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Sunyaev Zel'dovich study of filamentary structures between galaxy clusters

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The Sunyaev Zel'dovich (SZ) effect can be used to map the inter-cluster region between galaxy clusters especially in particular cases of superclusters of galaxies and pairs of galaxy clusters in the premerging phase. Such direct detection would be fundamental for the study of filamentary structures between galaxy clusters and shed light on the open problem of the missing baryons in our Universe as well as on the hierarchical structure formation scenario. We take as example the Abell401-Abell399 cluster pair, which has been observed at low-angular resolution by the Planck satellite and is a well-studied structure that exhibits double radio-halos, an ex-cess of X-ray emission in the bridge connecting the clusters, and even the presence of a shock front indicating the cluster pair's pre-merging status. The Planck satellite was able to model the emission from the bridge between the clusters pair despite the poor angular resolution ($\simeq$5') of its SZ maps, and proposed that at least part of the signal in the inter-cluster region (y$\simeq 5\times10^{-6}$ over a total of y$\simeq 15\times10^{-6}$) is due to a pre-existing filamentary structure. A bolometric camera observing at $\simeq$3mm, coupled to a 50-to-100m class radio telescope would be the ideal instrument in terms of angular resolution and sensitivity to disentangle different scenarios.

Multifrequency Behaviour of High Energy Cosmic Sources - XIII - MULTIF2019
3-8 June 2019
Palermo, Italy

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PoS(MULTIF2019)008

1. Introduction

The baryon distribution in the Universe is an open question for modern cosmology (see e.g. Nicastro et al., 2018). The observed baryonic matter in the local universe obtained from HI absorption, gas and stars in galaxy clusters, and X-ray emission is still small compared to what is predicted by nucleosynthesis (see, e.g., Fukugita et al., 1998), by Lyα forest absorption observations (see, e.g., Rauch et al., 1997), and by measurements of the CMB power spectrum (see, e.g., Planck collaboration, 2018). A diffuse baryonic dark matter could explain, at least in part, the apparent discrepancy between the observed and the expected baryon density. Hydrodynamical simulations of large-scale structures (see, e.g., Cen & Ostriker, 1999; Davé et al., 2001) show that at low redshifts, these missing baryons, which represent approximately half of the total baryon content of the universe, should lie in the temperature range of 10^5<T<10^7 K in a state of warm-hot gas not yet observed through their EUV and soft X-ray emission. Hydrodynamical simulations predict that this warm-hot intergalactic medium (WHIM) is arranged in the form of filamentary structures of low-density intergalactic medium connecting (and around) the clusters of galaxies into the so called cosmic web.

Galaxy clusters sit at the top of the matter distribution of the cosmic web, and are therefore important signpost to localize the possible distribution of cosmic filaments. They are the largest virialized structures of our universe and excellent laboratories for studying structures formation, merging phenomena, to investigate turbulent fluid motions, mass distributions and magnetic fields. Galaxy clusters are thus a unique tool for cosmology and astrophysics. Observations in a wide range of wavelengths, have highlighted the presence of diffuse large-scale synchrotron emission (radio halos, see e.g. Murgia et al., 2010), the presence of high temperature electrons in the intracluster medium through X-ray bremsstrahlung emission (see, e.g., Sarazin, 1986), as well as the inverse Compton scattering that the CMB photons undergo when passing through them: the Sunyaev Zel'dovich (SZ) effect (see, e.g. Carlstrom et al., 2002). The SZ effect (Sunyaev & Zeldovich, 1972) is the distortion of the Cosmic Microwave Background (CMB) frequency spectrum due to the energy injection originated from the hot electron gas in galaxy clusters and the surrounding medium. This secondary anisotropy effect produces a brightness change in the CMB that can be detected at millimeter and submillimeter wavelengths, appearing as a negative signal (with respect to the average CMB temperature) at frequencies below $\simeq$217GHz and as a positive signal at higher frequencies. The SZ intensity change directly depends on the electron density of the scattering medium, n_e, and on the electron temperature T_e, both integrated over the line of sight l, and its intensity can be described by the Comptonization parameter y:

$$y = \int n_e \sigma_T \frac{k_B T_e}{m_e c^2} dl \tag{1.1}$$

where σ_T is the Thomson cross section, k_B is the Boltzman constant, m_e is the electron mass, and c is the light speed in vacuum.

The SZ effect has now been detected through thousands of clusters of galaxies (see, e.g., Bleem et al., 2015; Hasselfield et al., 2013; Planck collaboration, 2015) and several observations have been undertaken in order to directly detect WHIM filaments through their SZ signature (see e.g., Battistelli et al., 2006; Planck collaboration, 2013). The gas within and around galaxy clusters is

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expected to be hotter and denser than the WHIM in filaments, making direct detection of the cluster gas more likely than WHIM filaments. Nevertheless, within the process of hierarchical formation via continuous accretion and merger events, we expect an increase of pressure which enhances the SZ signal, favoring the detection of the gas in superclusters of galaxies and between pairs of interacting clusters. Therefore, the bridge of inter-cluster matter between a pair of clusters is expected to be of higher thermal pressure than the average WHIM matter found in cosmic filaments (Dolag et al., 2006). In the pre-merging phase, filamentary structures are expected to exhibit an enhancement of plasma temperature whose detection would clearly prove the hierarchical structure formation scenario. It should be stressed that X-ray bremsstrahlung emission SX samples the same diffuse medium as the SZ effect with different dependency (i.e. $S_X \propto \int n_e^2 T_e^{0.5} dl$). Thus, X-ray measurements are practically limited to high density environments which lie relatively near to the galaxy cluster center, while SZ emission is relatively stronger when the density is low and the temperature is high. While statistical detections through stacking of neighbouring cluster-cluster or galaxy-galaxy pairs have been claimed (e.g. Tanimura et al., 2017; De graaff et al., 2017), so far there is no unambiguous direct SZ evidence of a filamentary structure between galaxy clusters able to prove the current structure formation scenario.

2. Galaxy cluster pair: the example of Abell 401-Abell 399

Abell 401 and Abell 399 (hereafter A401 and A399) is an exceptional pair of galaxy clusters separated in projection by an angular distance of 36’, corresponding to a linear separation of 3 Mpc in our chosen cosmology. The first example of a double radio halo was found in this close pair of galaxy clusters (Murgia et al., 2010; see Fig.1, left panel). The discovery of this double halo is extraordinary given the rarity of these radio sources in general, and that X-ray data (e.g. Sakelliou & Ponman 2004; Bourdin & Mazzotta 2008; Fujita et al., 2008) seem to suggest that the two clusters are still in a pre-merger state. Also, the presence of a large-scale diffuse radio filamentary-like structure connecting A399-A401 has been investigated with Lofar observations (Govoni et al., 2019).

Earlier observations show an excess of X-ray emission above the background level in the inter-cluster region (Fujita et al., 1996). Using XMM data, Sakelliou & Ponman (2004) obtained best-fitting models within the clusters in the inter-cluster region. They found that neither of the two clusters contains a cooling flow, and that they are nearly isothermal, with some small-scale inhomogeneities and an asymmetric brightness distribution. Since the X-ray studies show that the inter-cluster medium in this pair is compressed in this pre-merging process (Sakelliou & Ponman 2004), we expect that the increased pressure would increase the SZ signal. Akahori & Yoshikawa (2008) studied the non-equilibrium state of this system with simulated data and found that there might be significant shock layers at the edge of the linked region between the clusters that could produce a boost in the SZ signal. Furthermore, Suzaku observations found that the inter-cluster medium has a relatively high metallicity of 0.2 solar (Fujita et al., 2008). These works predicted a filamentary bridge with electron density of $n_e \simeq 10^{-4} cm^{-3}$ (Sakelliou & Ponman 2004; Fujita et al., 2008). Suzaku observations focused on the plasma in the filament located between the two clusters (Akamatsu et al., 2017). In the region between the clusters, they found a clear enhancement in the plasma temperature from $k_B T_e \simeq 4 keV$ to $\simeq 6.5 keV$ also indicating the presence of a shock

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front, a firm prediction of the hierarchical structure formation, together with the presence of WHIM filamentary structures. Akamatsu et al. (2017) modeled the plasma in the region and predicted a Comptonization parameter of y=(14.5±1.3) $\times$ 10^{-6}.

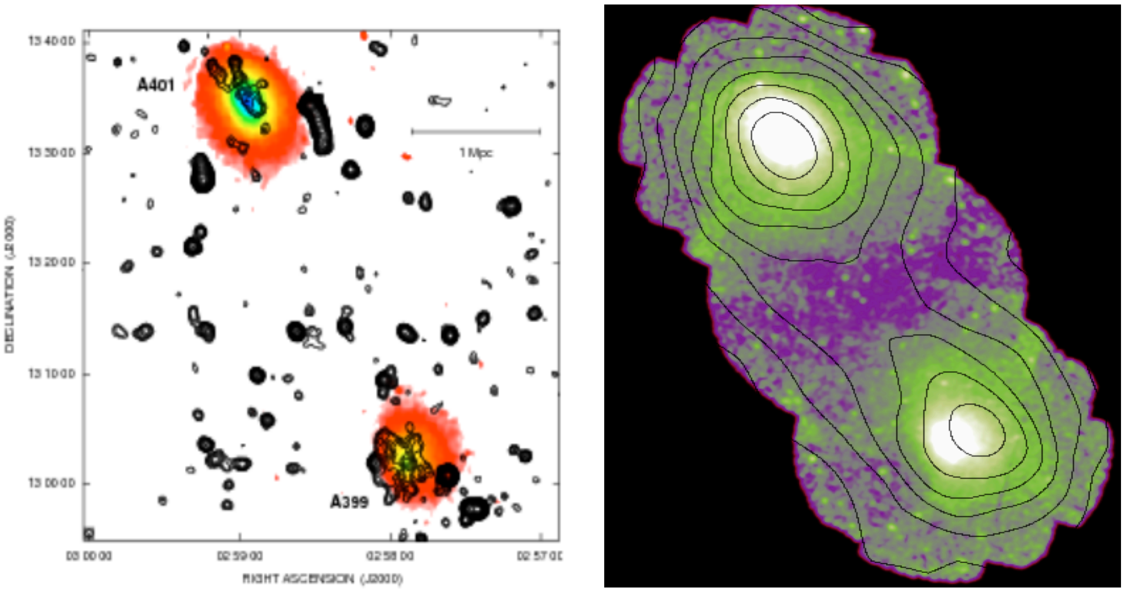

Figure 1: Left: total intensity radio contours at 1.4GHz of the system A399-A401 (picture adapted from Murgia et al. 2010), overlaid on the XMM X-ray image. Right: XMM map of A401-A399 cluster pairs with the Planck signal contours (black) overplotted.

The Planck collaboration (Planck collaboration, 2013) has reported tentative evidence for a filamentary structure between this pair of clusters (see Fig. 1, contours in right panel). They have analyzed the clusters' structure as well as their size and modeled (assuming spherical symmetry of the galaxy clusters) the signal profile removing the clusters signal from the map itself. This left a residual signal which was interpreted as a hot diffuse filamentary structure bridging the two clusters of $k_B T_e \simeq 7keV$ and of $n_e \simeq 3.7 \times 10^{-4} cm^{-3}$. The detected signal is at the level of y=15$\times$$10^{-6}$ which converts into a residual of y=5$\times$$10^{-6}$ from the filament itself (see Fig. 2 for details).

The Planck collaboration argued that since the clusters are at slightly different redshifts (z=0.07180 and z=0.073664), they are not on the same plane of the sky and their true separation is larger than $\simeq$3Mpc. Consequently they concluded that at least part of the inter cluster signal corresponds to baryons outside the clusters themselves. Nevertheless, the Planck collaboration (2013) warned that despite the evidence for a gas present in the inter-cluster region, one should raise the question about the origin of such gas. In a post merger scenario (despite not being favored by earlier observations), the inter-cluster signal could be just the result of the overlapping tails of the disturbed clusters. Also, they did not exclude the possibility that these clusters could be elongated due to their gravitational interaction, or that a bridge of matter may have formed between the clusters after an interaction. On the other hand, if confirmed, this model-dependent detection would represent an important milestone in the comprehension of large-scale structures and their formation. The limit

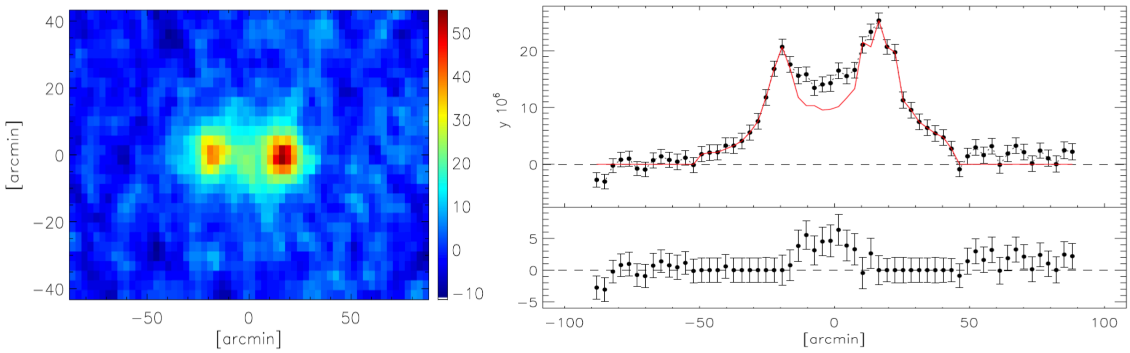

Figure 2: Left: map of Comptonization parameter (y$\simeq 10^{-6}$) as measured by Planck over the cluster pairs A401-A399. Right: y longitudinal profile (top part) and residual (bottom part) after subtracting the modeled contribution from the clusters (picture adapted from Planck collaboration, 2013).

of Planck observations is clearly connected to the poor angular resolution of the observations (5' from high frequency channels) as these filaments should have smaller-scale structures (see next section). In fact, only morphological studies have the power to unambiguously distinguish pre-merger from post-merger scenarios by resolving the gas distribution between the clusters pair and possibly WHIM filamentary structures. This calls for high angular resolution SZ measurements of the gas between the two clusters of galaxies which could lead to the first direct evidence of filamentary structures between clusters of galaxies forming the so-called cosmic web.

3. Observing the cosmic web

In this proceeding, we support the possibility of using 50-to-100m class telescopes with mm cameras to observe superclusters of galaxies and galaxy cluster pairs like A401-A399 in order to map the inter-cluster region between clusters with $\simeq$10" angular resolution. In order to obtain a firm prediction of the expected signal at 10" angular resolution, one can take advantage of cosmological numerical simulations. We adopted a high resolution Magnetohydrodynamical (MHD) simulation of a merging pair of galaxy clusters, obtained as in Vazza et al. (2018), using the cosmological adaptive mesh refinement ENZO code (Bryan et al. 2014).

We analyzed the catalog of clusters of a simulated box of (150 Mpc)^3 with a uniform resolution of 15 kpc corresponding to 11" in the sky, searching for close pairs of galaxy clusters leading to a similar configuration as A399-A401. We found at least two cases in which the projected configuration is compatible with A399-A401 within the simulated volume. We then produced forecasts of SZ signal as shown in Fig. 3.

In Fig. 3 we compare the SZ signal, related to the case of a pre-merging phase between the two clusters, observed with an angular resolution of 5' (top) and of 10" (bottom). By comparing the two, we have good reason to believe that the actual filamentary structure would not be observed at Planck's low angular resolution but would be accessible to the high resolution of a camera like MUSTANG2 at the Green Bank Telescope (Dicker, et al., 2014). It is in fact clear that the poor angular resolution of Planck does not unambiguously exclude the possibility that the connecting

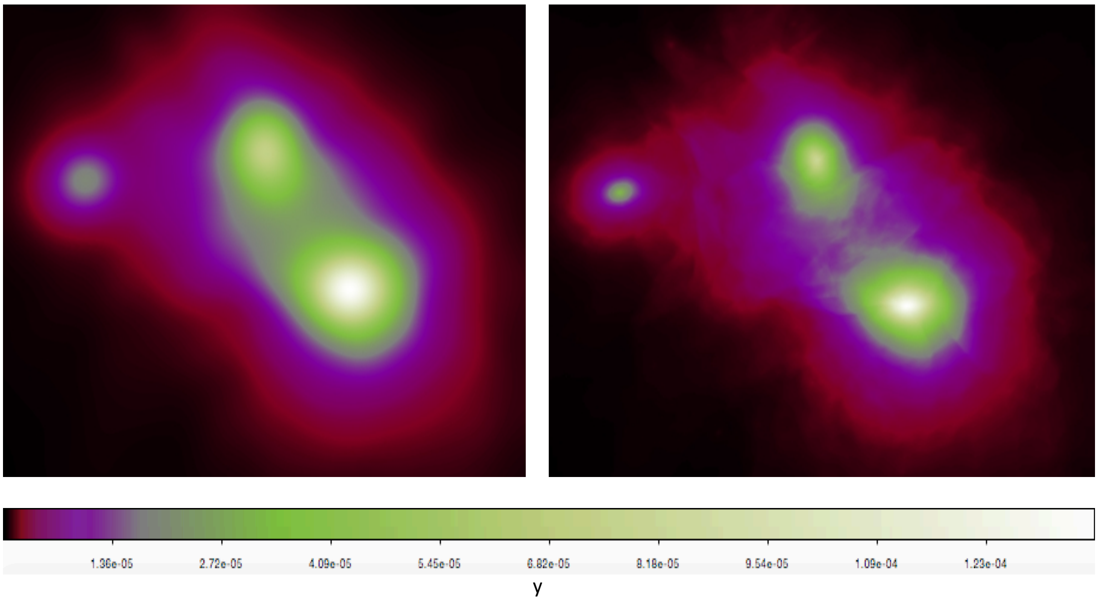

Figure 3: Simulated plasma signature within a A401-A399-like complex. The signal is in units of the Comptonization parameter y reaching $\simeq 1.5 \times 10^{-4}$ in the clusters centers. Left: map of Comptonization parameter smoothed at the Planck resolution of 5'. Right: same map of the SZ signal at the resolution of $\simeq$10". The physical scale of each panel side is 7.5Mpc.

structure is not due to the clusters' outskirts, or that it is the result of post-merging phenomena. Hydrodynamical simulations predict that the filamentary structure should be present and should be structured enough to show overdensities up to y=7×10^{-6} (i.e. in the bottom panel of Fig. 3 we have, within the filamentary structure, a structured signal between y$\simeq 0.9 \times 10^{-5}$ to y$\simeq 1.6 \times 10^{-5}$) consistent with that modeled by Planck. Furthermore, earlier cosmological simulations suggest that the density perpendicular to the collision axis would have an exponential profile (e.g., Dolag et al., 2006).

An ideal observation of the A401-A399 cluster pair would include a map of a $\simeq 30' \times 60'$ down to a sensitivity of y$\times 10^{-6}$. This may result in an out-of-reach request for most current state-of-the-art facilities although it may be considered as large legacy project with the additional problem of retrieving the large angular scales in mosaicking the pointings. Nevertheless, a targeted observation over typical 5' $\times$ 5' regions down to the same sensitivity would give unique information about the presence of filamentary structures between galaxy clusters. This would make use of the current state-of-the-art high resolution mm cameras like MUSTANG2 at GBT (Dicker, et al., 2014) or NIKA2 at IRAM (Calvo et al., 2016) characterized by field of views of the order of $\simeq$5' diameter therefore providing a high-pass filtered view of the large-scale SZ after atmospheric removal. Nevertheless, we should stress that larger cameras are currently being built (see eg., Zhu, et al. 2018) and work can be done in order to couple them with 50m-100m class telescopes able to be used up to mm wavelengths like Green Bank Telescope or the Sardinia Radio Telescope (Bolli, et al., 2015). In fact, probing such large structures would really benefit from both high angular resolution and the ability to recover large spatial scales (tens of arcminutes). These will progressively be accessible to possible upgrades for the GBT (e.g. a 12-15' field of view MUSTANG3 instrument on the GBT, TolTEC , or a W-band bolometric receiver for the SRT) and next generation large aperture facilities with > 1 deg fields of view (see e.g. LST, Kawabe, R., et al., 2016; AtLAST ; CMB-in-HD ; and CSST).

Waiting for the next generation large aperture facilities to be operating, we support the possibility of joint analysis with different instruments like MUSTANG-2 and AdvACT (De Bernardis et al., 2016; Henderson et al., 2016).

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