Reionization constraints on primordial magnetic fields

Kanhaiya L. Pandey\textsuperscript{1⋆}, T. Roy Choudhury\textsuperscript{1}, Shiv K. Sethi\textsuperscript{2} and Andrea Ferrara\textsuperscript{3}

\textsuperscript{1}National Centre for Radio Astrophysics, TIFR, Pune 411100, India
\textsuperscript{2}Raman Research Institute, Bangalore 560080, India
\textsuperscript{3}Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy

3 October 2014

ABSTRACT

We study the impact of the extra density fluctuations induced by primordial magnetic fields on the reionization history in the redshift range: 6 < z < 10. We perform a comprehensive MCMC physical analysis allowing the variation of parameters related to primordial magnetic fields (strength, $B_0$, and power-spectrum index $n_b$), reionization, and $\Lambda$CDM cosmological model. We find that magnetic field strengths in the range: $B_0 \simeq 0.05$–0.3 nG (for nearly scale-free power spectra) can significantly alter the reionization history in the above redshift range and can relieve the tension between the WMAP and quasar absorption spectra data. Our analysis puts upper-limits on the magnetic field strength $B_0 < 0.362, 0.116, 0.057$ nG (95% c.l.) for $n_b = -2.95, -2.9, -2.85$, respectively. These represent the strongest magnetic field constraints among those available from other cosmological observables.

Key words: dark ages, reionization, first stars – intergalactic medium – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

Magnetic fields are ubiquitously present in the universe and play an important role in various astrophysical processes: star formation, accretion disks, proto-planetary disks, formation and stability of jets, dynamics of inter stellar medium (ISM), etc. (e.g. Parker 1979, Zeldovich, Ruzmaikin, & Sokolov 1983). However their role is still not well understood on larger scales and in the cosmological context, e.g. in the process of formation of the early galaxies and structure formation (e.g. Widrow 2002). At present, the possible impact of cosmic magnetic fields is being investigated for a host of observables in astrophysics and cosmology. The probe of such fields is also one of the principle aims of many of the ongoing and upcoming large radio interferometers such as LOFAR\textsuperscript{3} and SKA\textsuperscript{4}.

Magnetic fields in the universe are known to be coherent over the scales of galaxies and galaxy clusters, $\sim 10$–50 kpc (e.g. Beck 2012, Widrow 2002). There is also evidence of coherent magnetic fields over super-cluster scales (Kim et al. 1989). These fields could have arisen from the dynamo amplification of very small seed fields ($\sim 10^{-9}$ G) generated in the early universe (e.g. Beck 2012). Alternatively, the observed fields might owe their origin to far stronger large scale primordial fields ($\sim 10^{-5}$ G) that could have been generated during inflation or other an early phase transition in the universe

\textsuperscript{3} Email: kanhaiya@ncra.tifr.res.in
\textsuperscript{1} http://www.lofar.org/
\textsuperscript{2} https://www.skatelescope.org/

\textsuperscript{5} October 2014

\textsuperscript{6} Copyright by the owner/author(s). Use permitted only under the terms of the Creative Commons Attribution License (by) http://creativecommons.org/licenses/by/3.0/
parameter MCMC analysis to compare with available data sets. The main goal is to check the level of constraints one can put on the primordial magnetic field.

There is another aspect related to the magnetic fields, early formation of galaxies and reionization which is worth considering. Models which are consistent with all available data sets usually require some efficient sources of ionizing photons at high redshifts, e.g., metal-free PopIII stars (Choudhury & Ferrara 2005; Mitra, Choudhury, & Ferrara 2011) in addition to the usual PopII stars. These PopIII sources, however, are unlikely to contribute significantly to the photon budget at lower redshifts $z \lesssim 9$ because of feedback effects, which is crucial in matching the low photoionization rate inferred from quasar absorption spectra $z \sim 6$ (Bolton & Haehnelt 2007). One can thus conclude that in order to match the data sets, one requires a high ionizing emissivity at $z \sim 10$ which should preferably decrease by $z \sim 6$. In this regard, the presence of magnetic fields may assist in producing large number of dark matter haloes at high redshifts, and hence would help in reconciling with data sets without invoking any other sources like PopIII stars. This paper considers the effect of primordial magnetic field on the structure formation as a viable source which can affect the reionization process appreciably.

The plan of the paper is as follows: we discuss the model of reionization and the impact of the inclusion of primordial magnetic field in the next section. The main results are presented in Section 3. We summarize our results and discuss their implications in section 4.

2 METHOD

We first briefly summarize the main features of the reionization model used in this paper; the details can be found in Choudhury & Ferrara (2005), Choudhury & Ferrara (2006) and Choudhury (2009). The model follows the ionization and thermal histories of neutral, HI and HeII regions simultaneously and self-consistently accounting for the IGM inhomogeneities based on a method outlined in Miralda-Escudé, Haehnelt, & Rees (2000). The density distribution of the IGM is assumed to be lognormal. The rate of number of ionizing photons per unit volume (i.e., ionizing emissivity) in the IGM from galaxies is assumed to be given by

$$n_{\text{ph}}(z) = n_b N_{\text{ion}} \frac{d f_{\text{coll}}}{d t},$$

where $n_b$ is the number density of baryons and $f_{\text{coll}}$ is the dark matter collapsed fraction. The proportionality constant $N_{\text{ion}}$ physically represents the number of ionizing photons in the IGM per baryon in collapsed objects. It can be written as

$$N_{\text{ion}} = \epsilon f_{\text{esc}} n_b m_p \int_{\nu_{\text{HI}}}^{\infty} d\nu \left[ \frac{d N_{\nu}}{d M} \right],$$

where $\epsilon$ is the fraction of baryons within collapsed haloes going into stars, $f_{\text{esc}}$ is the escape fraction of ionizing photons and $d N_{\nu}/d M$ gives the number of ionizing photons (i.e., those with frequencies higher than the ionization threshold $\nu_{\text{HI}}$) per frequency interval per unit stellar mass and is determined by the stellar IMF and the corresponding stellar spectra. We assume the stars to be Population II with subsolar metallicity $Z = 0.001 = 0.05 Z_\odot$ with a Salpeter IMF in the mass range 1 – 100 $M_\odot$. With this assumption, the parameter $N_{\text{ion}}$ will be given by

$$N_{\text{ion}} \approx 3200c_{\text{HI}} f_{\text{esc}, \text{HI}} = 3200 c_{\text{HI}},$$

where we have defined $c_{\text{HI}} \equiv c_{\text{HI}} f_{\text{esc}, \text{HI}}$. We assume $c_{\text{HI}}$ to be independent of redshift and consider it as a free parameter in our model. In this work, we do not invoke any other sources of reionization which are often done in other studies, e.g., metal-free PopIII stars. Our main aim would be to verify if the presence of magnetic fields is able to eliminate the requirement of PopIII stars and still give a good match to the data.

The collapse fraction, $f_{\text{coll}}$, depends on the minimum mass of star-forming haloes. In neutral regions, we assume it to be determined by atomic cooling (i.e. we neglect cooling through molecular hydrogen). However, the minimum mass will be larger in ionized regions because of radiative feedback. Our model can compute radiative feedback (suppressing star formation in low-mass haloes using a Jeans mass prescription) self-consistently from the evolution of the thermal properties of the IGM. The corresponding filtering scale, which depends on the temperature evolution of the IGM, is found to be typically around $\sim 30$ km s$^{-1}$.

The HI photoionization rate is given by

$$\Gamma_{\text{HI}}(z) = 4\pi (1+z)^3 \int_{\nu_{\text{HI}}}^{\infty} d\nu \lambda_{\text{mp}}(z, \nu) \bar{n}_e(z) \sigma_{\text{HI}}(\nu),$$

where $\sigma_{\text{HI}}$ is the photoionization cross section and $\lambda_{\text{mp}}$ is the mean free path of ionizing photons. The mean free path is modelled as $\lambda_{\text{mp}} \equiv \lambda_{\text{esc}}$, where

$$\lambda_{\text{mp}}(z) = \frac{\lambda_0}{(1 - F_V(z))^{2/3}},$$

where $F_V$ is the volume fraction of ionized regions and $\lambda_0$ is a normalization parameter. This parameter can be constrained using the redshift distribution of Lyman-limit systems

$$\frac{d N_{\text{LL}}}{dz} = \frac{c}{\sqrt{\pi} \lambda_{\text{mp}}(z) H(z)(1+z)},$$

Given a reionization history, we compute the angular power spectra $C_l$ of CMB temperature and $(E$-mode$)$ polarization anisotropies. We combine our calculations with the publicly available code CAMB1 (Lewis, Challinor, & Lasenby 2000) in order to do so. The crucial parameter which determines the $C_l$ is the electron scattering optical depth

$$\tau_\text{el}(z) = \sigma_T c \int_0^{\tau(z)} dt n_e(z) (1+z)^3,$$

where $n_e(z)$ is the comoving number density of free electrons and $\sigma_T$ is the Thomson cross section.

2.1 Inclusion of magnetic fields

The effect of the magnetic field is included by adding the additional matter power induced by these fields to the usual dark matter power spectrum $P_{\Delta M}(k)$. As we show below, the collapsed fraction $f_{\text{coll}}$, which determines the ionizing emissivity in equation (1), is a sensitive function of $P_{\Delta M}(k)$ and hence the inclusion of magnetic fields can significantly alter the reionization history.

We assume the primordial magnetic field to be a stochastic Gaussian field (see Mack, Kahniashvili, & Kosowsky 2002 and references therein). For a non-helical magnetic field, the

1 http://camb.info/
two-point correlation function of the tangled field can be written as:

\[ \langle B_i^*(k)B_j(k') \rangle = (2\pi)^3 \delta^{(3)}(k - k')P_{ij}(k)P_0(k). \]  

Here \( i \) and \( j \) are spatial indices, \( i, j \in (1, 2, 3), \) \( \hat{k}_i = k_i/k \) a unit wave vector, \( P_{ij}(k) = \delta_{ij} - \hat{k}_i\hat{k}_j \) the transverse plane projector, \( \delta^{(3)}(k - k') \) the Dirac delta function, and \( P_0(k) = A^2k^{5n} \) is the power spectrum of the magnetic field; here \( A \) normalizes the power in magnetic fields and \( n_B \) is the spectral index. The parameter \( A \) is computed by defining the RMS of magnetic field at cut off scale \( k_c; \) the RMS for \( k_c = 1 \) Mpc\(^{-1}\) is referred to as the magnetic field strength, \( B_0 \) (Kim, Olinto, & Rosner 1996, Gopal & Sethi 2003). The magnetic field power spectrum drops at small scales owing to dissipation in the pre-recombination era. The cut-off scale \( k_{\text{max}} \) is determined by the Alfvén wave damping scale \( k_{\text{max}}^{-1} \approx v_A L_S \), where \( v_A \) is the Alfvén velocity and \( L_S \) the Silk damping scale (Jedamzik, Katalinic, & Olinto 1998). \( k_{\text{max}} \) \( \approx 200 \) (1 nG/\( B_0 \)) Mpc\(^{-1}\).

The primordial magnetic field induces density perturbations in the post-recombination era which grow by gravitational collapse (Wasserman 1978, Kim, Olinto, & Rosner 1996, Gopal & Sethi 2003). The matter power spectrum induced by magnetic fields has the shape: \( P(k) \propto k^{2n_B+3} \) for \( n_B \leq -1.5; \) this matter power spectrum is cut off at the magnetic field Jeans’ scale: \( k_J \approx 15(2\pi nG/B_0) \) Mpc\(^{-1}\). (Kim, Olinto, & Rosner 1996, Gopal & Sethi 2003). The matter power spectrum is shown in the Figure 1 for different values of \( B_0 \) and \( n_B \) along with the power spectrum for the usual \( \Lambda \)CDM case. In the calculation of matter power spectrum in presence of magnetic field, we have used a sharp cut-off at the magnetic Jeans scale \( k_J \). It has been shown from other cosmological observables that the only class of acceptable magnetic field models correspond to the near scale-free models, \( n_B \approx -3 \) (e.g. Sethi & Subramanian 2005). Hence in this work we study only models with \( n_B \) very close to \(-3\).

In this paper we assume the sources of inflationary density perturbations and magnetic field generation to be uncorrelated. This allows us to add the two matter power spectra in quadrature for our computation. It should also be underlined that the presence of sub-nG fields does not substantially change the normalization of \( \sigma_8 \), as magnetic field induced matter power spectra make negligible contribution to the scales of interest: \( k \approx 0.01-0.5 \) Mpc\(^{-1}\). As noted above, the main impact of the extra matter power induced by magnetic fields is to increase the collapse fraction and alter its evolution. This induced power spectrum (Figure 1) causes collapse of mass haloes close to the magnetic field Jeans’ scale (e.g. Kahniashvili et al. 2010) and therefore changes ionization history which might not be reproducible by altering parameters within the framework of \( \Lambda \)CDM model.

\[ \]
We first discuss the effects of non-zero magnetic field on the reionization history. In addition to fixing Ω_m, Ω_b, h as mentioned above, we fix the values of the cosmological parameters σ_8 = 0.801, n_s = 0.963 to their best-fit values, and also fix n_b = −2.9. The arguments presented in this section would hold equally well for any other value of n_b close to −3. It is sufficient to vary the efficiency parameter ε_{II} and the magnetic field B_0 to understand the effect. The models and the parameters considered in this subsection are summarized in Table 1

| Parameter Model A  | Model B  | Model C  |
|-------------------|----------|----------|
| B_0 (nG)           | 0.0      | 0.0      | 0.08     |
| ε_{II}             | 0.006    | 0.0175   | 0.006    |

Table 1. Models used for discussing the effect of B_0 on reionization history.

Q_{III} and the hydrogen photoionization rate Γ_{HI} in Figure 2. We also compare the models with relevant observational data, i.e., with the WMAP7 constraints on τ_{el} (Komatsu et al. 2011) and the measurements of Γ_{HI} from Lyα forest data [Wyithe & Bolton 2011] [Becker & Bolton 2013]. Consider first model A, which has no magnetic field. The value of ε_{II} is chosen such that it is consistent with the upper limits of Γ_{HI} measurements at z = 6 (right hand panel), i.e., this is the largest ε_{II} consistent with the Lyα forest data. The left hand panel shows that this model underpredicts the value of τ_{el} given by the WMAP7 observations. If we try to match the τ_{el} constraints without introducing any additional physics, we have to increase the value of ε_{II}. Model B represents such a scenario where ε_{II} has been increased by a factor of ~3 compared to A. Now the model with τ_{el} is quite good, however, this model overpredicts the Γ_{HI} at z = 6 by a large amount.⁶

We now introduce a non-zero magnetic field B_0 = 0.08 nG (with n_b = −2.9) in our model. It is possible to repeat the following exercise with any other value of n_b by choosing an appropriate B_0. The efficiency parameter in model C is kept identical to model A. We now see that the model is able to match both the Γ_{HI} data at z = 6 and the τ_{el} constraints. This shows that magnetic field can be useful in relieving the tension between the CMB and QSO absorption line data sets. The main reason for this is that presence of magnetic field allows for early formation of galaxies and hence can drive early reionization. However, as reionization progresses, the radiative feedback effects become more important and eventually play a dominant role.

We plot the evolution of the electron scattering optical depth τ_{el}, the volume filling factor of ionized regions f_{coll}(> M) of haloes having mass greater than M for z = 10. Magnetic field values shown in the figure are in units of nG. The dashed lines are for the values of B_0 and n_b which are close to the best-fit values obtained from reionization constraints.

Figure 3. Collapsed fraction f_{coll}(> M) of haloes having mass greater than M for z = 10. Magnetic field values shown in the figure are in units of nG. The dashed lines are for the values of B_0 and n_b which are close to the best-fit values obtained from reionization constraints.

Figure 2. Effect of non-zero B_0 on quantities related to reionization. The left hand panel shows the evolution of electron scattering optical depth τ_{el}, the middle panel shows the volume filling factor of ionized regions and the right hand panel shows the evolution of the photoionization rate Γ_{HI}. We have also shown the observational data points, see text for details. The three models shown are summarized in Table 1.

3.2 Effect of magnetic fields on reionization history

We first discuss the effects of non-zero magnetic field on the reionization history. In addition to fixing Ω_m, Ω_b, h as mentioned above, we fix the values of the cosmological parameters σ_8 = 0.801, n_s = 0.963 to their best-fit values, and also fix n_b = −2.9. The arguments presented in this section would hold equally well for any other value of n_b close to −3. It is sufficient to vary the efficiency parameter ε_{II} and the magnetic field B_0 to understand the effect. The models and the parameters considered in this subsection are summarized in Table 1.

We plot the evolution of the electron scattering optical depth τ_{el}, the volume filling factor of ionized regions f_{coll}(> M) of haloes having mass greater than M for z = 10. Magnetic field values shown in the figure are in units of nG. The dashed lines are for the values of B_0 and n_b which are close to the best-fit values obtained from reionization constraints.

Figure 3. Collapsed fraction f_{coll}(> M) of haloes having mass greater than M for z = 10. Magnetic field values shown in the figure are in units of nG. The dashed lines are for the values of B_0 and n_b which are close to the best-fit values obtained from reionization constraints.
regulates the formation of ionizing sources at $z \sim 10$. This leads to a feedback-regulated, extended and photon-starved reionization which is required for good match with the data (Bolton & Haehnelt 2007; Mitra, Choudhury, & Ferrara 2011; Mitra, Choudhury, & Ferrara 2012). It also follows that this set of observations can also be used to put constraints on $B_0$.

There are alternate ways to achieve a reionization model which is consistent with all the data sets, e.g., by introducing star formation within minihaloes (Choudhury, Ferrara, & Gallerani 2008) or by including a population of metal-free stars at high redshifts (Choudhury & Ferrara 2006).

as too high a value of $B_0$ would lead to reionization too early and would violate the $\tau_{el}$ bounds.

In Figure 3, we show the collapsed fraction for different values of $B_0$ and the spectral index $n_B$. This figure allows us to understand the results of the current and the next section where we present detailed multi-parameter analysis. As noted above, the main impact of the primordial magnetic fields is to enhance density fluctuations at small scales (Figure 1). Figure 3 shows the impact of this addition to the collapsed fraction as a function of mass. The collapsed fraction is seen to be a sensitive and complex function of the parameter associated with primordial magnetic fields.

We could understand this dependence as follows.
For the magnetic field-induced density perturbations, the mass dispersion at a given scale: $\sigma(M) \propto B_0^2(n_B + 3)$ (Vasiliev & Sethi 2014). Also $\sigma(M) \propto M^{-2/3}$ above the magnetic field Jeans' scale which is a sharper fall as compared to the $\Lambda$CDM model in the relevant mass range. This also means that the collapsed fraction is dominated by a small range of mass scales around the magnetic field Jeans' scale (see e.g. Vasiliev & Sethi 2014, Figure 3). In the Press-Schechter formalism used to compute the collapsed fraction, the fraction increases with $\sigma(M)$ and could be exponentially sensitive to the mass dispersion. Therefore, we expect an increase in the mass fraction as $n_B$ is increased for a fixed $B_0$. A change in the value of $B_0$ results in two distinct effects: (i) $\sigma(M)$ increases which tends to increase the collapsed fraction (ii) the magnetic Jeans' length also increases (for details see discussion in section 2.2) which tends to decrease the collapsed fraction below the magnetic field Jeans' mass. The net effect of increasing the value of $B_0$ is to shift the collapsed fraction to larger masses while decreasing the fraction at smaller masses, as seen in Figure 3.

### 3.3 Constraints on $B_0$

In this section, we present results related to the constraints on $B_0$ based on detailed multi-parameter MCMC analysis.
Reionization and magnetic fields

We have modified the publicly available code COSMOMC\footnote{http://cosmologist.info/cosmomc} (Lewis & Bridle 2002) to account for generic reionization histories (Mitra, Choudhury, & Ferrara 2011; Pandolfi et al. 2011) and the effect of magnetic field on the matter power spectrum. We take three different values of $n_B = -2.95, -2.90, -2.85$ and for each case we vary five parameters, namely, $\sigma_8, n_s, B_0, \epsilon_{II}, \lambda_0$, keeping all the rest of the parameters fixed. We constrain these parameters using the WMAP7 data on temperature and $E$-mode polarization angular power spectra (Komatsu et al. 2011), the photoionization rate in the IGM inferred from the Ly$\alpha$ forest at $z \leq 6$ (Wyithe & Bolton 2011; Becker & Bolton 2013) and the redshift distribution of Lyman-limit systems at $z < 6$ (Songaila & Cowie 2010).

We would like to mention here that, we tried case $n_B = -2.99$ too but it turned out that the effect of magnetic field on the mass function of collapsed haloes is negligible in the mass scales relevant for reionization. The reason is that the magnetic field-induced mass fluctuations have the dependence $\sigma(M) \propto B_0^2(n_B + 3)$, and hence one requires very high value of $B_0$ to obtain any significant effect when $n_B \to -3$. The collapsed mass fraction $f_{\text{coll}}(\gtrsim M)$ for $B_0 \sim 1 \text{ nG}$ is almost same as the non-magnetic case for $M \lesssim 10^{12} \text{ M}_\odot$, see Figure 3, thus implying that no significant effect on reionization history

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{likelihood_constraints}
\caption{Likelihood constraints for $n_B = -2.85$.}
\end{figure}
can be expected. If we try to increase the collapse mass fraction by making magnetic field value very high, the effect starts to show at very large scales (e.g., $B_0 \sim 100$ nG shows significant effects only for $M \gtrsim 10^{12}$ M$_\odot$). The reason for this is that magnetic Jeans cut-off scale is roughly proportional to the magnetic field strength ($\kappa_J \propto B_0^{-1}$). Since the contribution of high mass haloes to the total ionizing photon budget is negligible, they hardly make any difference to the reionization history. Consequently the magnetic field seems to play no role for $n_B = -2.99$. This also suggests that the reionization starts to become insensitive to magnetic field effects as $n_B \to -3$.

We show the results for three fixed values of $n_B$; Figure 6 shows the likelihood contours for $n_B = -2.95$ (which is almost scale-free). The contours for $n_B = -2.90$ are shown in Figure 5 and the ones for $n_B = -2.85$ are shown in Figure 4. The results of our analysis are summarized in Table 2.

We can understand our main results based on the discussion in the previous subsection. The upper limit on $B_0$ lies in the range $0.36-0.06$ nG and this limit decreases as $n_B$ is increased in the range $n_B = -2.95$ to $-2.85$, as we expect from the discussion in the previous subsection. We note from the figures that $B_0$ is anti-correlated with the two parameters $\epsilon_{II}$ and $\lambda_0$. This is expected as a decrease in $\epsilon_{II}$ which results in inefficient production of ionizing photons which can be compensated by an increase in $B_0$ leading to early halo formation. Similarly a decrease in $\lambda_0$ leads to smaller values of the photoionization rate which too can be compensated by a higher $B_0$. It is also not surprising that $B_0$ is strongly correlated with the derived parameter $\tau_{el}$, as larger values of $B_0$ leads to early reionization and hence larger $\tau_{el}$.

Our analysis shows (Table 2) that the best-fit value of $B_0$ is always non-zero, i.e., one obtains a better match to the data when a non-zero magnetic field is included in the reionization model. However, it is not possible to rule out the non-magnetic cases within 2-$\sigma$ limits. We also find that the inferred values of the cosmological parameters $\sigma_8$ and $n_s$ are quite close to but slightly larger than those obtained by the WMAP7 team

| Parameter | $n_B = -2.95$ | $n_B = -2.90$ | $n_B = -2.85$ |
|-----------|---------------|---------------|---------------|
| $\sigma_8$ | 0.810 0.809 [0.787, 0.841] | 0.809 0.807 [0.787, 0.840] | 0.810 0.805 [0.787, 0.834] |
| $n_s$ | 0.970 0.972 [0.957, 0.987] | 0.972 0.972 [0.957, 0.987] | 0.974 0.972 [0.957, 0.986] |
| $B_0$ (nG) | 0.182 0.147 < 0.362 | 0.085 0.062 < 0.116 | 0.049 0.033 < 0.057 |
| $\epsilon_{II}$ | 0.0042 0.0049 [0.0022, 0.0088] | 0.0044 0.0051 [0.0027, 0.0085] | 0.0040 0.0052 [0.0030, 0.0086] |
| $\lambda_0$ | 2.339 2.188 [0.922, 4.654] | 2.278 2.065 [0.963, 3.766] | 2.532 1.980 [0.936, 3.829] |
| $\tau_{el}$ | 0.086 0.083 [0.062, 0.119] | 0.084 0.080 [0.062, 0.119] | 0.084 0.079 [0.062, 0.111] |
| $\tau_{re}$ | 6.400 6.599 [5.800, 7.800] | 6.400 6.568 [5.800, 7.600] | 6.200 6.603 [5.800, 7.800] |

Table 2. Parameter constraints

4 DISCUSSION

We studied the possible role primordial magnetic fields might play in explaining the reionization history of the universe in the redshift range $z \approx 6-10$. These fields enhance the power in the dark matter density fluctuations at small scales thus allowing early structure formation. Our main results are: (i) a non-zero $B_0$ helps in relieving the tension between CMB and quasar absorption line data sets in the photon-starved reionization scenario by enabling early structure formation, and (ii) the data sets can be useful in putting an upper-limit on $B_0$, we obtain $B_0 < 0.362, 0.116, 0.057$ nG (95 % c.l.) for $n_B = -2.95, -2.9, -2.85$, respectively.

Many cosmological observables have been analysed to constrain the amplitude and the spectral index of the magnetic field power spectrum: CMB observations, early structure formation, weak gravitational lensing, Lyman-$\alpha$ data, etc.; these considerations put upper bounds on $B_0$ in the range 0.3–1 nG (e.g., Trivedi, Seshadri, & Subramanian 2012; Kahniashvili et al. 2010; Shaw & Lewis 2012; Pandey & Sethi 2013; Caprini, Durrer, & Kahniashvili 2011).

We are consistent with these constraints. Our results are also within the bounds obtained from Big Bang Nucleosynthesis constraints which give $B_0 \lesssim 1$ nG (Suh & Mathews 1999). Interestingly, even magnetic fields of smaller magnitude $\sim 0.1$ nG can have an appreciable and potentially detectable impact on the reionization history. In the future, one can possibly improve these bounds by understanding some of the physical processes related to reionization (e.g., feedback) through detailed modelling.
REFERENCES

Beck R., 2012, Space Sci. Rev., 166, 215

Becker G. D., Bolton J. S., 2013, MNRAS, 436, 1023

Bolton J. S., Haehnelt M. G., 2007, MNRAS, 382, 325

Caprini C., Durrer R., Kahniashvili T., 2004, Phys. Rev. D, 69, 063006

Choudhury T. R., 2009, Current Science, 97, 841

Choudhury T. R., Ferrara A., 2005, MNRAS, 361, 577

Choudhury T. R., Ferrara A., 2006, MNRAS, 371, L55

Choudhury T. R., Ferrara A., Gallerani S., 2008, MNRAS, 385, L58

Fan X. et al., 2006, AJ, 132, 117

Gopal R., Sethi S. K., 2003, Journal of Astrophysics and Astronomy, 24, 51

Hinshaw G. et al., 2013, ApJS, 208, 19

Jedamzik K., Katalinić V., Olinto A. V., 1998, Phys. Rev. D, 57, 3264

Kahniashvili T., Tevzadze A. G., Sethi S. K., Pandey K., Ratra B., 2010, Phys. Rev. D, 82, 083005

Kim E.-J., Olinto A. V., Rosner R., 1996, ApJ, 468, 28

Kim K.-T., Kronberg P. P., Giovannini G., Venturi T., 1989, Nature, 341, 720

Komatsu E. et al., 2011, ApJS, 192, 18

Lewis A., 2004, Phys. Rev. D, 70, 043011

Lewis A., Bridle S., 2002, Phys. Rev. D, 66, 103511

Lewis A., Challinor A., Lasenby A., 2000, ApJ, 538, 473

Mack A., Kahniashvili T., Kosowsky A., 2002, Phys. Rev. D, 65, 123004

Miralda-Escudé J., Haehnelt M., Rees M. J., 2000, ApJ, 530, 1

Mitra S., Choudhury T. R., Ferrara A., 2011, MNRAS, 413, 1569

Mittr S., Choudhury T. R., Ferrara A., 2012, MNRAS, 419, 1480

Pandey K. L., Sethi S. K., 2012, ApJ, 748, 27

Pandey K. L., Sethi S. K., 2013, ApJ, 762, 15

Pandolfi S., Ferrara A., Choudhury T. R., Melchiorri A., Mitra S., 2011, Phys. Rev. D, 84, 123522

Parker E. N., 1979, Cosmical magnetic fields: Their origin and their activity

Planck Collaboration et al., 2013a, ArXiv e-prints

Planck Collaboration et al., 2013b, ArXiv e-prints

Ratra B., 1992, ApJ, 391, L1

Ryu D., Schleicher D. R. G., Treumann R. A., Tsagas C. G., Widrow L. M., 2012, Space Sci. Rev., 166, 1

Sethi S. K., Subramanian K., 2005, MNRAS, 356, 778

Sethi S. K., Subramanian K., 2009, J. Cosmology Astropart. Phys., 11, 21

Shaw J. R., Lewis A., 2012, Phys. Rev. D, 86, 043510

Songaila A., Cowie L. L., 2010, ApJ, 721, 1448

Suh I.-S., Mathews G. J., 1999, Phys. Rev. D, 59, 123002

Trivedi P., Seshadri T. R., Subramanian K., 2012, Physical Review Letters, 108, 231301

Turner M. S., Widrow L. M., 1988, Phys. Rev. D, 37, 2743

Vasiliev E. O., Sethi S. K., 2014, ApJ, 786, 142

Wasserman L., 1978, ApJ, 224, 337

Widrow L. M., 2002, Reviews of Modern Physics, 74, 775

Wyithe J. S. B., Bolton J. S., 2011, MNRAS, 412, 1926

Yamazaki D. G., Kajino T., Mathews G. J., Ichiki K., 2012, Phys. Rep., 517, 141

Zeldovich I. B., Ruzmaikin A. A., Sokolov D. D., ed, 1983, Magnetic fields in astrophysics, Vol. 3