Kinetic Sunyaev–Zel'dovich effect in rotating galaxy clusters from MUSIC simulations

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Ordered motions of the diffuse gas in clusters of galaxies (intra-cluster medium, ICM hereafter) can play a very important role in deriving accurate estimates of the masses of these large structures, by means of non-thermal pressure support. Indeed, cluster masses derived under the hypothesis of hydrostatic equilibrium, which accounts only for the contribution from thermal pressure, turn out to be underestimated up to ~ 20 per cent with respect to the true values, as derived directly from hydrodynamical cluster simulations (see e.g. Biffi et al., 2016, and references therein). In this context, the characterization of a possible rotation of the ICM could be useful to accurately recover cluster masses, that are fundamental for cosmology. This work focuses in particular on the investigation of rotational motions of the ICM from the study of the kinetic component of the Sunyaev–Zel'dovich effect (Sunyaev & Zel'dovich, 1970, 1980), kSZ hereafter. Indeed, kSZ measurements give the temperature distortion of the cosmic microwave background (CMB) produced by the overall motion of the gas in galaxy clusters in the CMB reference frame. The signal is proportional to the integration over the line of sight of the projected gas velocity times the electron number density, with no dependence on the radiation frequency in the non-relativistic approximation. Therefore, with the use of ancillary data (coming e.g. from X-ray photometric measurements) to disentangle the contribution from the electron number density to the kSZ signal, it would be possible to constrain the ICM velocity projected on the line of sight (see e.g. the recent results by Adam et al., 2017).

Since the observation of ICM rotation in particular is an extremely challenging task, we apply this study to synthetic galaxy clusters, in order to give a preliminary assessment on the feasibility of possible future measurements towards real clusters, with high-resolution and high-sensitivity instruments operating in the microwave band. We analyse data from the MUSIC[1] hydrodynamical N-body simulations (Sembolini et al., 2013), run with the TreePM+SPH GADGET-3 code and featuring high resolution. Our test clusters are extracted from the most massive objects in the MUSIC-2 sub-set, having virial masses $M_{\rm vir} > 5 \times 10^{14} h^{-1}$ M$_\odot$ (being $h = 0.7$ in the cosmological model adopted in these simulations) at redshift $z = 0$, whose rotational features have already been studied in the companion paper by (Baldi et al., 2017), focused on the properties of the angular momentum. In particular, with the aim of avoiding contaminating signal from the motion of large sub-structures within the clusters, we choose possible rotating candidates among the most relaxed objects, as classified according to two commonly used indicators of the dynamical state computed from the simulation data (i.e. the offset between positions of centre of mass and of the density peak, and the ratio between the mass of the largest sub-structure and the virial mass). To quantify the rotational state, we refer to the spin parameter of the gas, so that only clusters with $\lambda_{\rm gas} > 0.07$ are classified as rotating. With these criteria we get six rotating clusters out of the total initial sample (made of 258 objects). For each cluster, we produce mock maps of the temperature distortion produced by the kSZ effect using the `pymsz`[2] package. The expected signal feature produced by a rotation would be a symmetric dipole which, in the best observational conditions, would be aligned horizontally in the maps, as prescribed in the reference works on this topic by Cooray & Chen (2002) and Chluba & Mannheim (2002). In order to maximise the rotational signal in our mock maps, we set the line of sight to be orthogonal to the rotation axis of our clusters, which can be identified with the direction of the gas angular momentum vector at virial radius. We test six different lines of sight, all orthogonal to the rotation axis, in order to check the consistency of the dipole, which is expected to be unchanged across such different projections. To check whether it is possible to recover a modelling of the ICM rotation consistently with the results of Baldi et al. (2017), we compute a pixel-to-pixel fit to the maps. We produce theoretical kSZ maps corresponding to two cases (and we modify the calculation of the mock kSZ signal in a proper way): a rotation-only model and a more realistic rotation+bulk model, which accounts also for the cluster bulk motion. To compute the rotational term in the theoretical map

[1] `http://music.ft.uam.es`
[2] `https://github.com/weiguangcui/pymsz`

we use the vp2b rotational law, derived as a modified radial profile of the circular velocity of the gas in a Navarro-Frenk-White distribution of the dark matter density. To constrain the electron number density, which is needed as well in the calculation of the theoretical maps, we fit the numerical profiles from the simulation data to a simplified version of the model proposed in Vikhlinin et al. (2006). The free parameters left in the fit to the kSZ maps are therefore the scale radius and the scale velocity of the vp2b radial profile of the gas rotational velocity, and, in the complete case, the projection of the cluster bulk velocity on the line of sight.

From the fit to the kSZ maps we find that the scale radius and the scale velocity of the vp2b profiles are consistent within one standard deviation when comparing results from the two cases without and with the cluster bulk term. From the comparison with the results from the fit to the tangential velocity data of the simulations, we find instead agreement within one standard deviation for the scale radius, and within two sigma in some clusters in the case of the scale velocity. The latter parameter takes values that overestimate the expected ones of a factor of 1.5 on average, being of the order of $\sim 800\,\mathrm{km\,s^{-1}}$. This may be due to the contribution of high-velocity gas particles producing outliers in the signal when integrating along the line of sight that, nevertheless, do not affect the dipole structure significantly. The projection of the cluster bulk velocity along the different lines of sight is recovered with good agreement with respect to the true projections from the simulations. Values are generally overestimated by few tens of per cent, with larger discrepancies in few cases in which the true projected bulk velocity is smaller than $100\,\mathrm{km\,s^{-1}}$. An interesting result of this analysis is that the amplitude of the rotational signal as measured from the dipole in the best-fit theoretical maps is consistent with the estimates in the literature for relaxed galaxy clusters, being of the order of few tens of μK. We find that, on average, the ratio between such amplitude and the maximum signal measured from the best-fit maps accounting for the rotation+bulk case is of the order of 23 per cent. Therefore, possible future measurements of the ICM rotation through the study of temperature kSZ maps will require, as expected, a suitable high sensitivity provided the best observational conditions.

A more detailed study focused on observational aspects connected to a specific high-resolution microwave experiment (e.g. NIKA2), properly accounting for instrumental effects (e.g. systematics and noise) as well as for astrophysical contaminants will be the topic of a forthcoming paper. Also, we are working on the extension of the study of rotation of the baryonic component in our cluster sample through a multi-wavelength approach, i.e. with X-ray and optical spectroscopy towards the gas and the member galaxies, respectively.

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