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Searching for a dipole modulation in the large-scale structure of the Universe

R. Fernández-Cobos,[1,2★] P. Vielva,[1] D. Pietrobon,[3] A. Balbi,[4,5] E. Martínez-González[1] and R. B. Barreiro[1]

[1] *Instituto de Física de Cantabria, CSIC-Universidad de Cantabria, Avda. de los Castros s/n, E-39005 Santander, Spain*
[2] *Dpto. de Física Moderna, Universidad de Cantabria, Avda. los Castros s/n, E-39005 Santander, Spain*
[3] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[4] *Dipartimento di Fisica, Università di Roma 'Tor Vergata', Via Della Ricerca Scientifica, I-00133 Roma, Italy*
[5] *INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*

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ABSTRACT

Several statistical anomalies in the cosmic microwave background (CMB) temperature anisotropies seem to defy the assumption of a homogeneous and isotropic universe. In particular, a dipole modulation has been detected both in *WMAP* and *Planck* data. We adapt the methodology proposed by Eriksen et al. on CMB data to galaxy surveys, tracing the large-scale structure. We analyse the National Radio Astronomy Observatory (NRAO) and Very Large Array (VLA) Sky Survey data at a resolution of $\sim 2^{\circ}$ for three different flux thresholds: 2.5, 5.0 and 10.0 mJy, respectively. No evidence of a dipole modulation is found. This result suggests that the origin of the dipole asymmetry found in the CMB cannot be assigned to secondary anisotropies produced at redshifts around $z = 1$. However, it could still have been generated at redshifts higher or lower, such as the integrated Sachs–Wolfe effect produced by the local structures. Other all-sky surveys, like the infrared *WISE* catalogue, could help to explore with a high sensitivity a redshift interval closer than the one probed with NVSS.

Key words: methods: data analysis – large-scale structure of Universe.

1 INTRODUCTION

The acceptance of the cosmological principle requires that the Universe, on sufficiently large scales, is statistically isotropic and homogeneous. This assumption is widely supported by both the results obtained by the ESA *Planck* satellite (Planck Collaboration XV 2013) and the galaxy catalogues generated by the large-covering sky surveys carried out during the last decade, such as the Sloan Digital Sky Survey (York et al. 2000). However, several anomalies that seem to deviate from the orthodoxy were detected in the *WMAP* data, and recently confirmed by *Planck* (Planck Collaboration XXIII 2013). These hints of anomalous behaviour in the cosmic microwave background (CMB) observations include the detection of a non-Gaussian cold spot in the Southern galactic hemisphere (e.g. Vielva et al. 2004; Cruz et al. 2005), an alignment between the quadrupole and the octopole (e.g. de Oliveira-Costa et al. 2004; Schwarz et al. 2004; Land & Magueijo 2005), the lack of large-scale power (e.g. Berera, Fang & Hinshaw 1998; Spergel et al. 2003; Copi et al. 2007) or the so-called hemispherical asymmetry (e.g. Eriksen et al. 2004b; Hansen, Banday & Górski 2004; Park 2004).

In this paper, we focus on the characterization of this north–south hemispherical asymmetry. In particular, this anomaly was discovered in the 1-year *WMAP* data, in which several estimators calculated on different regions of the sphere show an anisotropic behaviour (see the previous references). It seems that the CMB anisotropy pattern in the Northern hemisphere has a lack of structure with respect to the Southern hemisphere. Inoue & Silk (2006) explored the possibility that the CMB anomalies could be caused by the presence of local voids. In particular, they showed that the north–south anisotropy is compatible with an asymmetric distribution of these local voids between the two hemispheres. In a later paper, Hansen et al. (2009) extended the analysis of Eriksen et al. (2004b) and Hansen et al. (2004) to higher angular multipoles, and confirmed this asymmetry. More recently, the Planck Collaboration (Planck Collaboration XXIII 2013) repeated the analysis of Eriksen et al. (2005), by computing the two-, three- and four-correlation functions of the data, and they obtained results in agreement with those provided with *WMAP* data. These hemispherical differences have been supported by subsequent analysis (e.g. Santos et al. 2013; Akrami et al. 2014).

Moreover, Gordon et al. (2005) proposed an effective model in terms of a dipole modulation that would characterize the hypothetical case in which the statistical isotropy is spontaneously broken

★ E-mail: cobos@ifca.unican.es

in the fluctuations observed from a given position. Bennett et al. (2011) explicity distinguished between a hemispherical asymmetry, in which the power spectrum changes discontinuously across a large circle on the sky, and a dipole asymmetry, in which the fluctuations are smoothly modulated by a cosine function across the sky. Assuming the Gordon et al. (2005) parametrization, Eriksen et al. (2007) estimated the amplitude and the direction of the modulation in the 3-year *WMAP* data. They found evidence of a preferred direction that in galactic coordinates points towards $(l,\ b) = (225°, -27°)$. In a later paper, Hoftuft et al. (2009) concluded that the best-fitting modulation amplitude for $\ell \le 64$ and the Internal Linear Combination (ILC) of the 5-year *WMAP* data with the KQ85 mask is $A_m = 0.072 \pm\ 0.022$ and the preferred direction points towards $(l,\ b) = (224°,\ -22°) \pm\ 24°$. Finally, the Planck Collaboration, also following the methodology presented by Eriksen et al. (2007), detected this dipole modulation with consistent results with those obtained with the *WMAP* data (Planck Collaboration XXIII 2013). Indeed, the bipolar spherical harmonic formalism has also been applied by Planck Collaboration XXIII (2013) to demonstrate that a dipole modulation term is sufficient to account for this asymmetry.

Several theoretical proposals that try to explain this dipole asymmetry, such as models with a modulation of the reionization optical depth or a modulated scale-dependent isocurvature component, can also be found in the literature (see e.g. Dai et al. 2013, and references therein). For instance, Ackerman, Carroll & Wise (2007) studied the possibility of an asymmetric pattern in the CMB as an imprint of a primordial preferred direction during inflation. A theoretical model developed within a framework of single-field inflation was proposed by Donoghue, Dutta & Ross (2009). McDonald (2013) presented a modulated reheating model. An alternative model in which an spectator field has a fast roll phase was presented by Mazumdar & Wang (2013) and an inflation version with a contracting phase was proposed by Liu, Guo & Piao (2013). D'Amico et al. (2013) analysed a model of inflation in which the particle production leads to a dipole modulation. And, more recently, Liddle & Cortês (2013) proposed a marginally open model for the universe which could explain, in particular, the dipole power asymmetry.

The main motivation of this analysis is to shed light on the possible cosmological origin of the CMB dipole asymmetry by checking whether it is also detected in the large-scale structure (LSS) data. The galaxy distribution is an exceptional observable to collate a possible isotropy breaking, because it traces the gravitational potential (see, for instance, Akbar Abolhasani et al. 2014). In the case that some catalogues were analysed and no preferred direction was found, the CMB asymmetry could be due to, for instance, a secondary anisotropy located into a different redshift range than those which were considered. In fact, several authors addressed this problem by searching in the integrated Sachs–Wolfe field the cause of the preferred axis found in the CMB (see e.g. Francis & Peacock 2010; Rassat & Starck 2013).

In particular, we analyse here the galaxy distribution provided by the National Radio Astronomy Observatory (NRAO) and Very Large Array (VLA) Sky Survey[1] (Condon et al. 1998). This survey is appropriate to carry out cosmological analysis, such as cross-correlations with CMB data to characterize the integrated Sachs–Wolfe effect (e.g. Boughn & Crittenden 2004; Vielva, Martínez-González & Tucci 2006; McEwen et al. 2007; Giannantonio et al. 2012; Schiavon et al. 2012; Barreiro et al. 2013; Planck Collaboration XIX 2013) or to find constraints on primordial non-Gaussianity (see, for instance, Xia et al. 2011; Marcos-Caballero et al. 2013; Giannantonio et al. 2014).

This paper is structured as follows. The methodology is explained in Section 2. Then, we describe the NVSS data in Section 3. The results obtained both for simulated and real data are presented in Section 4. Finally, conclusions are shown in Section 5.

2 THE METHOD

The Bayesian approaches computed with Monte Carlo samplers are widely used in the CMB data analysis (e.g. Eriksen et al. 2004a; Jewell, Levin & Anderson 2004; Wandelt, Larson & Lakshminarayanan 2004; Chu et al. 2005). We employ here an adapted version of the framework used by Eriksen et al. (2007) to characterize the dipole asymmetry in LSS data.

A phenomenological model, like the one proposed by Gordon et al. (2005) for the CMB data, is assumed to describe the fluctuations of the number density of galaxies $\boldsymbol{\delta}$ in terms of a modulation of the isotropic signal in the direction $\boldsymbol{x}_m$ as

$$\delta(\boldsymbol{x}) = d_k(\boldsymbol{x}, \boldsymbol{x_k}) + [1 + d_m(\boldsymbol{x}, \boldsymbol{x_m})]\,[s(\boldsymbol{x}) + n_p(\boldsymbol{x})], \quad (1)$$

where $\delta(\boldsymbol{x}) \equiv [n(\boldsymbol{x}) - \bar{n}]/\bar{n}$, being $n(\boldsymbol{x})$ the number of counts integrated in the area of the pixel centred in the direction $\boldsymbol{x}$ and $\bar{n}$ the average number of counts per pixel. The isotropic Gaussian random field of the number density fluctuations predicted by the standard model is represented by $s(\boldsymbol{x})$, while $n_p(\boldsymbol{x})$ refers to the intrinsic Poisson noise of the galaxy count. The dipole terms are considered as $d_i(\boldsymbol{x}_i, \boldsymbol{x}) \equiv A_i \cos\theta_{x,x_i}$, with θ_{x,x_i} denoting the angular distance between the unitary vectors $\boldsymbol{x}$ and $\boldsymbol{x}_i$ and $i = \{k, m\}$. The subscript m refers to a dipole modulation with a preferred direction $\boldsymbol{x_m}$, and the subscript k denotes the additive dipole term in the direction $\boldsymbol{x_k}$. This latter term accounts for both the dominant kinetic component because of our local motion and the residual dipole due to a partial-sky coverage. As the well-known CMB dipole anisotropy, a corresponding effect is also present in the number density of galaxies due to a combination of Doppler boosting and relativistic aberration (see, for instance, Singal 2011; Gibelyou & Huterer 2012; Kothari et al. 2013; Rubart & Schwarz 2013).

The model depends on six parameters which determine the dimensionless amplitudes of the dipole terms A_i and their orientations $\boldsymbol{x}_i$, which are parametrized by two angles. Contrary to what happens in the CMB experiments, where the instrumental noise is an extra contribution from the detector electronics, the noise term here represents an uncertainty which is intrinsic to the measure. For this reason, the main difference with respect to the model used by Hoftuft et al. (2009) is that we also modulate this noise term. The average number of counts per pixel is large enough to consider that the noise contribution is well described by a Gaussian distribution. The dimensionless noise term is assumed to have variance $\sigma_p^2 = 1/\bar{n}$.

The previous definition of the data set implies that the modulated fluctuations of the number density of galaxies $\boldsymbol{\delta}$ are well characterized by an anisotropic, but still Gaussian, random field. The covariance matrix of these data can be expressed as

$$\mathbf{C}_{\rm mod}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta) = f_{x_\alpha}\left[\mathbf{C}_{\rm iso}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta) + \mathbf{N}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta)\right] f_{x_\beta}, \quad (2)$$

where f_{x_j} depends on the dipole modulation parameters, $f_{x_j} \equiv 1 + A_m \cos\theta_{x_j,x_m}$ (with $j = \alpha$ or β), and $\mathbf{N}$ is a diagonal matrix that takes into account the Poisson noise where all non-zero terms are equal to σ_p^2.

[1] http://www.cv.nrao.edu/nvss/

The covariance matrix of the isotropic signal $\mathbf{C}_{\rm iso}$ is constructed as

$$\mathbf{C}_{\rm iso}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta) = \frac{1}{4\pi}\sum_{\ell=2}^{\ell_{\rm max}} (2\ell+1)\, C_\ell^{\rm GG} P_\ell(\cos\theta_{\boldsymbol{x}_\alpha,\boldsymbol{x}_\beta}), \quad (3)$$

where $C_\ell^{\rm GG}$ is a theoretical model for the power spectrum of the data and P_ℓ denotes the Legendre polynomial of order ℓ. The noise term is large enough to solve the regularization problems mentioned by Eriksen et al. (2007), so we do not need to add any artificial contribution. Applying a χ^2 test to ensure the consistency between the covariance matrix of the isotropic signal and the simulated maps, it was found that the optimum value for $\ell_{\rm max}$ is $3N_{\rm side} - 1$, where $N_{\rm side}$ is an integer defined in the HEALPIX tessellation (Górski et al. 2005) so that the number of pixels needed to cover the sphere is $N_{\rm pix} = 12N_{\rm side}^2$.

The parameters of the model are estimated by maximizing the posterior probability. Since both the number density of galaxies and its intrinsic noise are assumed to be Gaussian, the log-likelihood can be written as

$$-\log \mathfrak{L} = \frac{1}{2}\left(\boldsymbol{d}^T \mathbf{C}_{\rm mod}^{-1}\boldsymbol{d} + \log|\boldsymbol{d}|\right), \quad (4)$$

ignoring an irrelevant constant. In our particular case, both the covariance matrix $\mathbf{C}_{\rm mod}$ and the data set $\boldsymbol{d} \equiv \boldsymbol{\delta} - \boldsymbol{d}_k$ depend on the parameters of the modelling. To estimate the amplitude and the orientation of the dipole modulation, we marginalize over the other parameters, including the three ones which characterize the amplitude and direction of the additive dipole.

We use an adapted version of the COSMOMC[2] code (Lewis & Bridle 2002) to sample the likelihood described by the equation (4). In practice, the covariance matrix $\mathbf{C}_{\rm mod}$ depends on three parameters $(A_m, \cos\theta, \phi)$, where θ is the colatitude and ϕ the galactic longitude. Actually, the solution is degenerate because of the symmetry of the problem. In case of detection, there would be a solution with positive amplitude and a certain orientation, and its complementary, which corresponds to a rotation of π in the direction and a sign change in the amplitude. To avoid this inconvenience, we constrain the galactic longitude into a range of size π to select only a half of the sphere. This π range for the galactic longitude is determined after exploring the whole 2π range with some preliminary runs. The final range is selected such as the maximum value of the posterior of this parameter is approximately centred on it.

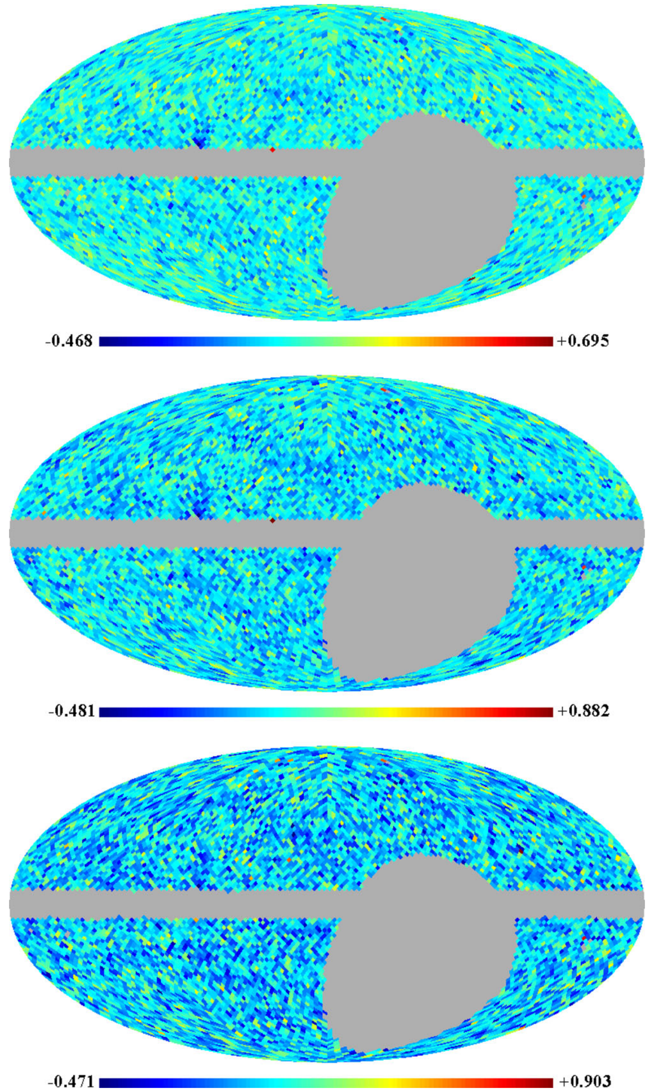

Figure 1. HEALPIX maps of fluctuations of the NVSS number density of galaxies at $N_{\rm side} = 32$, computed for different flux threholds. From top to bottom, the maps correspond to a flux threshold of: 2.5, 5.0 and 10.0 mJy, respectively.

3 THE NVSS DATA

We construct several dimensionless HEALPIX (Górski et al. 2005) maps of the fluctuations of the number density of galaxies $\delta(\boldsymbol{x})$ from NVSS. This catalogue is a 1.4 GHz continuum total intensity and linear polarization survey which explores the largest sky-coverage so far (the sky north of J2000.0 $\delta \geq -40°$) and gives reliability in order to consider that the objects which appear are extragalactic. Although active galactic nuclei are the dominant contribution in radio catalogues at 1.4 GHz, Condon et al. (1998) showed that star-forming galaxies constitute about 30 per cent of the NVSS sources above 1 mJy. However, this portion decreases rapidly as higher flux thresholds are considered. The star-forming galaxies of NVSS are nearby sources and they might distort the global pattern (Planck Collaboration XIX 2013). In particular, three different cases are explored in this paper: we only take into account those sources whose flux value is greater than 2.5, 5.0 and 10.0 mJy, respectively. All these maps are created at a HEALPIX resolution of $N_{\rm side} = 32$ and are shown in Fig. 1.

In addition, it is well known that the NVSS data present systematic effects due to the adoption of two different configurations, depending on the declination angle (e.g. Blake & Wall 2002). We follow the procedure explained by Marcos-Caballero et al. (2013) in order to correct the variation of the mean number density of galaxies with the declination angle. The map is divided into 70 stripes which cover equal area. Taking into account the mean value in each stripe, the galaxy counting per pixel is rescaled so that the mean value in each band is the same as the mean computed within the whole map. We only make this correction for the threshold of 2.5 mJy, because in the rest of cases we assume that the systematic effects are negligible. We have carried out a series of analyses to check whether this declination correction could either introduce a fake modulation pattern or, conversely, mitigate a real one. Our simulations show that this is not the case. Even more, we have also

[2] http://cosmologist.info/cosmomc/

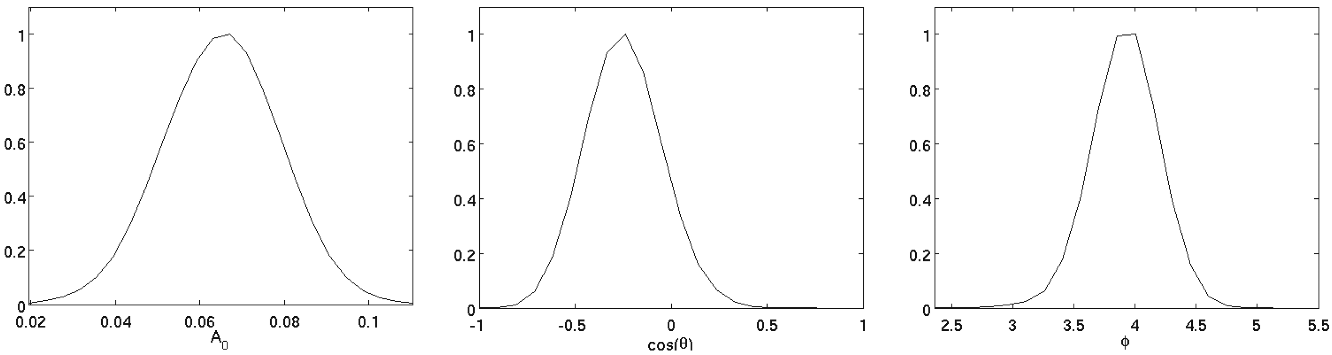

Figure 2. Marginalized likelihoods of the parameters of the dipole model for a simulated NVSS map with a flux threshold of 5.0 mJy and a dipole modulation with an amplitude $A_m = 0.072$ and a preferred direction which points towards $(l, b) = (224^\circ, -22^\circ)$.

analysed the NVSS data without any correction for the 2.5 mJy flux cut, and no difference has been found.

The exclusion mask has been constructed as a combination of two requeriments. On the one hand, we impose a threshold in declination (excluding pixels with $\delta < -40^\circ$), because NVSS only comprises observations performed from the Northern hemisphere and the tropical latitudes. On the other hand, we exclude a region 14° wide which covers the galactic plane in order to discard a possible contamination from galactic objects.

Finally, we consider the estimation of the galaxy power spectrum $C_\ell^{\rm GG}$ proposed by Marcos-Caballero et al. (2013). Since there are difficulties to describe theoretically the NVSS data due to a power excess presented at large scales, many methods have been used to model the statistical properties of this survey (e.g. Dunlop & Peacock 1990; Boughn & Crittenden 2002; Ho et al. 2008; de Zotti et al. 2010). Marcos-Caballero et al. (2013) performed a joint fitting of the NVSS power spectrum and the distribution of galaxies as a function of redshift in the Combined EIS-NVSS Survey Of Radio Sources (Best et al. 2003; Brookes et al. 2006). In particular, they used a gamma distribution in order to parametrize the redshift distribution of galaxies.

4 RESULTS

In this section, we discuss the expected results of the method in the case in which the LSS presents a dipole modulation like that found in the CMB. And, then, we also present the application to the NVSS data.

4.1 Amplitude estimation forecast

We test the sensitivity of NVSS to detect a dipole modulation as that found in the CMB data, by simulating an NVSS-like realization. A flux threshold of 5.0 mJy, the model proposed by Marcos-Caballero et al. (2013) and the Poisson noise are considered. We use HEALPIX to construct an isotropic Gaussian map at $N_{\rm side} = 32$ of the $\boldsymbol{\delta}$ field from the theoretical power spectrum $C_\ell^{\rm GG}$.

We include a multiplicative dipole modulation as that found by Hoftuft et al. (2009) in the CMB temperature anisotropies, i.e. with an amplitude $A_m = 0.072$ and a preferred direction which points towards $(l, b) = (224^\circ, -22^\circ)$. Since the propagation of anisotropies, due to the the Sachs–Wolfe and the integrated Sachs–Wolfe effects, is well described by a linear regime, one of the possible cases is that the relative amplitude of the dipole modulation is similar to that found in the CMB.

A detection of a non-negligible dipole modulation is obtained with a sensitivity of 5.5σ. The direction of the dipole modulation is recovered with an uncertainty of 17°. The shapes of the marginalized likelihoods for the three parameters of the dipole modulation are shown in Fig. 2.

4.2 Application to the NVSS data

An estimation of the parameters which characterize a hypothetical dipole modulation is computed for three different cases, with a flux threshold of 2.5, 5.0 and 10.0 mJy, respectively. We conclude that no detection of a dipole modulation is found in any case. The estimated values for the amplitude are shown in Table 1. All of them are compatible with zero at a significance level less than 1σ.

This absence of dipole modulation contrary to the findings in the CMB temperature anisotropies suggests that the dipole asymmetry is not caused by a secondary anisotropy located at $z \sim 1$. The result does not support the hypothesis of an anisotropic breaking during an early phase of the universe, because the modulation should be linearly propagated to the LSS distribution. Then, a possible cause of the dipole modulation found in the CMB could be sought in catalogues of nearby objects, since it is more likely that the local structure is statistically deviated from the homogeneous and isotropic overall pattern. But this is not the only possibility. For instance, there could be topological defects whose distribution generates a hemispherical asymmetry at higher redshift. In particular, the number of textures expected by models is sufficiently small to present an anisotropic distribution (Cruz et al. 2007).

As the mean value of the redshift distribution of NVSS is $\bar{z} = 1.2$, more local surveys, such as the *Wide-field Infrared Survey Explorer* (Wright et al. 2010), may be useful in forthcoming research. In this sense, we also explored the Two Micron All-Sky Survey (Skrutskie et al. 2006) data, by applying the same methodology that is described in this paper. However, the difficulty to avoid the very nearby structure prevented us to reach any conclusion. This survey

Table 1. Marginalized amplitude of a dipole modulation in the NVSS for different flux thresholds. The average number of counts per steradian is denoted by $\bar{n}_{\rm s}$.

Threshold (mJy)	$\bar{n}_{\rm s}$	A_m
2.5	158 594.34	0.003 ± 0.015
5.0	92 273.41	0.011 ± 0.016
10.0	55 496.39	0.007 ± 0.014

was used by several authors in order to reconstruct the integrated Sachs–Wolfe field, which could trace a secondary anisotropy that define a preferred axis on the sky (e.g. Francis & Peacock 2010; Rassat & Starck 2013).

5 CONCLUSIONS

After the confirmation of the CMB statistical anomalies by the *Planck* results (Planck Collaboration XXIII 2013), the LSS provides an alternative observable to study the origin of these deviations. In particular, an asymmetry usually parametrized as a dipole modulation across the sky was detected by several authors in the CMB temperature anisotropies. We adapt here the method described by Eriksen et al. (2007) to deal with LSS data.

Two possibilities are considered: the asymmetry could be due to an intrinsic isotropy breaking occurred in the early Universe or it could be caused by a secondary anisotropy induced by an anisotropic distribution of the local galaxy distribution. If different LSS surveys presented a sort of dipole modulation with a similar preferred direction than that observed in the CMB temperature anisotropies, it would be an indicator that the cause of this anomaly has to be sought in the physical mechanisms of generation of primordial fluctuations. But, if this preferred direction was not detected at all in LSS data, the CMB asymmetry could be due to, for instance, a secondary anisotropy located in a more local or further galaxy distribution than the one traced by the surveys we are considering.

The methodology is proven reliable with an NVSS-like simulation with a dipole amplitude as intense as that measured in the CMB data. However, no preferred direction is detected in the NVSS data for three different flux thresholds: 2.5, 5.0 and 10.0 mJy, respectively.

Assuming a linear propagation of the dipole modulation hypothetically generated during an early phase of the universe, the apparent absence of detection in the LSS at $z \sim 1$ suggests that the dipole power modulation found in the CMB had to be generated in a late cosmological epoch different from this one. Avoiding other considerations, those models based on anisotropic modifications of standard inflation (e.g. Donoghue et al. 2009; D'Amico et al. 2013; McDonald 2013) might be compromised to reconcile their predictions with observation. This result motivates forthcoming studies with other surveys which explore the more local structure distribution. A detection of a dipole modulation in the nearby galaxy distribution might explain the CMB asymmetry in terms of a secondary anisotropy.

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REFERENCES

Ackerman L., Carroll S. M., Wise M. B., 2007, Phys. Rev. D, 75, 083502
Akbar Abolhasani A., Baghram S., Firouzjahi H., Namjoo M. H., 2014, Phys. Rev. D, 89, 063511
Akrami Y., Fantaye Y., Shafieloo A., Eriksen H. K., Hansen F. K., Banday A. J., Górski K. M., 2014, ApJ, 784, L42
Barreiro R. B., Vielva P., Marcos-Caballero A., Martínez-González E., 2013, MNRAS, 430, 259
Bennett C. L. et al., 2011, ApJS, 192, 17
Berera A., Fang L.-Z., Hinshaw G., 1998, Phys. Rev. D, 57, 2207
Best P. N., Arts J. N., Röttgering H. J. A., Rengelink R., Brookes M. H., Wall J., 2003, MNRAS, 346, 627
Blake C., Wall J., 2002, Nature, 416, 150
Boughn S. P., Crittenden R. G., 2002, Phys. Rev. Lett., 88, 021302
Boughn S., Crittenden R., 2004, Nature, 427, 45
Brookes M. H., Best P. N., Rengelink R., Röttgering H. J. A., 2006, MNRAS, 366, 1265
Chu M., Eriksen H. K., Knox L., Górski K. M., Jewell J. B., Larson D. L., O'Dwyer I. J., Wandelt B. D., 2005, Phys. Rev. D, 71, 103002
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Copi C. J., Huterer D., Schwarz D. J., Starkman G. D., 2007, Phys. Rev. D, 75, 023507
Cruz M., Martínez-González E., Vielva P., Cayón L., 2005, MNRAS, 356, 29
Cruz M., Turok N., Vielva P., Martínez-González E., Hobson M., 2007, Science, 318, 1612
Dai L., Jeong D., Kamionkowski M., Chluba J., 2013, Phys. Rev. D, 87, 123005
D'Amico G., Gobbetti R., Kleban M., Schillo M., 2013, J. Cosmol. Astropart. Phys., 11, 13
de Oliveira-Costa A., Tegmark M., Zaldarriaga M., Hamilton A., 2004, Phys. Rev. D, 69, 063516
de Zotti G., Massardi M., Negrello M., Wall J., 2010, A&AR, 18, 1
Donoghue J. F., Dutta K., Ross A., 2009, Phys. Rev. D, 80, 023526
Dunlop J. S., Peacock J. A., 1990, MNRAS, 247, 19
Eriksen H. K. et al., 2004a, ApJS, 155, 227
Eriksen H. K., Novikov D. I., Lilje P. B., Banday A. J., Górski K. M., 2004b, ApJ, 612, 64
Eriksen H. K., Banday A. J., Górski K. M., Lilje P. B., 2005, ApJ, 622, 58
Eriksen H. K., Banday A. J., Górski K. M., Hansen F. K., Lilje P. B., 2007, ApJ, 660, L81
Francis C. L., Peacock J. A., 2010, MNRAS, 406, 14
Giannantonio T., Crittenden R., Nichol R., Ross A. J., 2012, MNRAS, 426, 2581
Giannantonio T., Ross A. J., Percival W. J., Crittenden R., Bacher D., Kilbinger M., Nichol R., Weller J., 2014, Phys. Rev. D, 89, 023511
Gibelyou C., Huterer D., 2012, MNRAS, 427, 1994
Gordon C., Hu W., Huterer D., Crawford T., 2005, Phys. Rev. D, 72, 103002
Górski K. M., Hivon E., Banday A. J., Wandelt B. D., Hansen F. K., Reinecke M., Bartelmann M., 2005, ApJ, 622, 759
Hansen F. K., Banday A. J., Górski K. M., 2004, MNRAS, 354, 641
Hansen F. K., Banday A. J., Górski K. M., Eriksen H. K., Lilje P. B., 2009, ApJ, 704, 1448
Ho S., Hirata C., Padmanabhan N., Seljak U., Bahcall N., 2008, Phys. Rev. D, 78, 043519
Hoftuft J., Eriksen H. K., Banday A. J., Górski K. M., Hansen F. K., Lilje P. B., 2009, ApJ, 699, 985
Inoue K. T., Silk J., 2006, ApJ, 648, 23
Jewell J., Levin S., Anderson C. H., 2004, ApJ, 609, 1
Land K., Magueijo J., 2005, Phys. Rev. Lett., 95, 071301
Lewis A., Bridle S., 2002, Phys. Rev. D, 66, 103511
Liddle A. R., Cortês M., 2013, Phys. Rev. Lett., 111, 111302
Liu Z.-G., Guo Z.-K., Piao Y.-S., 2013, Phys. Rev. D, 88, 063539
McDonald J., 2013, J. Cosmol. Astropart. Phys., 11, 41
McEwen J. D., Vielva P., Hobson M. P., Martínez-González E., Lasenby A. N., 2007, MNRAS, 376, 1211

Marcos-Caballero A., Vielva P., Martinez-Gonzalez E., Finelli F., Gruppuso A., Schiavon F., 2013, preprint (arXiv:1312.0530)
Mazumdar A., Wang L., 2013, J. Cosmol. Astropart. Phys., 10, 49
Park C.-G., 2004, MNRAS, 349, 313
Planck Collaboration XIX, 2013, submitted to A&A, preprint (arXiv:1303.5079)
Planck Collaboration XV, 2013, submitted to A&A, preprint (arXiv:1303.5075)
Planck Collaboration XXIII, 2013, submitted to A&A, preprint (arXiv:1303.5083)
Rassat A., Starck J.-L., 2013, A&A, 557, L1
Rubart M., Schwarz D. J., 2013, A&A, 555, A117
Santos L., Cabella P., Villela T., Balbi A., Vittorio N., Alexandre Wuensche C., 2013, preprint (arXiv:1311.0714)
Schiavon F., Finelli F., Gruppuso A., Marcos-Caballero A., Vielva P., Crittenden R. G., Barreiro R. B., Martinez-Gonzalez E., 2012, MNRAS, 427, 3044
Schwarz D. J., Starkman G. D., Huterer D., Copi C. J., 2004, Phys. Rev. Lett., 93, 221301
Singal A. K., 2011, ApJ, 742, L23
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Spergel D. N. et al., 2003, ApJS, 148, 175
Tiwari P., Kothari R., Naskar A., Nadkarni-Ghosh S., Jain P., 2013, preprint (arXiv:1307.1947)
Vielva P., Martínez-González E., Barreiro R. B., Sanz J. L., Cayón L., 2004, ApJ, 609, 22
Vielva P., Martínez-González E., Tucci M., 2006, MNRAS, 365, 891
Wandelt B. D., Larson D. L., Lakshminarayanan A., 2004, Phys. Rev. D, 70, 083511
Wright E. L. et al., 2010, AJ, 140, 1868
Xia J.-Q., Baccigalupi C., Matarrese S., Verde L., Viel M., 2011, J. Cosmol. Astropart. Phys., 8, 33
York D. G. et al., 2000, AJ, 120, 1579

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