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High-resolution SZ imaging of clusters of galaxies with the NIKA2 camera at the IRAM 30-m telescope

F. Mayet[1], R. Adam[1,2], P. Ade[3], P. André[4], M. Arnaud[4], H. Aussel[4], I. Bartalucci[4], A. Beelen[5], A. Benoît[6], A. Bideaud[3], O. Bourrion[1], M. Calvo[6], A. Catalano[1], B. Comis[1], M. De Petris[7], F.-X. Désert[8], S. Doyle[3], E. F. C. Driessen[9], J. Goupy[6], C. Kramer[10], G. Lagache[11], S. Leclercq[9], J. F. Lestrade[12], J. F. Macías-Pérez[1], P. Mauskopf[3,13], A. Monfardini[6], E. Pascale[3], L. Perotto[1], E. Pointecouteau[14], G. Pisano[3], N. Ponthieu[8], G. W. Pratt[4], V. Revéret[4], A. Ritacco[10], C. Romero[9], H. Roussel[15], F. Ruppin[1], K. Schuster[9], A. Sievers[10], S. Triqueneaux[6], C. Tucker[3], R. Zylka[9]

[1] *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble Alpes, CNRS/IN2P3, 53, avenue des Martyrs, Grenoble, France*

[2] *Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Blvd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France*

[3] *Astronomy Instrumentation Group, University of Cardiff, UK*

[4] *Laboratoire AIM, CEA/IRFU, CNRS/INSU, Université Paris Diderot, CEA-Saclay, 91191 Gif-Sur-Yvette, France*

[5] *Institut d'Astrophysique Spatiale (IAS), CNRS and Université Paris Sud, Orsay, France*

[6] *Institut Néel, CNRS and Université Grenoble Alpes, France*

[7] *Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*

[8] *Institut de Planétologie et d'Astrophysique de Grenoble, Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France*

[9] *Institut de RadioAstronomie Millimétrique (IRAM), Grenoble, France*

[10] *Institut de RadioAstronomie Millimétrique (IRAM), Granada, Spain*

[11] *Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France*

[12] *LERMA, CNRS, Observatoire de Paris, 61 avenue de l'observatoire, Paris, France*

[13] *School of Earth and Space Exploration and Department of Physics, Arizona State University, Tempe, AZ 85287*

[14] *Université de Toulouse, UPS-OMP, Institut de Recherche en Astrophysique et Planétologie (IRAP), Toulouse, France*

[15] *Institut d'Astrophysique de Paris, Sorbonne Universités, UPMC Univ. Paris 06, CNRS UMR 7095, 75014 Paris, France*

The development of precision cosmology with clusters of galaxies requires high-angular resolution Sunyaev-Zel'dovich (SZ) observations. As for now, arcmin resolution SZ observations (*e.g.* SPT, ACT and Planck) only allowed detailed studies of the intra cluster medium for low redshift clusters ($z < 0.2$). With both a wide field of view (6.5 arcmin) and a high angular resolution (17.7 and 11.2 arcsec at 150 and 260 GHz), the NIKA2 camera installed at the IRAM 30-m telescope (Pico Veleta, Spain), will bring valuable information in the field of SZ imaging of clusters of galaxies. The NIKA2 SZ observation program will allow us to observe a large sample of clusters (50) at redshifts between 0.4 and 0.9. As a pilot study for NIKA2, several clusters of galaxies have been observed with the pathfinder, NIKA, at the IRAM 30-m telescope to cover the various configurations and observation conditions expected for NIKA2.

1 The NIKA2 camera at the IRAM 30-m telescope

NIKA2 is a millimetre camera [1,2], made of Kinetic Inductance Detectors (KID) and operated at 150 mK, which has been installed in September 2015 at the focus of the IRAM 30-m telescope. NIKA2 observes the sky at 150 and 260 GHz with a wide field of view (FOV), 6.5 arcmin (2896 detectors), a high-angular resolution (17.7 and 11.2 arcsec, respectively), and a state-of-the-art sensitivity (6 and 20 mJy.s$^{1/2}$, respectively). The NIKA camera [3,4,5,6,7] was a pathfinder of NIKA2 that has been operated at the IRAM 30-m telescope from 2012 to 2015 with a smaller field of view (1.8 arcmin) due to the reduced number of KIDs (356). The performance of these cameras at the IRAM 30-m telescope is described in [2,7].

The NIKA2 camera is well suited for high-resolution SZ observations of cluster of galaxies for several reasons. First, it is a dual-band camera operating at frequencies for which the SZ signal is negative and slightly positive respectively. The 260-GHz map may be used for the detection for point sources or as a template of the atmospheric noise. Then, a high angular resolution and a large field of view [2] enable NIKA2 to well match intermediate and high redshift clusters. Moreover, as the NIKA2 field of view is about the size of the beam of the Planck's intruments, the combination of Planck and NIKA2 data will enable a SZ mapping of clusters of galaxies at all scales, from the core to the outskirts (up to R_{500}). Eventually, the sensitivity in Compton parameter units is expected to be of the order of 10^{-4} per hour and per beam, allowing us to obtain reliable SZ mapping at high signal-to-noise ratio in a few hours per cluster.

2 The need for high-resolution SZ imaging of clusters

The SZ effect [8,9,10] is an inverse Compton scattering of CMB photons on hot electrons of the intra-cluster medium. It induces a shift of the CMB black-body spectrum to higher frequency, with a decrease of the CMB intensity below 217 GHz and an increase above. The SZ effect is thus a spectral distortion of the CMB spectrum. This is the reason why it is redshift-independent and can thus be used for the observation of high-redshift clusters. The SZ signal is the Compton parameter y, which is proportional to the electronic pressure $P_{\rm e}$ integrated along the line of sight, as $y \propto \int P_{\rm e} dl$. SZ observations provide imaging of the line-of-sight integrated pressure of the intra-cluster medium (ICM). They can be combined with X-ray observation (which surface brightness is related to the electronic density, $S_X \propto \int n_e^2 \Lambda(T_e, Z) dl$) in order to probe the clusters physical properties.

Clusters of galaxies constitute powerful tools to study cosmology as their number and distribution in mass and redshift is dependent of the geometry of the Universe. Cosmological parameters [11,12] have been constrained by using cluster counts, as a function of redshift and mass, for a sample of clusters identified by their SZ effect by the Planck Satellite [13,14], the Atacama Cosmology Telescope (ACT) [15] and the South Pole Telescope (SPT) [16]. However, it requires an estimation of the cluster halo mass, which is commonly obtained from X-ray observation assuming clusters are in hydrostatic equilibrium. In order to leverage large samples with inhomogeneous follow-up data and to estimate the selection function, a mass-to-observable scaling law is also needed to relate cluster observables, *e.g.* the integrated Compton parameter, with cluster parameters, such as the total mass. The calibration precision of this law is subject to our current understanding of the intra-cluster gas physics. Biases in the absolute mass calibration, such as a departure from hydrostatic equilibrium, which may increase with redshift, must be taken into account. The scatter in the mass-observable relation, linked to the intrinsic cluster physics, must also be included in the analysis.

Currently, there is a tension [12] between CMB and cluster estimation of the matter density Ω_M and the amplitude of density fluctuations σ_8. This may be due to an incorrect estimation of the total mass of the cluster, via the mass-observable relation, in particular the scatter around the relation that may depend on the redshift, the internal structure and/or the dynamical state of the considered cluster. High-resolution SZ imaging of high-redshift cluster are thus needed to study their intra-cluster properties, such as dynamical states (mergers) and morphology (departure from sphericity). It must be combined with other probes, in particular X-ray, within the framework of multi-probe analysis of clusters of galaxies.

3 SZ imaging of clusters of galaxies with the NIKA camera

The NIKA camera has been used as a pathfinder for NIKA2, to demonstrate the possibility to use large arrays of KIDs in millimeter astronomy [17,18]. In order to validate the use of a KID-based camera for SZ science, *i.e.* faint and diffuse signals, we have mapped the SZ signal in the direction of five clusters of galaxies [19,20,21,22,23,24] and combined with X-ray data to study the radial distribution of the thermodynamical properties of their intra-cluster medium, *i.e.* pressure, density, temperature, and entropy radial profiles. This methodology is typically what is expected from the NIKA2 SZ large program and highlights the possibility of measuring thermodynamical profiles of high-redshift clusters, with a small integration time and without X-ray spectroscopy. The various SZ observations with NIKA, see tab. 1, are:

- RX J1347.5-1145, a well-known and strong SZ source, allowed us to perform the first SZ cartography ever achieved with a KID-based camera [19]. In particular, we confirm that this cluster is an ongoing merger.
- CL J1226.9+3332, a high-redshift cluster, has been shown to present cluster parameters, mass and integrated Compton parameter, consistent with the Planck best-fit scaling relation [11] obtained with a sample of nearby clusters. Although no conclusion can be drawn from a single high-redshift cluster, it highlights the interest of the NIKA2 SZ large program that is dedicated to the observation of a cluster sample with redshift up to 0.9.
- MACS J1423.9+2404 has been used to explore the impact of the presence of point sources [21].
- MACS J0717.5+3745 has been used to report the first mapping of the kinetic Sunyaev-Zel'dovich signal towards a cluster [22] as well as the first mapping of the hot gas temperature using X-ray and SZ imaging [24], providing an independant cross-calibration of X-ray spectroscopic measurements.
- PSZ1 G045.85+57.71 has been used to demonstrate the possibility to use NIKA2 for a high-resolution follow-up of Planck-discovered clusters [23]. We have also proposed a new non-parametric deprojection procedure to extract the pressure profile, which has been shown to be in good agreement with X-ray data, obtained with spectroscopy. The uncertainty on the integrated Compton parameter is reduced by a factor 2 with respect to Planck result [23].

Cluster	z	Obs. time (h)	Ref.
RX J1347.5-1145	0.45	5.5	19
CL J1226.9+3332	0.89	7.8	20,25
MACS J1423.9+2404	0.54	1.5	21
MACS J0717.5+3745	0.55	13.1	22,24
PSZ1 G045.85+57.71	0.61	4.3	23

Table 1: *Overview of cluster observations with NIKA at the IRAM 30-m telescope.*

4 The NIKA2 SZ large program

The NIKA2 SZ large program is a follow-up of Planck- and ACT-discovered clusters and is part of the NIKA2 Guaranteed time. The NIKA2 cluster sample contains 50 clusters with redshift ranging between 0.4 and 0.9, selected from the Planck [13,14] and ACT catalogs [15]. This representative sample will be used for redshift evolution and cosmological studies. In particular, redshift bins present an homogeneous coverage of cluster mass range as reconstructed from the integrated Compton parameter. The excellent sensitivity of NIKA2 [2] will allow us to obtain reliable SZ mapping of clusters of galaxies in only few hours (1 to 5 hours). The NIKA2 SZ data will be combined with ancillary data (X-ray, optical and radio). The study of the thermodynamic properties of the ICM will lead to significant improvements on the use of clusters of galaxies to draw cosmological constraints. With the full sample, we aim at studying:

• the thermodynamic properties of the cluster (temperature, entropy and mass radial profiles),
• the redshift evolution of the scaling law and of the cluster pressure profiles up to high redshift,
• the cluster morphology and the dynamical state at high redshift (departure from spherical symmetry, merging events, cooling processes).

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