

MAGNETOGENESIS AT COSMIC DAWN

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Abstract. We present a mechanism for generating cosmological magnetic fields during the Epoch of Reionization, based on the photoionization of intergalactic hydrogen. A general formula is presented, together with an example numerical application which yields magnetic field strengths between 10^{-23} to 10^{-19} G on intersource scales. This mechanism, which operates all along Reionization around any ionizing source, participates to the premagnetization of the whole intergalactic medium. Also, the spatial configuration of these fields may help discriminate them from those produced by other mechanisms in future observations.

Keywords: Cosmology:theory, magnetic fields, large-scale structure of universe

1 Introduction

The Universe is magnetized at all scales: magnetic fields are observed in stars, galaxies and galaxy clusters, at essentially every stage of their evolution. The origin of such fields is however still an open question, especially on cosmological scales (e.g. Ryu et al. (2012)). The current paradigm is based on the idea that they were first generated very early in the history of the Universe with very weak strengths. Only then were they amplified during the formation of large scale structures, essentially through turbulent motions, and thus reached the values we observe today. However the evolution of structures has been strongly non-linear, i.e. far too complex for us to recover, from present day measurements, any information on the strength and configuration of the fields at the time they were generated. But recent high energy gamma ray observations suggest that a substantial fraction, if not the whole, of the intergalactic space is magnetized too. This is extremely interesting since unlike within structures, the non-linearity in the intergalactic medium has been only mild at most. Therefore, intergalactic magnetic fields may have conserved signatures of their initial properties. Understanding present-day intergalactic magnetic fields could thus be the key to understanding the origin of cosmic magnetism. Numerous mechanisms to account for the existence of such fields have already been proposed. But none of them is entirely satisfactory. The difficulty is to generate large enough strengths at large enough scales. Usually proposed mechanisms fail to comply with both requirements at the same time, or they need to invoke exotic physics in order to do so.

2 The mechanism

Revisiting Langer et al. (2005), we present an analytical model of cosmological magnetogenesis based on plasma-radiation interactions which occur during the Epoch of Reionization. As the first luminous objects formed, they emitted ionizing radiation which photoionized the neutral intergalactic medium (IGM), thus generating currents and inducing magnetic fields. The reionization of the Universe was accomplished by Population III stars, first galaxies and first quasars. Each source formed a fully ionized area (Str  mgren sphere) around itself but long mean free path photons (UV and X) escaped into the IGM. Those photons knocked out free a fraction of bound electrons and transferred to them their momentum, generating radial currents and induced magnetic fields. But magnetic fields generated by adjacent currents compensate each other, unless these currents have different intensities. This condition is actually satisfied thanks to inhomogeneities in the IGM. Therefore magnetic fields

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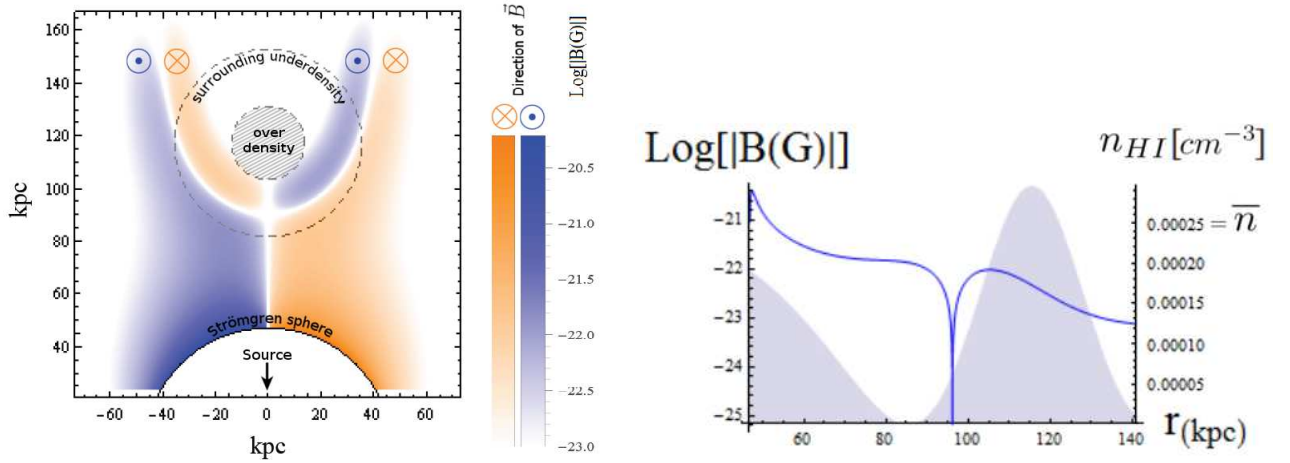


Fig. 1. **Left:** Spatial distribution around an IGM inhomogeneity of the B -field (in Gauss) with a $z = 10$ galaxy source. The symbols \odot and \otimes indicate that the field points towards and away from the reader, respectively. **Right:** Strength of the B -field along a path through the inhomogeneity (sketched in grey).

are generated *where the IGM is inhomogeneous*. More precisely, we show in detail in Durrive & Langer (2014) that sources generate outside their Strömgen spheres the following magnetic field:

$$\vec{B}(t, \vec{r}) = \frac{1}{ex_e} \left(N_1 \frac{\vec{\nabla} x_e}{x_e} + N_2 \vec{\nabla} \int_{r_s}^r n_{HI} dr \right) \times \frac{\hat{r}}{4\pi r^2} t$$

where, for $i = 1, 2$, $N_i(t, \vec{r}) = \int_{\nu_0}^{\infty} f_{mt} \sigma_{\nu}^i L_{\nu} e^{-\tau_{\nu}} d\nu$. In this expression, the first term is local while the second is global. They correspond to the necessity that two adjacent currents have different intensities. This is satisfied either when the matter configuration differs in two adjacent volume elements, or when the intensity of the ionizing radiation incident on two adjacent volume elements differs. This is reflected in the equation above, where the local term corresponds to local inhomogeneities in the electron fraction, and the global term corresponds to the transverse variation of photon absorption along adjacent lines-of-sight. In addition, we recover naturally the geometric dilution of photons, the strength being proportional to r^{-2} . Note also that the strength is linearly growing with time, essentially because we assumed a constant luminosity, and the mechanism operates until the source dies. N_1 and N_2 characterize the impact that the source has at distance \vec{r} at time t . Indeed, they contain the fraction of momentum transferred from photons to electrons f_{mt} , the photoionization cross section σ_{ν} , the spectrum of the source L_{ν} and the optical depth τ_{ν} .

This analytical formula is valid for any ionizing source during Reionization. As an illustrative numerical application, we considered the case of Population III clusters and first galaxies with spectra computed with the Yggdrasil model (Zackrisson et al. (2003)), as well as quasars with spectra fitted from observations (Shang et al. (2011)), with a mildly non-linear inhomogeneity outside the Strömgen sphere of the source. The results are that, depending on their spectrum, luminosity, lifetime and epoch, different sources generate different magnetic fields (cf. figures 1 and 2). Namely, Pop III clusters generate stronger fields on short scales, while quasars

Redshift	Source	Log[B(G)]	scale (kpc)	$\frac{1}{2}d_{intersource}$ (kpc)
30	Pop III	-19 / -21	0.3/1	10
20		-19 / -21	0.5/1	
20	First galaxy	-20 / -22	10/15	25
10		-21 / -22	30/100	
10	Quasar	-21 / -22	300/1000	1000
6		-22 / -23	500/1500	

Fig. 2. Typical values of the resulting fields and scales.

magnetize less but over huge distances. First galaxies combine high amplitudes and large scales (intersource scales). Also, the geometrical configuration of the fields reflects the axisymmetry of the matter distribution with respect to the ionizing source, and fields generated in overdensities have opposite orientation to those generated in underdensities (cf. figure 1).

3 Conclusion

The mechanism presented here operates with any ionizing source, at any time during the Epoch of Reionization. The resulting magnetic strengths are comparable to those generated by other astrophysical mechanisms, but they appear on entire intersource distances. Therefore it contributes to the premagnetization of the whole Universe. Also, the specific spatial configuration of the generated fields might help discriminate from other cosmological magnetogenesis mechanisms with future observations (e.g. SKA) of the evolved magnetic fields.

In future work we shall consider more realistic (aspherical) Strömgren spheres. It will increase the anisotropy, thus should increase the strength of the fields as they rely on gradients. Also, it will be interesting to look at the statistical properties at large scales by considering a distribution of inhomogeneities. Finally, the processing of the fields by large scale turbulence from structure formation will be considered.

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