. This forces our constraint to $B_0 \lesssim 3nG$. This constraint will be improved once the Schechter function is observed more accurately. Again, we checked that the uncertainties in the redshift evolution have no impact on our results. From the observed ionization degree, we thus find an overall constraint $B_0 \lesssim 2 - 3$ nG.

In Fig. 3 we show the ionization degree at different redshifts as a function of the co-moving field strength. The plot illustrates the sensitivity of our constraint to the redshift at which the ionization degree is measured. In particular our constraint would be slightly weaker if based on data at $z = 6$, while it would considerably improve if a high ionization degree at $z = 8$ could be observationally established. At even higher redshifts, our model predicts the presence of a substantial neutral fraction in the IGM which could be translated into a further independent constraint.

4 DISCUSSION AND OUTLOOK

Using the combined constraints from the observed Thomson optical depth, the ionization degree of the IGM at $z = 7$ and the observed UV luminosity function at high redshifts, we have derived robust upper limits of $2 - 3$ nG, virtually
independent of the CL, on the strength of primordial magnetic fields. Previous work (e.g. Sethi & Subramanian 2003; Tashiro & Sugiyama 2006; Schleicher et al. 2008, see also Introduction) found similar limits but generally was based on the Thomson optical depth only, used less refined physical models, had a lower CL. However, the similarity of conclusion also suggests that we are approaching the intrinsic limitation of the methods.

Our results are mostly based on the lower cutoff of the luminosity function of galaxies contributing ionizing photons, set by the magnetic Jeans mass (Eq. 7). On the other hand, heating effects due to ambipolar diffusion are important for $B_0$ close to 10 nG, which is ruled out by CMB observations. Our constraints on the primordial magnetic field would mostly strengthened by measurements of a high ionization degree at redshift $z \gtrsim 8$. This is simply because the earlier the IGM is reionized, the more important becomes the contribution of ionizing photons from halos whose collapse is hindered by primordial magnetic fields. However, improvements beyond an order of magnitude are likely out of reach, as the formation of structure at the magnetic Jeans mass corresponding to $10^{-10}$ G (see Eq. 7) is severely affected by other feedback processes (e.g., discussion in Bouwens et al. 2011). Other limiting factors in the derivation of our constraints are mostly due to uncertainties in the UV luminosity function at high redshift and lack of information about the IGM ionization fraction at redshift higher than 7. There is reason to expect good progress in these areas in the near future. For example, JWST will provide a unique opportunity to probe the IGM at and beyond redshift 10, Lyman $\alpha$ emitters may provide additional information on the strength of the photoionizing background (e.g. Latif et al. 2011), while the Planck satellite will provide an improved measurement of the Thomson optical depth. These additional data may help to improve our understanding both with respect to reionization and the origin of magnetic fields.

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REFERENCES

Ando M., Doi K., Susa H., 2010, ApJ, 716, 1566
Banerjee R., Jedamzik K., 2003, Physical Review Letters, 91, 251301
Barrow J. D., Ferreira P. G., Silk J., 1997, PRL, 78, 3610
Battaner E., Florido E., Jimenez-Vicente J., 1997, A&A, 326, 13
Baym G., BÖdeker D., McLerran L., 1996, PRD, 53, 662
Beck R., Brandenburg A., Moss D., Shukurov A., Sokoloff D., 1996, ARA&A, 34, 155
Bernet M. L., Miniati F., Lilly S. J., Kronberg P. P., Dessauges-Zavadsky M., 2008, Nature, 454, 302
Bertone S., Vogt C., Enßlin T., 2006, MNRAS, 370, 319
Bolton J. S., Haehnelt M. G., Warren S. J., Hewett P. C., Mortlock D. J., Venemans B. P., McMahon R. G., Simpson C., 2011, ArXiv e-prints
Bouwens R. J., Illingworth G. D., Oesch P. A., Labbe I., Trenti M., van Dokkum P., Franx M., Stiavelli M., Carollo C. M., Magee D., Gonzalez V., 2010, ArXiv e-prints
Bouwens R. J., Illingworth G. D., Oesch P. A., Trenti M., Labbe I., Franx M., Stiavelli M., Carollo C. M., van Dokkum P., Magee D., 2011, ArXiv e-prints
Broderick A. E., Chang P., Pfrommer C., 2011, ArXiv e-prints
Caprini C., Durrer R., Fenu E., 2009, JCAP, 11, 1
Cheng B., Olinto A. V., 1994, PRD, 50, 2421
Clarke T. E., Kronberg P. B., Böhringer H., 2001, ApJL, 547, L111
Coles P., 1992, Comments on Astrophysics, 16, 45
Dubois Y., Teyssier R., 2008, A&A, 482, L13
Durrer R., 2007, NewAR, 51, 275
Federrath C., Chabrier G., Scholer J., Banerjee R., Klessen R. S., Schleicher D. R. G., 2011, Physical Review Letters, 107, 114504
Gnedin N. Y., Hui L., 1998, MNRAS, 296, 44
Grasso D., Rubinstein H. R., 1996, Phys. Lett. B, 379, 73
Grasso D., Rubinstein H. R., 2001, Phys. Rep., 348, 163
Kim E.-J., Olinto A. V., Rosner R., 1996, ApJ, 468, 28
Komatsu et al. 2011, ApJS, 192, 18
Latif M. A., Schleicher D. R. G., Spaans M., Zaroubi S., 2011, A&A, 532, A66+
Madau P., Haardt F., Rees M. J., 1999, ApJ, 514, 648
Madau P., Pozzetti L., Dickinson M., 1998, ApJ, 498, 106
Miniati F., Bell A. R., 2011, ApJ, 729, 73
Miniati F., Ferrara A., White S. D. M., Bianchi S., 2004, MNRAS, 348, 964
Miniati F., Martin D. F., 2011, ApJS, 195, 5
Mortlock et al. 2011, Nature, 474, 616
Murphy E. J., 2009, ApJ, 706, 482
Neronov A., Vovk I., 2010, Science, 328, 73
Quashnock J. M., Loeb A., Spergel D. N., 1989, ApJL, 344, L49
Ryu D., Kang H., Cho J., Das S., 2008, Science, 320, 909
Salvaterra R., Ferrara A., Dayal P., 2011, MNRAS, 414, 847
Schleicher D. R. G., Banerjee R., Klessen R. S., 2008, PRD, 78, 083005
Schleicher D. R. G., Banerjee R., Sur S., Arshakian T. G., Klessen R. S., Beck R., Spaans M., 2010, A&A, 522, A115+
Schlickeiser R., Shukla P. K., 2003, ApJL, 599, L57
Scholer J., Schleicher D., Federrath C., Klessen R., Banerjee R., 2011, ArXiv e-prints 1109.4571
Seager S., Sasselov D. D., Scott D., 1999, ApJL, 523, L1
Sethi S. K., Subramanian K., 2005, MNRAS, 356, 778
Sigel G., Olinto A. V., Jedamzik K., 1997, PRD, 55, 4582
Srbinovský J. A., Wyithe J. S. B., 2010, PASA, 27, 110
Subramanian K., 2006, Astron. Nachr., 327, 403
Subramanian K., Barrow J. D., 1998, PRD, 58, 083052
Sur S., Schleicher D. R. G., Banerjee R., Federrath C., Klessen R. S., 2010, ApJL, 721, L134
Tashiro H., Sugiyama N., 2006, MNRAS, 368, 965

2 Homepage JWST: http://www.stsci.edu/jwst/
3 Homepage Planck: http://www.rssd.esa.int/index.php?project=Planck
Tavecchio F., Ghisellini G., Foschini L., Bonnoli G., Ghirlanda G., Coppi P., 2010, MNRAS, 406, L70
Taylor A. M., Vovk I., Neronov A., 2011, A&A, 529, A144+
Turner M. S., Widrow L. M., 1988, PRD, 37, 2743
Yamazaki D. G., Ichiki K., Kajino T., Mathews G. J., 2010,
Advances in Astronomy, 2010