Searching for Faraday rotation in cosmic microwave background polarization

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ABSTRACT
We use the Wilkinson Microwave Anisotropy Probe (WMAP) 9th-year foreground reduced data at 33, 41 and 61 GHz to derive a Faraday rotation at map and at angular power spectrum levels taking into account their observational errors. A processing mask provided by WMAP is used to avoid contamination from the disc of our Galaxy and local spurs. We have found a Faraday rotation component at both, map and power spectrum levels. The lack of correlation of the Faraday rotation with Galactic Faraday rotation, synchrotron and dust polarization from our Galaxy or with cosmic microwave background anisotropies or lensing suggests that it could be originated at reionization ($\ell \lesssim 12$). Even if the detected Faraday rotation signal is weak, the present study could contribute to establish magnetic fields strengths of $B_0 \sim 10^{-8}$ G at reionization.

Key words: magnetic fields – polarization – cosmic background radiation – dark ages, reionization, first stars.

1 INTRODUCTION
It is a well-known fact that magnetic fields are present in all astrophysical systems from planets and stars to galaxies and clusters of galaxies. They have been observed at very large redshifts (see e.g. Kronberg et al. 2008, and references therein) and in the intra-cluster region (see e.g. Ferrari et al. 2008). Considerable attention is being paid therefore to observe primordial magnetic fields and to study their hypothetical dynamical effects on the evolution of the large-scale structure. At present, only upper boundaries have been obtained, being strengths of the order of $\lesssim 4$ nG, the lowest upper limits (Paolotti & Finelli 2013; Planck Collaboration XVI 2014; Planck Collaboration XIX 2016). It has been estimated that magnetic fields strengths lower than about 1 nG would have a negligible influence on the evolution of the large-scale structure and in the process of galaxy formation (see e.g. Battaner, Florido & Jimenez-Vicente 1997; Florido & Battaner 1997) but larger values than 10 nG could be excessive.

As usual, we speak of a ‘comoving’ magnetic field $B_0 = Ba^2$, where $B$ is the physical field and $a$ the cosmic scale factor. This $B_0$ would be the physical field observed today in the magnetohydrodynamics (MHD) limit and in absence of gains and losses other than dilution in the expansion. This ‘comoving’ field allows the comparison between fields at different epochs. A ‘comoving’ field of 1 nG would correspond at recombination to a physical field of the order of some mG.

The purpose of this work is to establish upper limits on magnetic field strengths at low-$\ell$ multipoles derived from the observational data obtained by Wilkinson Microwave Anisotropy Probe (WMAP; Bennett et al. 2013; Hinshaw et al. 2013) and the identification of the epoch at which they are present. For this task we have looked for Faraday rotation (FR), at both, the map and the angular power spectrum levels, taking into account its characteristic $\lambda^2$ dependence. If some FR was detected, this could be due to four different causes, i.e.

(a) primordial FR produced at recombination at $z \sim 1100$;
(b) FR produced at reionization or later, at $z \lesssim 10$;
(c) residuals of imperfectly decontaminated Galactic contribution;
(d) simple noise.

Primordial FR at recombination has been studied at power spectra level, through the conversion of primordial E-modes into B-modes due to the presence of a primordial magnetic field (PMF) that induces FR (Kosowsky et al. 2005). WMAP5 and WMAP7 results provide $B_0 \lesssim 10^{-7}$ G (see Kohniashvili, Maravin & Kosowsky 2009; Pogosian et al. 2011).

We search for pre-galactic FR and the identification of the epoch at which it was produced. This identification would permit us the assessment of the physical processes at that epoch and the relative importance of magnetic fields then at work.

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For obtaining confidence in the identification of the FR source, we can take into account the correlations with cosmic microwave background (CMB) anisotropies, lensing and Galactic maps, the galactic dependence of the Galactic components and the range of multipoles at detected FR anisotropy angular spectrum.

We report a FR signal, which is weak but with a signal-to-noise ratio (S/N) large enough in some restricted multipoles ranges at power spectrum level and in some sky regions at map level. Given the low upper limits found by Planck Collaboration XVI (2014) and Planck Collaboration XIX (2016), and if the insufficient separation of components made by WMAP, a primordial origin could be rejected. An interesting possibility would be that the FR would have been produced at reionization or/and later. We here favour this interpretation, even if its assessment is deserved for Planck and future experiments like PRISM1 (André et al. 2014), Square Kilometre Array (SKA)² and Low-Frequency Array (LOFAR).³ This would be a first tentative to observe magnetic fields around reionization which could introduce crucial light for understanding the formation of galaxies.

This paper is organized as follows. In the next section, we present the description of FR at map and power spectrum levels as well as the estimation used to obtain the rotation measure. In Section 3, the observational data, the noise computation and the masks are described. In Section 4, it is discussed the Galactic foregrounds which could contaminate our signal. In Section 5, we present our results and the discussion and finally, in Section 6, we present our conclusions.

2 FARADAY ROTATION OF CMB POLARIZATION

The mechanism that polarizes the CMB radiation is the Thomson scattering of photons with free electrons at recombination and at reionization epochs. This radiation is linearly polarized and is described by the Stokes $Q$ and $U$ parameters at each observational frequency. The presence of a magnetic field at recombination and/or at reionization would produce a rotation of the CMB polarization plane, the so-called Faraday rotation. This signal could be detected at map and at power spectrum levels. Both of them provide complementary information about the signal as discussed below.

2.1 Faraday rotation at map level

FR at map level allows us to identify those regions of the sky where the FR signal could be measurable. The observational $Q$ and $U$ maps are used to obtain our FR map as described below. On one hand, the polarization angle $\phi$ is related to the observational polarization $(Q_i, U_i)$ parameters at a given frequency $\nu$ through

$$\phi_i = \frac{1}{2} \arctan \left( \frac{U_i}{Q_i} \right) + \frac{\pi}{2}. \quad (1)$$

On the other hand, the rotated angle is given by

$$\phi = \phi_0 + (RM) \lambda^2, \quad (2)$$

where $\phi_0$ is the angle of intrinsic polarization, $\lambda$ the observational wavelength and $RM$ is the rotation measure given by

$$RM = K \int_L n_e(x, n) B_0(x, n) \, dx, \quad (3)$$

where $K = \frac{\lambda^3}{2\pi n_e \sigma_B^2} = 2.624 \times 10^{-17}$ is a constant (in rad G$^{-1}$), $n_e$ is the thermal electron density (in cm$^{-3}$), $B_0$ is the strength of the magnetic field along the line of sight (in G), $dx$ is the distance along the line of sight (in cm), $L$ is the size of the FR active region along the line of sight and $n$ is the direction along the line of sight. In CGS units, $RM$ is given in rad cm$^{-2}$. In a first approximation, the $RM$ could be obtained as

$$RM = K \int L n_e(x, n) \, dx, \quad (4)$$

being $(B_0)$ a mean-weighted magnetic field strength, i.e.

$$\langle B_0 \rangle = \frac{\int L n_e(x, n) B_0(x, n) \, dx}{\int L n_e(x, n) \, dx}. \quad (5)$$

In this expression the magnetic field strength is defined as an average along the line of sight. We must note that no assumption is considered for the magnetic field distribution. To obtain FR maps from observations, the expressions given by equations (1) and (2) are used. The computation of the observational noise of the polarization angle in equation (1) is described in Section 3. In general, the method used to compute the $RM$ and the angle of intrinsic polarization $\phi_0$ that appear in equation (2) is by minimizing the $\chi^2$ distribution, i.e. $\frac{\partial \chi^2}{\partial \phi_0} = 0$ and $\frac{\partial \chi^2}{\partial \phi_B} = 0$, respectively; being $\chi^2$

$$\chi^2 = \sum_{i=1}^{N} \left( \frac{\phi_{i \text{obs}} - \phi_{i \text{theo}}}{\sigma_{i \phi}} \right)^2. \quad (6)$$

Here $\phi_{i \text{obs}}$ is the polarization angle given by equation (2), $\phi_{i \text{theo}}$ is the observational polarization angle obtained by using observational data provided through equation (1) and $\sigma_{i \phi}$ is the observational error of the $\phi_{i \text{obs}}$ which it is obtained as described in Section 3.1. The sum runs over the total number of pixels $i$. The minimization of the $\chi^2$ given by equation (6) yields

$$\phi_i = \sum_{j=1}^{ni} \frac{\phi_j}{\sigma_{ij}} - \sum_{j=1}^{ni} \frac{\phi_j^2}{\sigma_{ij}^2} \sum_{j=1}^{ni} \frac{1}{\sigma_{ij}^2}, \quad (7)$$

$$RM = \sum_{i=1}^{ni} \frac{\phi_i}{\sigma_{iB}} - \sum_{i=1}^{ni} \frac{\phi_i^2}{\sigma_{iB}^2} - \sum_{i=1}^{ni} \frac{\phi_i^2}{\sigma_{iB}^2} \sum_{j=1}^{ni} \frac{\phi_j^2}{\sigma_{ij}^2}. \quad (8)$$

The sum runs over $i$ which denotes the observational frequency, being $ni$ the total number of frequencies.

The error associated with the $RM$, $\sigma_{RM}$, is given by the diagonal of the inverse Hessian matrix for a weighted error least-squares fit ($\sigma_{RM} = \frac{\chi^2}{\partial \chi^2}$), i.e.

$$\sigma_{RM}^2 = \sum_{i=1}^{ni} \frac{1}{\sigma_{iB}^2} \left( \sum_{j=1}^{ni} \frac{1}{\sigma_{ij}^2} + \sum_{j=1}^{ni} \frac{1}{\sigma_{ij}^2} \right) - \left( \sum_{i=1}^{ni} \frac{\phi_i^2}{\sigma_{iB}^2} \right)^2. \quad (9)$$

This error would contain the statistical and spatial variations that are present in the $RM$ maps.
2.2 Faraday rotation at power spectrum level

From FR maps we derive the FR angular power spectrum. This is a powerful tool to put upper bounds for the FR. Fluctuations of $RM$ shown in FR maps could be expanded in spherical harmonics as

$$
\delta RM(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi),
$$

where $a_{\ell m}$ are the coefficients of the expansion in spherical harmonics, $Y_{\ell m}$ are the spherical harmonics and $(\theta, \phi)$ are the spherical coordinates. The expansion coefficients $a_{\ell m}$ are integrals over the complete sphere, i.e.

$$
a_{\ell m} = \int d\Omega RM(\theta, \phi) Y_{\ell m}^*(\theta, \phi),
$$

being $d\Omega$ the solid angle element on the sphere. These coefficients are numerically computed by using the ANAFAST tool from HEALPix package (Górski et al. 2005). These coefficients are complex and satisfy the condition

$$
\langle a_{\ell m}^* a_{\ell m'} \rangle = C_{\ell} \delta_{\ell \ell'} \delta_{mm'},
$$

where $\delta_{\ell \ell'}$ and $\delta_{mm'}$ are $\delta$-Kronecker and $C_{\ell}$ is the power spectrum of the RM anisotropies, which can be obtained as

$$
C_{\ell} = \frac{1}{2 \ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}.
$$

The $C_{\ell}$ is related to the two-point correlation function $C(\theta)$ through

$$
C(\theta) = \sum_{\ell} \frac{(2\ell + 1)}{4\pi} C_{\ell} P_{\ell}(\cos \theta),
$$

where $\theta$ is the angle between two different directions $\hat{n}_1$ and $\hat{n}_2$ on the sky and $P_{\ell}(\cos \theta)$ are the Legendre polynomials. It is noticeable that this is the result of an ensemble over all possible skies. For low $\ell$ or equivalently, for large scales, there are few independent directions on the sky to compute equation (14). This fact implies that the statistics at these scales is affected by the cosmic variance, which is given by

$$
\Delta C_{\ell} = \frac{\sqrt{2}C_{\ell}}{\sqrt{f_{\text{sky}} \sqrt{2\ell + 1}}},
$$

where $f_{\text{sky}}$ is the fraction of the observable sky being $f_{\text{sky}} = 1$ for the full sky. Moreover, if a fractional sky is considered, for example as when applying a mask over the maps as considered in our analysis, this induces multipole coupling between the different multipoles which are independent for full sky analysis given by equation (13) because the expansion coefficients $a_{\ell m}$ become non-orthogonal. The multipole coupling could be analytically described by a spherical harmonic transforms that includes the specific characteristics of the RM maps as, for example masks for brighter Galactic regions as the Galactic plane, through the computation of a window function that allows us to obtain an unbiased $C_{\ell}$. This is done with the Monte Carlo Apodized Spherical Transform Estimator (MASTER; see Hivon et al. 2002, for details).

2.3 Estimation of the magnetic field at recombination and reionization

The $RM$ in equation (4) can be simplified in the cases of recombination and reionization if we take into account the definition of the optical depth for the Thomson scattering, i.e.

$$
\tau = \int n_e(x, n) dx,
$$

where $\sigma_T$ is the Thomson cross-section, i.e. $\sigma_T = 6.63 \times 10^{-25}$ cm$^2$. In the absence of reionization, $\tau \sim 0$.

Then equation (4) can be simplified as

$$
RM = K \langle B_\ell \rangle \frac{\tau}{\sigma_T},
$$

If values of the optical depth are assumed, we have a simple way to estimate $\langle B_\ell \rangle$ once $RM$ is derived from the observations. This is a very appropriate way at recombination as $\tau$ cannot be very different from unity and at reionization where the $\tau$ is derived from CMB observations. It must be noted that the reionization model – instantaneous or non-instantaneous – does not affect our computations. We only use the derived values for the optical depth of WMAP9, i.e. $\tau = 0.089 \pm 0.014$ (Hinshaw et al. 2013) and the most recent value derived by Planck, i.e. $\tau = 0.066 \pm 0.016$ when lensing and temperature data are combined (Planck Collaboration XIII 2015). Another way is the direct estimation of the integral $\int n_e(x, n)$ over the line of sight, being a top hat function the simple assumption, for example.

3 OBSERVATIONAL DATA

We use WMAP 9th-year degraded polarization data (Bennett et al. 2013). These maps are publicly available and have been generated in HEALPix pixelization scheme (Górski et al. 2005) at resolution 4, i.e. $\text{NSIDE} = 16$. The number of total pixels is 3072 with a pixel size of $\sim 3.6$. WMAP provides $(Q,U)$ maps at 23, 33, 41, 61 and 94 GHz and their corresponding inverse covariance matrices. Two different categories are provided for maps and inverse covariance matrices, i.e. foreground reduced (for the last four frequencies and used for cosmological purposes) and non-reduced (for all frequencies and used for component separation or Galactic purposes). Foreground cleaned data include the polarization processing mask used by the WMAP team. This mask excludes the polarized emission of the Galactic plane, the North Polar Spur and other well-known polarized sources. Combinations of four and three frequencies of foreground reduced maps (33, 41, 61 and 94 GHz) are used to search for FR at map level. Non-reduced 23 GHz band is used to check the Galactic residuals in the reduced data together with the polarized emission at 1.4 GHz measured by Dominion Radio Astrophysical Observatory (DRAO; Wolleben et al. 2006) as described in Section 4. The observational Galactic Faraday rotation (GFR) described by an all-sky Faraday depth map and provided by Oppermann et al. (2015) is used to check for Galactic foregrounds too. This map is synthesized from the huge amount of rotation measurement of extragalactic radio sources (EGRS).

The Internal Linear Combination (ILC) map is used to find correlation with the CMB anisotropies, primary and secondary anisotropies. This map contains the common signal that could be

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http://healpix.sourceforge.net/

http://lambda.gsfc.nasa.gov/product/map/dr5/m_products.cfm

http://www.mpa-garching.mpg.de/ift/faraday/
attributable to the CMB anisotropies by minimizing the foreground signals. This map is frequency independent and can contain extragalactic foregrounds as the lensing effect. The lensing effect is a signature of the mass distribution at intermediate redshifts, i.e. 0.1 < z < 5 and has a peak at multipole ℓ ≈ 350 (Planck Collaboration XV 2015) which corresponds to a scale of 0.5. The lensing is expected to blur the acoustic peaks of the angular power spectra, produce small-scale fluctuations, non-Gaussianity and a conversion of primordial E-modes into B-modes. To take into account this effect, we have downloaded the lensing potential map observed by the Planck Collaboration.\(^7\) The lensing map provided by the Planck Collaboration is based on the minimum-variance lensing potential (see Planck Collaboration XV 2015, for details). The data provided are the convergence \(\kappa_{\ell m}\) which is related to the lensing potential through \(\kappa_{\ell m} = \frac{1}{\ell} (\ell + 1) \phi_{\ell m}\). The convergence gives us information about the magnification of an image. From the convergence we can obtain the lensing potential map inferred by Planck data.

All maps are used in the degraded resolution NSIDE = 16.

### 3.1 Noise maps

Noise maps for observational Stokes \((Q, U)\) parameters and for the observational polarization angle that appear in equation (1), i.e. \(\sigma_\phi\), are computed by using two different methods.

(i) **Method 1.** It uses the inverse covariance matrices provided by WMAP\(^9\). The inversion of these matrices is needed for obtaining the variance and covariance of the observational \(Q\) and \(U\) maps that are used for the computation of the error maps of the Faraday signal. For low-resolution foreground reduced maps, the inverse covariance matrices have the noise characteristics of the WMAP satellite. This fact is important for multipoles \(\ell \lesssim 16\) as pointed out by the WMAP team (Bennett et al. 2013). These matrices are singular. The zeros of the diagonal must be eliminated to invert the matrices. These zero values come from the polarization processing mask used for obtaining foreground reduced maps.\(^8\) To invert the matrices, we can identify the pixel number with its corresponding signal if it is non-masked or with a zero value if the corresponding pixel is masked, by taking into account the processing mask for polarization provided by WMAP. After that, we can eliminate those masked pixels of the diagonal (zero values), and we invert the matrices by using a Gaussian elimination method. Finally, we reorder the pixels to their corresponding number by including the masked ones, i.e. the zeros in those pixels that are masked by the processing polarization mask. The matrices are provided in number of counts as explained by the WMAP team. To obtain them in temperature units, they have been multiplied out by \(\sigma_0\) (mK) value for foreground reduced maps, i.e. \(\sigma_0 = 2.166\) mK for 33 GHz, \(\sigma_0 = 2.641\) mK for 41 GHz, \(\sigma_0 = 3.339\) mK for 61 GHz and \(\sigma_0 = 6.832\) mK for 94 GHz as pointed out by the WMAP team. A detailed description of these matrices is given in the LAMBDA webpage.\(^9\)

The inversion of the inverse covariance matrices per frequency band gives us the covariance matrices. They contain the variance for \(Q\) and \(U\), i.e. \(\sigma_Q^2\) and \(\sigma_U^2\), as well as the covariance matrix which includes the correlation between the noise of \(Q\) and \(U\), i.e. \(\sigma_{QU}\). With these covariance matrices, we can obtain the observational error for the polarization angle in equation (2) by applying error propagation:

\[
\sigma_\phi^2 = \frac{1}{4} \frac{U^2}{(Q^2 + U^2)^2} \sigma_Q^2 + \frac{1}{4} \frac{Q^2}{(Q^2 + U^2)^2} \sigma_U^2 - \frac{1}{2} \frac{QU}{(Q^2 + U^2)^2} \sigma_{QU}.
\]

Before using equation (18), we have checked that the covariance, \(\sigma_{QU}\), verifies the Cauchy–Schwarz criterion, i.e.

\[
|\sigma_{QU}| \leq \sqrt{\sigma_Q^2 \sigma_U^2}.
\]

For those pixels that do not verify equation (19), the covariance \(\sigma_{QU}\) have been set to zero. The number of pixels that do not verify the criterion is low, 14 for the \(Q\) parameter and 15 for the \(U\) parameter.

(ii) **Method 2.** This uses foreground reduced maps at the highest resolution, i.e. NSIDE = 512 to obtain the variance maps \(\sigma_Q^2\) and \(\sigma_U^2\). Here we assume no spatial correlation between the noise of \(Q\) and \(U\) parameters, i.e. \(\sigma_{QU} = 0\). To compute the variance \(\sigma_Q^2\) and \(\sigma_U^2\) at our resolution, i.e. NSIDE = 16 (pixel size \(\sim 3.6\)), we have degraded the original maps at NSIDE = 64 (pixel size \(\sim 0.9\)) in a first step. For a given pixel \(i\) in our final pixilation scheme (NSIDE = 16), we obtain the associated noise \(\sigma_Q(i)\) and \(\sigma_U(i)\) by computing the square root of the variance of the \(\sim 0.9\) pixels inside a radius of 2' from the centre of our pixel \(i\) for \(Q\) and \(U\), respectively. This method has been explained in Waelkens et al. (2009) and Ruiz-Granados, Rubiño-Martín & Battaner (2010) in detail. To compute the noise map for the polarization angle \(\sigma_\phi\) we have performed a Monte Carlo (MC) simulation with \(N_{\text{sim}} = 5000\) realizations of pairs of \(Q\) and \(U\), with a mean value equal to the observed \(Q\) and \(U\) maps for each frequency and variance \(\sigma_Q^2(i)\) and \(\sigma_U^2(i)\) given by the method described above.

This method takes into account a properly characterization of fluctuations coming from random magnetic fields that contributes to the polarized emission coming from our Galaxy or from primordial CMB polarization.

### 3.2 Masks

We mainly consider the WMAP\(^9\) polarization processing mask. This mask excludes the Galactic disc, the North Polar Spur and other well-known polarized sources. A mask for the South hemisphere has been added to this WMAP mask when DRAO measurements are used because these last ones do not include it. Local structures with high polarized emission as the North Polar Spur could significantly contaminate our signal (see Ruiz-Granados et al. 2010, for details) and they are taken into account in polarization processing mask from WMAP. The WMAP\(^9\) processing mask contains a total of pixels of \(N_{\text{pix}} = 2255\) which corresponds to a \(f_{\text{sky}} \sim 73.4\) per cent. For the analysis that excludes the South hemisphere and the polarization processing mask, \(N_{\text{pix}} = 1711\) which corresponds to a \(f_{\text{sky}} \sim 55.7\) per cent.

### 4 GALACTIC FOREGROUNDS IN POLARIZATION

Foreground reduced maps of polarized emission are used in searching for FR maps, but as pointed out by Page et al. (2007), the component separation methods used for cleaning CMB maps in polarization are able to clean up to 85 per cent of the synchrotron emission for frequencies lower than \(\nu \lesssim 40\) GHz. Moreover Page et al. (2007) remarked that this emission is dominant at \(\ell \lesssim 50\). This means that our FR maps or power spectrum could contain

\(^7\) [http://wiki.cosmos.esa.int/planckpla2015/index.php/Specialy_processed_maps](http://wiki.cosmos.esa.int/planckpla2015/index.php/Specialy_processed_maps)

\(^8\) [http://lambda.gsfc.nasa.gov/product/map/dr5/maps_band_forered_r4_quinv_9yr_get.cfm](http://lambda.gsfc.nasa.gov/product/map/dr5/maps_band_forered_r4_quinv_9yr_get.cfm)

some polarized signal coming from the Galaxy. The template fitting procedure used to obtain the reduced maps could leave some Galactic signal due to the linear propagation of templates by using internal linear combination or by maximizing the entropy methods (Bennett et al. 2013). Both methods fit templates for synchrotron and dust without considering an specific magnetic field model for the Galaxy or the emission of local regions as the Fan or the North Polar Spur.

The frequency channel less contaminated is 61 GHz, while polarized dust emission is important at 94 GHz. To clean synchrotron emission in polarization, the WMAP team uses the 23 GHz frequency band while for the dust they use the template provided by Finkbeiner, Davis & Schlegel (1999) for model eight (see Page et al. 2007; Bennett et al. 2013, for details). In spite of confidence on component separation methods used by the WMAP team to obtain foreground reduced maps, we check that no contamination arising from the Galactic emission is present in these maps. To this aim we use not only the Galactic templates used by the WMAP team, but also the DRAO measurements at 1.4 GHz, simulations of synchrotron emission as well as the GFR depth from EGRS derived by Oppermann et al. (2015) or simulations for GFR by fixing a Galactic magnetic field model. This is motivated by the fact that at lower frequencies as 1.4 GHz, the emission is completely coming from Galactic synchrotron emission and it could be useful to improve its cleaning. The use of the GFR is an additional tool that allows us to clean Galactic residuals and extragalactic signals coming from EGRS. The GFR is not used in the component separation methods, so it could be a complement to check that the foreground cleaning methods work properly.

The presence of Galactic magnetic fields arises in two different Galactic foregrounds that must be taken into account in our analysis, i.e. polarized Galactic emission (i.e. synchrotron and dust emission) and GFR. In Ruiz-Granados & Florida (2016) it is shown a detailed analysis of these polarized foregrounds both at map and at power spectra levels. Here we show a summary of that results applied to our purposes.

4.1 Galactic polarized emission

Polarized Galactic emission could contaminate foreground reduced maps. At lower frequencies, i.e. from 1.4 to 23 GHz, the maps are dominated by polarized synchrotron emission while at higher frequencies, i.e. $ν > 140$ GHz, the emission is dominated by the polarized dust emission.

We assume that these components have been properly cleaned from the reduced maps provided by the WMAP team, but in any case we consider them as a possible foreground. We use directly the degraded Stokes $(Q,U)$ maps at 1.4 and 23 GHz to characterize this emission. The $K$-band (i.e. 23 GHz) is used as a template for the Galactic synchrotron emission as done by the WMAP team. We have used it together with the 1.4 GHz polarized measurements by DRAO10 (Wolfeben et al. 2006). High-frequency foreground reduced maps could have a portion of polarized emission coming from dust. We use the template for the dust from the WMAP9 team, i.e. the Stokes $(Q,U)$ parameters and the direction of the polarization angle obtained by using equation (1) are used. All these maps are provided at $\text{NSIDE} = 512$ and they are degraded at $\text{NSIDE} = 16$ by using the UDGRADE tool from HEALPix package if some of them are not provided in this resolution.

4.2 Galactic Faraday rotation

GFR could introduce some foreground residuals in our signal. To characterize the GFR at map level, three different methods are used: (1) GFR from all-sky maps at 1.4 GHz combined with 23 GHz, (2) the Faraday depth map from EGRS provided by Oppermann et al. (2015) and (3) GFR coming from simulations for a given model of the Galactic magnetic field (GMF) distribution.

(i) Method 1. We compute the observational GFR by using the Stokes $(Q,U)$ parameters at 1.4 and 23 GHz. First, we have downgraded both maps at $\text{NSIDE} = 16$. WMAP 23 GHz maps are multiplied by the South hemisphere mask that excludes the South hemisphere observations that has not been taken into account in the 1.4 GHz maps. Once we have $(Q,U)$ maps, the polarization angle is derived from equation (2). The corresponding error map (i.e. $σ(Q,U)$) is obtained by using method 2 described in Section 2.2, for 23 and 1.4 GHz maps, respectively. The Galactic RM and its error map are obtained by using equations (8) and (9), respectively, while the intrinsic Galactic polarization angle is obtained by using equation (7).

(ii) Method 2. The second characterization of the Galactic RM uses directly the Faraday depth map provided by Oppermann et al. (2015) degraded at $\text{NSIDE} = 16$.

(iii) Method 3. We use GFR simulations by fixing a model for the regular component of the Galactic magnetic field distribution. In particular we use the results for the halo field which is the best fit for the 23 GHz WMAP 5th-year data. It has an axisymmetric distribution with a pitch angle of $p \sim 20°$, a radial scale factor of $r_1 \sim 3$ kpc and a tilt angle of $\chi_0 \sim 30°$ (see Ruiz-Granados et al. 2010, for details). Simulations of Stokes $(Q,U)$, the polarization angle and the FR maps are done taking into account those parameters for the halo magnetic field at 1.4 and 23 GHz. On the other hand, GFR simulations are obtained by using equation (3) and fixing the thermal electron distribution (see e.g. Stepanov et al. 2008).

It is important to note that magnetic fields in the Galactic halo are weaker than those present in the Galactic disc and they are the most important contaminant out of the Galactic disc that has been excluded from our data.

5 RESULTS AND DISCUSSION

In this section, we present our FR maps derived from the foreground reduced maps provided by the WMAP 9th-year results and their corresponding angular power spectrum.

5.1 Results at map level

The rotation measure maps have been obtained by using two combination of foreground reduced maps: (1) 33–41–61–94 GHz and (2) 33–41–61 GHz. The noise maps associated with the RM maps have been obtained by using two different methods: (i) inverse covariance matrices provided by WMAP and (ii) MC simulations as described in Section 3.1. Moreover to derive them, we have considered two different values for the optical depth at reionization: the value derived by WMAP, i.e. $τ_1 = 0.089 \pm 0.014$ (Hinshaw et al. 2013) and also the value derived by Planck, i.e. $τ_2 = 0.066 \pm 0.016$ (Planck Collaboration XIII 2015). As discussed below, we only present maps computed by using $τ_1$.

Fig. 1 shows the observational RM and its corresponding error map, i.e. $σ_{RM}$ computed with the inverse covariance matrices provided by WMAP for case (1), i.e. when combining 33, 41, 61 and 94 GHz (on the left-hand panel) and for case (2), i.e. when combining 33, 41 and 61 GHz (see the right-hand panel).

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10 http://www3.mpi-bon.de/div/konti/26msurvey/publ.html
Figure 1. Left: observational $RM$ (top) and $\sigma_{RM}$ obtained by using covariance matrices to compute the noise (bottom), when combining 33, 41, 61 and 94 GHz. Right: observational $RM$ (top) and $\sigma_{RM}$ obtained by using the covariance matrices (bottom), when combining 33, 41 and 61 GHz.

In Fig. 2 it is shown the observational $RM$ and its corresponding error map $\sigma_{RM}$ when MC simulations are used. In the left-hand panel it is shown results for combinations of 33, 41, 61 and 94 GHz and in the right-hand panel, the results for 33, 41 and 61 GHz. We have checked that the $RM$ maps in Figs 1 and 2 have not any Galactic signal. This has been done in terms of Pearson’s correlation coefficient pixel-to-pixel. The Pearson’s correlation coefficient is given by

$$r = \frac{n \sum_{i} x_i y_i - \sum_{i} x_i \sum_{i} y_i}{\sqrt{n \sum_{i} x_i^2 - \left( \sum_{i} x_i \right)^2} \sqrt{n \sum_{i} y_i^2 - \left( \sum_{i} y_i \right)^2}},$$

where the sum runs over $i$, the pixel number; $n$ is the total number of pixels; $x$ is the map 1 and $y$ represents the map 2. The error of $r$ is

$$\Delta r = \sqrt{1 - r^2 / \sqrt{N_{\text{pix}} - 2}},$$

being $N_{\text{pix}}$ the number of pixels out of mask. As the comparison is done pixel-to-pixel, all maps are at the same resolution. The significance of this correlation value is given by the $t$-Student distribution, i.e. $t_{\alpha, \nu} = |r| / \Delta r$. This value gives the probability of rejecting the correlation within a given confidence level. Another important value to obtain is the determination coefficient which is given by $R^2$ that in the case of the linear correlation is

$$R^2 = r^2.$$

This last coefficient illustrates the part of variance of the observational $RM$ signal present at the different maps we are comparing.

As discussed Section 4, the foreground reduced maps at a frequency band could be contaminated by Galactic signals. At the lower resolution, if there is any Galactic signal due to turbulent magnetic fields, they would be taken into account through the variance terms of the noise maps. Instead, the main component that could affect our results is the regular component of the Galactic magnetic field which is responsible for synchrotron emission and for the GFR at large scales. We have performed several tests especially for those signals coming from the regular component of the Galactic magnetic field. These could mainly contribute through GFR to the $RM$ maps that we have obtained. But also an inefficient template cleaning could leave an imprint of the polarized synchrotron emission or the polarized dust emission of our Galaxy.

To describe our tentative Galactic contaminants we have used the Galactic $RM$ maps derived from the combination of non-foreground reduced 1.4 and 23 GHz bands, the observational map of $RM$ of EGRS obtained by Oppermann et al. (2015) and also the simulation of Galactic $RM$ maps obtained by fixing GMF model. Moreover, we have checked that there are no residuals of the observational polarized synchrotron emission and of the dust templates used by WMAP as explained above.

Another interpretation for our $RM$ maps is that they could be simply noise. To test it, we have computed a noise simulation and we have correlated it with our $RM$ maps. This is done by carrying out a CMB simulation with the CAMB code\(^{11}\) (Lewis, Challinor & Lasenby 2000), by fixing the cosmological parameters to those constrained by WMAP (Hinshaw et al. 2013) for the $\Lambda$ cold dark matter (LCDM) model. Once we have the angular power spectra, in temperature and polarization, we have used the SYNFAST tool of the HEALPix package for synthesizing CMB maps. We have applied it to obtain 1000 different CMB maps that we have averaged to obtain the one we have used to compute the noise. Our final map corresponds to a simple Gaussian distribution in polarization which is used to compute the noise map by following the same prescription described in method 2 (see Section 3.1). These noise maps are written down as noise $Q_{\text{CMB}}$, noise $U_{\text{CMB}}$ and noise $\phi_{\text{CMB}}$ in our tables. Note that $\phi_{\text{CMB}}$ is the polarization angle derived from equation (1) for the averaged map.

We have tested that our $RM$ signal is not coming from CMB anisotropies. To take this into account, we have cross-correlated the

\(^{11}\) http://camb.info/
Faraday rotation in CMB polarization

RM with the ILC map. Since this map could contain not only primary CMB anisotropies, but also secondary anisotropies, we have considered the lensing map provided by the Planck Collaboration (Planck Collaboration XV 2015).

The correlation has been computed between the observational RM maps in Figs 1 and 2 and the different signals coming from the Galaxy, the recombination epoch, the lensing effect or the noise simulations. In particular, we have considered: (a) the CMB temperature map degraded at the same resolution, (b) the observational Galactic RM obtained by combining non-foreground reduced bands at 1.4 and 23 GHz, (c) the observational Galactic RM derived from EGRS, (d) the simulated Galactic RM with an axisymmetric model for the Galactic magnetic field (halo component), (e) the observational $Q$ and $U$ parameters at 23 GHz which characterize the polarized Galactic synchrotron emission and (f) the template for the polarized Galactic dust emission characterized by $(Q, U)$ and the angle of polarization. The correlation with noise is in (g) noise coming from $Q_{CMB}$, (h) noise coming from $U_{CMB}$, (i) noise coming from the polarization angle derived from the CMB simulated noise maps, i.e. $\phi_{CMB}$ and (j) the lensing potential map provided by the Planck Collaboration.

Table 1 shows the correlation results for the observational RM map obtained when covariance matrices provided by the WMAP team are used for computing the noise $\sigma_{RM}$. Combination of four frequencies, i.e. 33, 41, 61 and 94 GHz are considered. Moreover for the correlation coefficient $r$, its corresponding error, the significance of the correlation and the determination coefficient $R^2$ value are computed. Table 2 shows the same as pointed out in Table 1 when the $\sigma_{RM}$ is computed by using MC simulations. Regarding the statistical results for four frequencies combinations, the correlation coefficients are low for each comparison. The significance (third column) is the value which allows us to reject or not the correlation result. At a 95 per cent confidence level, the value of the tabulated two tailed $t$-Student distribution is $t_{0.05, m} = 1.960$ being $\alpha = 0.05$ (95 per cent CL) and $m$ the degree of freedom which in our case is the number of pixels out of the corresponding mask, i.e. $m = 2255$ or 1711. For a 99 per cent confidence level, $t_{0.01, m} = 2.576$ being $\alpha = 0.01$. We compare these values $t_{0.05, m} = 1.960$ and $t_{0.01, m} = 2.576$ with those values shown in the third column of Tables 1 and 2. We observe that all correlations could be neglected: those for the Galactic foregrounds or the primordial CMB, with the exception of those values obtained between our signal and the template for the dust polarization angle. Moreover, when the MC method is used for computing the $\sigma_{RM}$, the correlation with the noise could not be rejected yet, at least at the 95 per cent confidence level. These results would indicate that a residual of polarized dust emission is present in our RM signal when 33, 41, 61 and 94 GHz are considered. As mentioned above, dust polarization dominates at higher frequencies and so, we can conclude that the band of 94 GHz contains a residual of dust. In what follows we do not consider this band for the analysis of the angular power spectrum.

In Table 3, it is shown the same as in Table 1 but considering only three frequencies, i.e. 33, 41 and 61 GHz. Table 4 shows the same as in Table 2 but considering only three frequency bands, i.e. 33, 41 and 61 GHz. Regarding the statistical results shown in Tables 3 and 4, we can safely conclude that there is no correlation between the CMB primordial signal, the Galactic foregrounds or the noise and our RM signal. This conclusion is valid with a 99 per cent confidence level (i.e. $|t| < t_{0.01, m} = 2.576$ with $\alpha = 0.01$) for the case in which the error RM map is computed with both, MC simulations or by using the inverse covariance matrices.

For the 33, 41 and 61 GHz combination, the lack of correlation between the ILC map and also the lensing potential map and our RM
mainly to the small scales. The lack of correlation between our mordial signals, because secondary anisotropies would contribute at this map resolution, the ILC map could be attributable to pri-
signal suggests that our signal is not related to CMB anisotropies. At this map resolution, the ILC map could be attributable to primordial signals, because secondary anisotropies would contribute mainly to the small scales. The lack of correlation between our signal and the lensing potential map could point to this fact. No correlation between simulated noise and the RM signal is found. The lack of correlation between the Galactic foregrounds as polarized synchrotron emission, polarized dust emission or GFR and our

### Table 1

| Maps                          | $r + \Delta r$ | Significance ($|t|$) | $R^2$          |
|-------------------------------|----------------|---------------------|---------------|
| CMB temperature               | 0.009 ± 0.015  | 0.62                | $8.52 \times 10^{-5}$ |
| Obs. Galactic RM (1.4–23 GHz)| 0.037 ± 0.024  | 1.53                | $1.4 \times 10^{-3}$   |
| Obs. Galactic RM (EGRS)       | 0.024 ± 0.015  | 1.60                | $5.67 \times 10^{-4}$   |
| Sim. Galactic RM (23 GHz) halo| 0.038 ± 0.030  | 1.27                | $1.4 \times 10^{-3}$   |
| $U_{23}$-galactic             | −0.020 ± 0.015 | 1.37                | $4.1 \times 10^{-4}$   |
| $Q_{23}$-galactic             | 0.019 ± 0.015  | 1.27                | $3.6 \times 10^{-4}$   |
| $U_{dust}$-galactic           | 0.016 ± 0.015  | 1.08                | $2.6 \times 10^{-4}$   |
| $Q_{dust}$-galactic           | 0.009 ± 0.015  | 0.60                | $7.95 \times 10^{-5}$  |
| $\phi_{dust}$-galactic       | 0.034 ± 0.015  | 2.28                | $1.1 \times 10^{-3}$   |
| Noise $Q_{CMB}$               | −0.028 ± 0.015 | 1.92                | $8.2 \times 10^{-4}$   |
| Noise $U_{CMB}$               | −0.014 ± 0.015 | 0.92                | $1.8 \times 10^{-4}$   |
| Noise $\phi_{CMB}$            | 0.004 ± 0.015  | 0.25                | $1.39 \times 10^{-5}$  |
| Lensing potential             | 0.012 ± 0.015  | 0.81                | $1.45 \times 10^{-4}$  |

### Table 2

The same as shown in Table 1 with noise maps computed by using MC simulations.

| Maps                          | $r + \Delta r$ | Significance ($|t|$) | $R^2$          |
|-------------------------------|----------------|---------------------|---------------|
| CMB temperature               | −0.025 ± 0.015 | 1.66                | $6.0 \times 10^{-4}$   |
| Obs. Galactic RM (1.4–23 GHz)| 0.047 ± 0.024  | 1.93                | $2.2 \times 10^{-3}$   |
| Obs. Galactic RM (EGRS)       | 0.022 ± 0.015  | 1.48                | $4.8 \times 10^{-4}$   |
| Sim. Galactic RM (23 GHz) halo| 0.049 ± 0.029  | 1.68                | $2.5 \times 10^{-3}$   |
| $U_{23}$-galactic             | 0.015 ± 0.015  | 1.02                | $2.3 \times 10^{-4}$   |
| $Q_{23}$-galactic             | −0.021 ± 0.015 | 1.42                | $4.5 \times 10^{-4}$   |
| $U_{dust}$-galactic           | −0.015 ± 0.015 | 1.02                | $2.3 \times 10^{-4}$   |
| $Q_{dust}$-galactic           | −0.027 ± 0.015 | 1.79                | $7.1 \times 10^{-4}$   |
| $\phi_{dust}$-galactic       | 0.049 ± 0.015  | 3.32                | $2.4 \times 10^{-3}$   |
| Noise $Q_{CMB}$               | −0.037 ± 0.015 | 2.50                | $1.4 \times 10^{-3}$   |
| Noise $U_{CMB}$               | −0.017 ± 0.015 | 1.12                | $2.87 \times 10^{-4}$  |
| Noise $\phi_{CMB}$            | 0.019 ± 0.015  | 1.27                | $3.61 \times 10^{-4}$  |
| Lensing potential             | 0.011 ± 0.015  | 0.77                | $1.30 \times 10^{-4}$  |

### Table 3

The same as shown in Table 1 with noise maps computed by using covariance matrices for three frequencies.

| Maps                          | $r + \Delta r$ | Significance ($|t|$) | $R^2$          |
|-------------------------------|----------------|---------------------|---------------|
| CMB temperature               | 0.008 ± 0.015  | 0.53                | $6.23 \times 10^{-5}$   |
| Obs. Galactic RM (1.4–23 GHz)| 0.050 ± 0.024  | 2.07                | $2.5 \times 10^{-3}$   |
| Obs. Galactic RM (EGRS)       | 0.008 ± 0.015  | 0.57                | $7.2 \times 10^{-5}$   |
| Sim. Galactic RM (23 GHz) halo| 0.003 ± 0.029  | 0.92                | $7.4 \times 10^{-6}$   |
| $U_{23}$-galactic             | −0.019 ± 0.015 | 1.28                | $3.6 \times 10^{-4}$   |
| $Q_{23}$-galactic             | 0.020 ± 0.015  | 1.34                | $4.02 \times 10^{-4}$  |
| $U_{dust}$-galactic           | 0.014 ± 0.015  | 0.97                | $2.07 \times 10^{-4}$  |
| $Q_{dust}$-galactic           | 0.009 ± 0.015  | 0.64                | $9.18 \times 10^{-5}$  |
| $\phi_{dust}$-galactic       | 0.0014 ± 0.015 | 0.09                | $1.9 \times 10^{-6}$   |
| Noise $Q_{CMB}$               | −0.018 ± 0.015 | 1.20                | $3.1 \times 10^{-4}$   |
| Noise $U_{CMB}$               | −0.009 ± 0.015 | 0.60                | $8.06 \times 10^{-5}$  |
| Noise $\phi_{CMB}$            | 0.017 ± 0.015  | 1.17                | $3.03 \times 10^{-4}$  |
| Lensing potential             | 0.033 ± 0.015  | 2.24                | $1.12 \times 10^{-3}$  |
signal points out that the $RM$ map has no Galactic residual with a 99 per cent of confidence level.

Moreover, we have tested that the Galactic templates used in our analysis properly characterize the Galactic foregrounds. This is done in terms of the correlation. We have found that there is a strong correlation between Stokes parameters at 23 and 1.4 GHz, as well as, 23 GHz and dust, with $r \gtrsim 90$ per cent for both, $Q$ and $U$, and for the polarized angle. The correlation between the observational Galactic $RM$ map derived from 1.4 and 23 GHz and $RM$ coming from EGRS shows no significant correlation, i.e. $r \sim 3$–4 per cent but this is expected since both data set are completely independent. All correlation coefficients show that our templates used for characterizing the Galactic emission and the GFR are a good approximation of both Galactic contributions.

Finally, it is remarkable that $RM$ maps are useful to obtain those regions of the sky where the signal could be significant. The method on how the noise of the $RM$ maps is computed has a direct influence in the significance of the signal. We have found that the use of the covariance matrices provides the best way to obtain the noise in terms of $S/N$. When the covariance matrices are used to compute the observational error $RM$ map, we have obtained that there are $\approx 58$ per cent of total of pixels has $|S/N| > 1$, $\approx 30$ per cent has $|S/N| > 2$ and $\approx 12$ per cent has $|S/N| > 3$.

Finally we have to mention that the observational polarization angle $\phi$ is constrained to values between 0 and $\pi$. This implies an ambiguous determination on $\phi$ called $nt\pi$ ambiguity. There are some extended assumptions to solve this problem: by fixing an arbitrary $RM$ maximum value and by considering that there is no ambiguity between two close frequencies. Here we assume that the proximity of these frequencies provide $WMAP$, i.e. 33, 41 and 61 GHz, does not introduce any ambiguity because we assume that the proximity of these frequencies do not allow to rotate the angle too much.

### Table 4. The same as shown in Table 2 with noise maps computed by using MC simulations for three frequencies.

| Maps                              | $r + \Delta r$ | Significance ($|r|$) | $R^2$  |
|-----------------------------------|----------------|----------------------|--------|
| CMB temperature                   | $-0.015 \pm 0.015$ | 1.04  | $2.4 \times 10^{-4}$ |
| Obs. Galactic $RM$ (1.4–23 GHz) | $0.048 \pm 0.024$  | 1.96  | $2.3 \times 10^{-3}$ |
| Obs. Galactic $RM$ (EGRS)        | $0.022 \pm 0.015$  | 1.47  | $4.8 \times 10^{-4}$ |
| Sim. Galactic $RM$ (23 GHz) halo | $-0.026 \pm 0.029$ | 0.88  | $6.8 \times 10^{-4}$ |
| $U_{23}$-galactic                | $0.005 \pm 0.015$  | 0.36  | $2.8 \times 10^{-5}$ |
| $Q_{23}$-galactic                | $-0.006 \pm 0.015$ | 0.40  | $3.6 \times 10^{-5}$ |
| $U_{23}$-dust-galactic           | $-0.006 \pm 0.015$ | 0.40  | $3.6 \times 10^{-5}$ |
| $Q_{23}$-dust-galactic           | $-0.014 \pm 0.015$ | 0.91  | $1.8 \times 10^{-4}$ |
| $\phi_{23}$-galactic             | $0.021 \pm 0.015$  | 1.43  | $4.6 \times 10^{-4}$ |
| Noise $Q_{CMB}$                   | $-0.027 \pm 0.015$ | 1.80  | $7.2 \times 10^{-3}$ |
| Noise $U_{CMB}$                   | $-0.001 \pm 0.015$ | 0.06  | $7.6 \times 10^{-7}$ |
| Noise $\phi_{CMB}$               | $0.009 \pm 0.015$  | 0.58  | $7.4 \times 10^{-5}$ |
| Lensing potential                 | $0.031 \pm 0.015$  | 2.10  | $9.82 \times 10^{-4}$ |

5.2 Results at power spectrum level

The $RM$ maps in Figs 1 and 2 are used to extract their power spectrum. The power spectrum takes into account the cosmic variance and also the mask effects as described in Section 2.2. At this level, the signal is used to derive the angular scales, or equivalently the multipole range, at which the $RM$ is significant. This could be useful to obtain the constraints on the magnetic field strength at those angular scales.

In Fig. 4 it is shown the power spectrum of the $RM$ maps $C^{RM}_{\ell}$ for three frequencies combinations. In black it is represented the $C^{RM}_{\ell}$ when MC simulations are used to obtain the error of the $RM$ map and in red colour it is represented the $C^{RM}_{\ell}$ when covariance matrices are used to compute the $\sigma_{RM}$. To extract the $C^{RM}_{\ell}$ from the $RM$ maps, we have used the anafast tool of the healpix package.

The error bars of the $C^{RM}_{\ell}$ include the values derived from the $\sigma_{RM}$ maps and the cosmic variance. Moreover, both angular power spectra have been deconvolved by using MASTER prescriptions (Hivon et al. 2002). It is remarkable that the $RM$ values are a direct result from the observations. The different peaks are clear for low multipoles $\ell \lesssim 12$ or equivalently for large angular scales. This multipole range corresponds to the reionization epoch. Moreover, the $C^{RM}_{\ell}$ could be used to obtain the two-point correlation function given by equation (14). This function is directly related to the $RM$ values in different sky regions through $C(\theta) \propto (RM(r)RM_{\theta} + \delta r)$. Here the $RM$ is obtained by using equation (17) by taking into account the two different values for optical depth at reionization we are considering. Fig. 5 shows the two-point correlation function. In colour black it is shown the $C(\theta)$ when the noise is computed with covariance matrices (continuum line) or with MC simulations (dot line). In red colour is delimited the error region. Continuum
into account the two different values for the optical depth $\tau_1$ and $\tau_2$, respectively. These computations have been averaged for $\ell = (2–6)$. The two-point correlation function for multipoles $\ell = 2–6$ allows us to interpret the $C_\ell^{\text{RM}}$ in terms of magnetic fields strength. The order of magnitude for this magnetic field strength is $B_0 \sim 10^{-8}$ G, and as it can be deduced from the error bars, it seems to constitute a detection. Two error bars are shown. The first one corresponds to the error of $C_\ell^{\text{RM}}$ and the second one, when the error associated with the optical depth value is also included.

Here we are not claiming for a detection of FR in all-sky maps but we are finding a weak signal as shown in the angular power spectrum in Fig. 4. At map level, we are able to identify the regions of the sky where we have a significant RM signal (see Figs 1–3). At power spectrum level, we are able to identify that the low-$\ell$ peaks correspond with the reionization epoch and to derive the magnetic field strengths from the analysis of the two-point angular correlation function. The use of two methods for computing the observational noise has been illustrative to describe how well behaves MC simulations for these computations. However, the method that best characterize the noise of WMAP is the inverse covariance matrices provided by WMAP. Finally, the two different values of the optical depth considered only show an impact on the values of the magnetic field strength but not at map or power spectrum levels. The main impact is on increasing the error bars of the constrained magnetic field strength as shown in Table 5.

### 6 CONCLUSIONS

All-sky CMB polarization is a powerful tool to directly find FR distribution at larger scales. This FR signal provides information about pre-galactic magnetic fields.

Here we have considered foreground cleaned maps at 33, 41, 61 and 94 GHz from polarized WMAP9 data set degraded at their lowest resolution. By using two different methods to compute the noise maps, we have found out a pure observational RM maps when four and three frequencies are considered. These maps include the processing mask for polarization provided by the WMAP team. The angular power spectrum and the two-point correlation function have been obtained from these two RM maps. Their corresponding errors have been computed by taking into account the two different noise maps and including the cosmic variance and the effect of the mask.

Polarized Galactic emission could be a contaminant in our results. We have cross-correlated our RM maps with the Galactic RM coming from the combination of 1.4 and 23 GHz, the Galactic Faraday depth provided by Oppermann et al. (2015), the RM map derived from fixing an axisymmetric model for the regular component of the Galactic magnetic field, the Stokes ($Q, U$) parameters at 23 GHz that are used to characterize the polarized synchrotron emission of the Galaxy and the Stokes ($Q, U$) parameters and the polarization angle provided by WMAP as polarized dust emission of our Galaxy. The mask for processing polarization data provided by WMAP9 is used.

<table>
<thead>
<tr>
<th>Noise type</th>
<th>$\phi(\nu = 30\text{GHz})$ (in $^\circ$)</th>
<th>$\phi(\nu = 70\text{GHz})$ (in $^\circ$)</th>
<th>$\langle B_{\ell}(G) \rangle$ (with $\tau_1$)</th>
<th>$\langle B_{\ell}(G) \rangle$ (with $\tau_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC simulation</td>
<td>$36.0 \pm 20.6$</td>
<td>$6.30 \pm 3.72$</td>
<td>$(4.63 \pm 2.57 \pm 29.5) \times 10^{-8}$</td>
<td>$(6.88 \pm 3.81 \pm 25.8) \times 10^{-8}$</td>
</tr>
<tr>
<td>Covariance matrices</td>
<td>$35.5 \pm 24.9$</td>
<td>$6.30 \pm 4.46$</td>
<td>$(4.46 \pm 3.01 \pm 28.4) \times 10^{-8}$</td>
<td>$(6.62 \pm 4.58 \pm 24.8) \times 10^{-8}$</td>
</tr>
</tbody>
</table>
We have also cross-correlated our RM maps with the ILC map provided by WMAP9 results to look for any relation with CMB anisotropies. At the resolution we are working, the main contribution could be attributable to primary anisotropies and so, to the recombination epoch. Additionally, we have cross-correlated our results with the lensing potential map derived by the Planck Collaboration degraded at our resolution. No correlation is found because at this resolution the lensing effect is expected to be diluted. Another interpretation could be that we are detecting simple white noise. We can reject this interpretation at least in the multipole range $\ell < 15$ where the S/N is higher than 10.

Some residual of polarized angle due to the dust emission has been found when the 94-GHz band is included. This motivates that we only validate RM maps derived from the combination of 33, 41 and 61 GHz. We have found a negligible correlation in all cases what would suggest that the RM signal obtained is neither a residual Galactic foreground nor produced at recombination. Our tentative interpretation is therefore that the observed FR has been produced at reionization.

The relative large values of the observed FR also suggest that they are not produced at recombination where upper limits have been established by Planck. These values are also low to consider that they are because of Galactic magnetism. Also, the angular power spectrum shows a range of multipoles for $\ell \lesssim 12$, a typical range of reionization. The very low correlation found between our FR signal and the temperature map from the last scattering surface is consistent with the interpretation that the observed FR is not primordial.

The weak RM found reported here is obtained statistically at the spectrum level and at very low multipoles. At this low-$\ell$ range, and a frequency of 70 GHz, the rotated angled produced by the FR would be of the order of few degrees, which corresponds to magnetic frequency of 70 GHz, the rotated angled produced by the FR would of

$\ell$ spectrum level and at very low multipoles. At this low-

$\ell$ are very large around $\ell \sim 30$. This angular scale corresponds to ‘comoving’ diameters coincident with the larger quasar systems found by Einasto et al. (2014). These noticeable large values would suggest that magnetic fields could have a non-negligible influence on galactic and cluster formation.

Moreover, recent results obtained by Planck satellite indicate that there is a large S/N in multipoles corresponding to reionization peak, i.e. $\ell \lesssim 10$ which it is not only due to foreground emission (Planck Collaboration X 2016). This signal excess could be interpreted in terms of the presence of magnetic fields at reionization.

This work would provide a first observational result about the presence of magnetic fields at reionization. The detection of magnetic field at this epoch of the Universe could have an impact on our knowledge of the structure formation. Observations of LOFAR, SKA or Planck are crucial to support the scenario suggested in this paper.

Magnetic fields at high redshift have been studied by Kronberg et al. (2008) finding high-redshift EGRS at $z \sim 3.7$ producing RM values of 20–80 rad m$^{-2}$. Observed reionization RM values reach up to $\sim 10^4$ rad m$^{-2}$ as shown in Fig. 1. This similarity in the order of magnitude supports our tentative assumption. All values of magnetized strengths are ‘comoving’, i.e. the dilution due to the expansion is corrected.

The interpretation of this Faraday rotation signal as being produced at the epoch of reionization could be favoured by the fact that early stellar objects and early active galactic nuclei have been proposed as ejecting sources of magnetic fields into the intergalactic medium at this epoch (e.g. Kronberg 2005).

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