

Crab nebula at 260 GHz with the NKA2 polarimeter

Implications for the polarization angle calibration of future CMB experiments

A. Ritacco^{1,2,*}, R. Adam³, P. Ade⁴, H. Ajeddig⁵, P. André⁵, E. Artis⁶, J. Aumont⁷, H. Ausseil⁵, A. Beelen¹, A. Benoit⁸, S. Berta⁹, L. Bing¹⁰, O. Bourrion⁶, M. Calvo⁸, A. Catalano⁶, M. De Petris¹¹, F.-X. Désert¹², S. Doyle⁴, E. F. C. Driessen⁹, A. Gomez¹³, J. Goupy⁸, F. Kéruzoré⁶, C. Kramer¹⁴, B. Ladjelate¹⁴, G. Lagache¹⁰, S. Leclercq⁹, J.-F. Lestrade¹⁵, J.-F. Macías-Pérez⁶, A. Maury⁵, P. Mauskopf^{4,16}, F. Mayet⁶, A. Monfardini⁸, M. Muñoz-Echeverría⁶, L. Perotto⁶, G. Pisano⁴, N. Ponthieu¹², V. Revéret⁵, A. J. Rigby⁴, C. Romero¹⁷, H. Roussel¹⁸, F. Ruppin¹⁹, K. Schuster⁹, S. Shu²⁰, A. Sievers¹⁴, C. Tucker⁴, and R. Zylka⁹

¹Institut d'Astrophysique Spatiale (IAS), CNRS, Université Paris Sud, Orsay, France

²Laboratoire de Physique de l'École Normale Supérieure, ENS, PSL Research University, CNRS, Sorbonne Université, Université de Paris, 75005 Paris, France

³LLR (Laboratoire Leprince-Ringuet), CNRS, École Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

⁴School of Physics and Astronomy, Cardiff University, Queen's Buildings, The Parade, Cardiff, CF24 3AA, UK

⁵AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, 91191 Gif-sur-Yvette, France

⁶Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 53, avenue des Martyrs, 38000 Grenoble, France

⁷CNRS, IRAP, 9 Av. colonel Roche, BP 44346, 31028 Toulouse cedex 4, France

⁸Institut Néel, CNRS, Université Grenoble Alpes, France

⁹Institut de RadioAstronomie Millimétrique (IRAM), Grenoble, France

¹⁰Aix Marseille Univ, CNRS, CNES, LAM (Laboratoire d'Astrophysique de Marseille), Marseille, France

¹¹Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy

¹²Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

¹³Centro de Astrobiología (CSIC-INTA), Torrejón de Ardoz, 28850 Madrid, Spain

¹⁴Instituto de Radioastronomía Milimétrica (IRAM), Granada, Spain

¹⁵LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, UPMC, 75014 Paris, France

¹⁶School of Earth and Space Exploration and Department of Physics, Arizona State University, Tempe, AZ 85287, USA

¹⁷Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA, 19104, USA

¹⁸Institut d'Astrophysique de Paris, CNRS (UMR7095), 98 bis boulevard Arago, 75014 Paris, France

¹⁹Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

²⁰Caltech, Pasadena, CA 91125, USA

Abstract. The quest for primordial gravitational waves enclosed in the Cosmic Microwave Background (CMB) polarization B-modes signal motivates the

*e-mail: alessia.ritacco@phys.ens.fr

development of a new generation of high sensitive experiments (e.g. CMB-S4, LiteBIRD), thus allowing to probe the inflationary epoch in the early Universe. However, this will be only possible by ensuring a high control of the instrumental systematic effects and an accurate absolute calibration of the polarization angle.

The Crab nebula is known to be a polarization calibrator on the sky for CMB experiments. Already used for the Planck satellite it exhibits a high polarized signal at microwave wavelengths. In this work we present Crab polarization observations obtained, in the 260 GHz frequency band, with the NIKA2 instrument. Furthermore, we discuss the accuracy needed on such a measurement to improve the constraints on the absolute angle calibration for CMB experiments.

1 Introduction

Cosmic Microwave Background (CMB) observations have allowed us to establish the current standard model for cosmology, a.k.a the Λ CDM model. The inflation theory [1, 2] has been introduced to explain an observational evidence that the Universe appears to be almost exactly spatially-flat and uniform in all directions. This theory postulates that the Universe exponentially expanded in a tiny fraction of a second in the early times and predicts the existence of a relic background of primordial gravitational waves, which produces a distinct, curl-like signature in the polarization of the CMB, a.k.a CMB B-modes. The search for primordial gravitational waves B-modes, which are a direct probe of inflation, is one of the main ambitious goals of the modern cosmology and it motivates the development of several facilities from ground (e.g. BICEP3+Keck, CLASS, SO, SPT3G, S4, AdvACTPOL, QUIJOTE), balloon-borne to space experiments (PIPER, PICO, LiteBIRD). These experiments share the goal of detecting the tensor-to-scalar ratio r , which gives the relative amplitude of the primordial tensor (B-modes) and scalar perturbations (E-modes) of the CMB. This parameter gives the energy scale of inflation and in many well-motivated models, still consistent with observations, is predicted to be between 10^{-2} and 10^{-4} [3, 4].

In order to reach the sensitivity required for an unambiguous detection of the primordial B-modes we need i) to increase the signal-to-noise ratio by scaling up the number of detectors; ii) to use optical systems as half-wave-plates, which modulates the sky polarization signal and filters out low frequency noise; iii) and to reduce residual systematic effects [5, 6]. Furthermore the determination of the polarization angle absolute calibration is crucial to ensure an unbiased detection of the polarization orientation of the CMB.

A recent study [7, 8] addressed this issue by using the brightest polarized astrophysical object in the microwave sky, the Crab nebula (or Tau A). They point out that the polarization angle is constant and stable in a frequency range of 23-353 GHz consisting with a mean angle of $-88.26^\circ \pm 0.27^\circ$ (Galactic coordinates), which would allow us to calibrate experiments with an accuracy enabling the measurement of $r \sim 0.01$, far from inflationary theoretical models predictions of at least $r \sim 10^{-3}$.

In the following we present the preliminary results from Crab nebula polarization observations obtained with NIKA2 during the commissioning campaign of November 2020. We will discuss how improving the precision on these measurements could allow us to reach the sensitivity requirements for the detection of the primordial CMB B-modes.

2 NIKA2 observations

The NIKA2 instrument [10] performs high angular resolution simultaneous observations at 1.15 and 2.05 mm, from the IRAM 30m telescope, being the 1.15 mm (260 GHz) channel

also able to detect the linear polarization. In total intensity it is operating for open time observations since 2017 [9], when it also started the commissioning phase of its polarization facilities. The NIKA2 polarimeter consists of a continuously rotating Half-Wave-Plate (HWP) [5] placed at ambient temperature in front of the NIKA2 cryostat window. The detection of the linear polarization expressed through the Stokes parameters Q and U is possible thanks to two detector arrays placed at ~ 100 mK in the 260 GHz channel inside the cryostat [11]. For more details on the polarization system see [5].

2.1 Crab nebula observations

The Crab nebula has an extension of 5×7 arcminutes in the sky and it exhibits a high polarization, of the order of $\sim 20\%$ of the total intensity at the peak emission position of the nebula. [8] presented a compendium of all available observations in a large range of frequencies (23-353 GHz) and demonstrated that the synchrotron emission is responsible for both the total intensity and polarization observed. Moreover they found a strong case for stability of the polarization angle, which places the Crab nebula as a good candidate for a polarization angle calibrator for CMB experiments. However at higher frequencies (above 200 GHz) the sample is smaller, contributing to increase the uncertainty on the angle stability.

Observations performed with the NIKA2 polarimeter would increase the precision on the polarization angle estimation. Observations on the the Crab nebula have been performed with the NIKA2 instrument during three commissioning campaigns, on December 2018, February and November 2020. The polarization Stokes Q and U maps obtained from 70 minutes of observation performed during the campaign of November 2020 are shown in figure 1.

The left panel of figure 2 shows the Crab polarization angles estimated during the three campaigns. The averaged polarization angle (solid black line) is computed as median of the polarization angles, estimated as $\psi_{Gal} = 0.5 \arctan U/Q$ (where the Stokes Q and U have been computed by integrating the emission flux over a $7'$ diameter where $SNR > 3$ in Stokes Q and U maps) of the three data sets and corresponds to $-87.195 \pm 0.806^\circ$, expressed in galactic coordinates. Notice that the angles have been corrected for a $-5.6 \pm 1^\circ$ offset in absolute angle calibration on the sky as measured in OMC1 and 3C286 targets, being 1° the uncertainty accounting for the stability of this offset over almost two years of observations. Taking only the November 2020 data, which are the most reliable across the two years we obtain the median value of $\psi = -87.23 \pm 0.29$ deg. On the right panel of the figure we compare this result to other experiments [8]. Making the assumption that in the future we will be able to constrain the absolute offset angle and reduce the 1° uncertainty to negligible values, we use the November data to calculate the total weighted polarization angle (including the results of all experiments). In this case we obtain $\psi = -87.55 \pm 0.22^\circ$, which would strongly reduce the uncertainty on the polarization angle reconstruction at higher frequencies.

Notice that we consider equations reported in [8] to compute unbiased estimates for polarization quantities given in this work.

3 Polarized Spectral Energy Distribution

The polarized spectral energy distribution of the Crab nebula has been determined for the first time in [8]. Figure 3 left panel shows the polarized intensity map obtained as $P = \sqrt{Q^2 + U^2}$ at 260 GHz with NIKA2 and on right the spectral energy distribution as estimated by [8] accounting also for the NIKA2 value (red), which is $P = 13.22 \pm 0.15$ (dev. standard) ± 1.2 (10% calibr. error). We notice that the polarized flux measured is in very good agreement with expectations. In polarization there is no filtering of the large angular scales [9] and thus, the whole intensity is recovered.

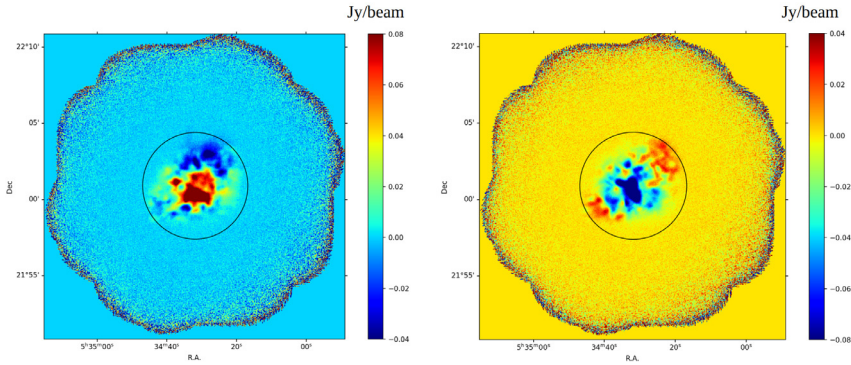


Figure 1. From left to right: Stokes Q and U maps of the Crab nebula observed at 260 GHz during the commissioning campaign of November 2020. The circle overplotted indicates the region, within a diameter of 7' arcmin, where the polarization angle is computed.

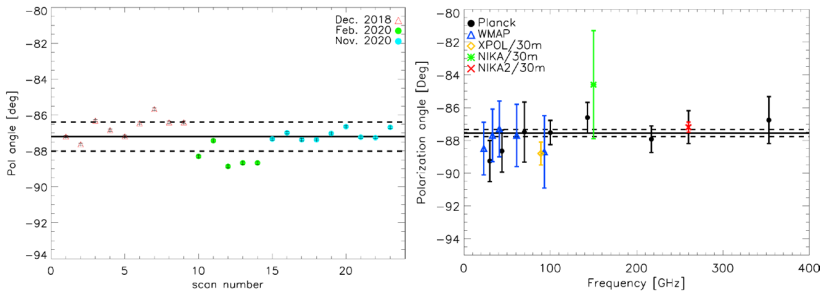


Figure 2. Left: Variation of polarization angles measured with NIKA2-POL for the mean angle over the Crab nebula during three commissioning campaigns. The thick black line shows the median value, the dashed lines delineate the 0.8° standard deviation over all scans, spanning ~ 2 years. Right: NIKA2-POL mean polarization angle over the Crab nebula, obtained in the last campaign, vs other experiments [8]. The red error bar represents the uncertainty on the NIKA2 value, computed as dispersion within the observing scans of Nov. 2020, and the black error bar shows the absolute 1° uncertainty due to the absolute angle calibration offset.

4 CMB experiment absolute calibration challenge

The stability of the polarization angle with frequency is the key to use the Crab nebula as a sky calibrator. The absolute calibration of the polarization angle is of a particular importance for a CMB experiment targeting the measurement of the primordial gravitational waves through the CMB polarization B-modes. Indeed, a miscalibration of an angle $\Delta\psi$ is equivalent to a rotation of the polarization plane by the same angle, mixing the true linear polarization Q and U and consequently the polarized angular power spectra that describe the amplitude of the signal. In the CMB and because the CMB polarization E-modes power spectrum C_ℓ^{EE} is greater than B-modes one C_ℓ^{BB} , this is often referred to as an ‘‘E to B leakage’’ and reads:

$$\tilde{C}_\ell^{BB} = C_\ell^{BB} \cos^2 2\Delta\psi + C_\ell^{EE} \sin^2 2\Delta\psi \Leftrightarrow \Delta C_\ell^{BB} \simeq (2\Delta\psi)^2 C_\ell^{EE} \quad (1)$$

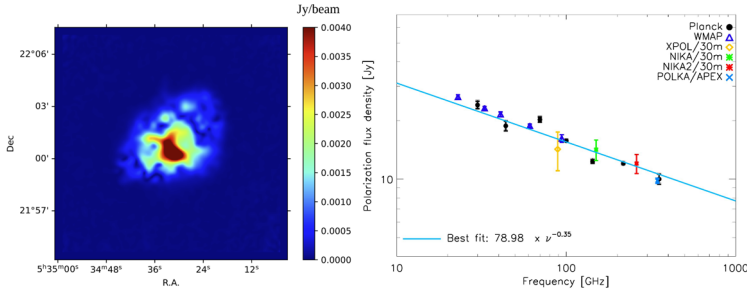


Figure 3. Left: NIKA2 polarization intensity P map. Right: spectral energy distribution obtained by previous measurements [8] accounting for the new value obtained with NIKA2 (red).

where ΔC_ℓ^{BB} represents the spurious bias component. In order to use the Crab nebula polarization angle ψ as an absolute angle calibrator for CMB experiments, we are interested in its uncertainty $\Delta\psi$. In the following we present preliminary results on the bias computed for the parameter r as depending by the uncertainty on ψ . We update a previous study [7] with the new value given by NIKA2 at 260 GHz. Notice that we make the strong assumption that we would be able to reduce the uncertainty on the polarization angle calibration offset of NIKA2 to a negligible value. In other words, we assume here that the NIKA2 polarization angle uncertainty is only due to instabilities of the instrument itself. Figure 4 shows on left panel the $\Delta D_\ell^{BB} = \ell(\ell + 1)/(2\pi) \Delta C_\ell^{BB}$ power spectrum bias from $E - B$ mixing due to miscalibration of the absolute polarization angle. On the right panel we show the likelihood analysis on the r parameter. The different cases considered are taken from [7] updating the two plots with the value measured at 260 GHz by NIKA2 in its best configuration taking only the data from the November 2020 commissioning campaign.

Figure 4 shows that NIKA2 polarization angle stability improves the uncertainty Δr by 30% w.r.t previous studies [7] enabling to approach the requirements for the measurement of the r parameter with a total uncertainty due to miscalibration on the polarization angle of $\Delta r = 5 \times 10^{-4}$. This is promising for CMB experiments development but we need to carefully assess the NIKA2 absolute polarization angle offset.

5 Conclusion

In this paper we show the results obtained on Crab nebula polarization observations during the commissioning phase of the NIKA2-Pol instrument. Comparing the three commissioning campaigns across 2018 and 2020 we have found that the data sets on the Crab and others sky calibrators, e.g. Orion OMC-1 and 3c286, are consistent with an absolute polarization angle calibration offset of -5.6 ± 1 deg. This systematic uncertainty prevents us, for instance, to use NIKA2 Crab nebula polarization angle value as reference for CMB experiments. Though, the NIKA2 Crab nebula observations appears to be very consistent between one scan to another, especially in optimal weather conditions reducing dramatically the statistical error associated. Propagating this value to the likelihood analysis in order to estimate the total bias on the detection of the r parameter for the CMB B-modes detection, we see that we could reach the requirements for the next generation CMB experiments. This is a strong assumption on NIKA2 polarization performances and we are currently investigating possible ways to reduce the uncertainties on the NIKA2 polarization angle offset.

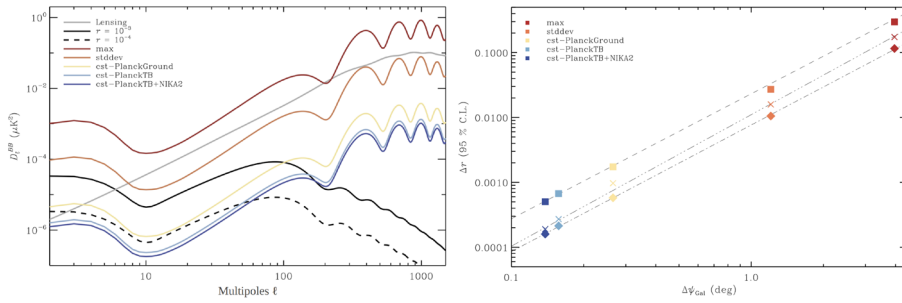


Figure 4. Left panel: power spectrum bias from $E - B$ mixing due to the miscalibration of the absolute polarization angle. This bias is plotted for the different absolute calibration errors $\Delta\psi$ presented in [7]. The Λ CDM best fit D_ℓ^{BB} primordial tensor model for $r = 10^{-3}$ and $r = 10^{-4}$ (solid and dashed black lines, respectively) and D_ℓ^{BB} lensing model (gray line) are also displayed. Right panel: likelihood posterior on r biases (with respect to an input signal of $r = 0$) for the different cases presented in [7], from 10 000 Monte-Carlo simulations, as a function of the combined error on the angle $\Delta\psi_{Gal}$ in degrees. They are computed independently for the recombination bump ($30 < \ell < 300$, squares), the reionization bump ($2 < \ell < 30$, diamonds) and the combination of both ($2 < \ell < 300$, crosses).

Acknowledgements

We would like to thank the IRAM staff for their support during the campaigns. The NIKA2 dilution cryostat has been designed and built at the Institut Néel. In particular, we acknowledge the crucial contribution of the Cryogenics Group, and in particular Gregory Garde, Henri Rodenas, Jean Paul Leggeri, Philippe Camus. This work has been partially funded by the Foundation Nanoscience Grenoble and the LabEx FOCUS ANR-11-LABX-0013. This work is supported by the French National Research Agency under the contracts "MKIDS", "NIKA" and ANR-15-CE31-0017 and in the framework of the "Investissements d'avenir" program (ANR-15-IDEX-02). This work has benefited from the support of the European Research Council Advanced Grant ORISTARS under the European Union's Seventh Framework Programme (Grant Agreement no. 291294). F.R. acknowledges financial supports provided by NASA through SAO Award Number SV2-82023 issued by the Chandra X-Ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060.

References

- [1] Guth, Alan H., *Phys. Rev. D* **23**, 347–356 (1981)
- [2] Linde, A.D., *Physics Letters B* **116**, 335-339 (1982)
- [3] Hazumi M. and LiteBIRD collaboration, *Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave* **11443**, 431 – 450 (2020)
- [4] Zhilei Xu and Simons Observatory collaboration, *AAS* **5**, 100 (2021)
- [5] Ritacco A., Ponthieu N., Catalano A., *et al.* *A&A* **599**, A34 (2017)
- [6] O’Dea, Daniel and Challinor, Anthony and Johnson, Bradley *MNRAS* **376**, (2006)
- [7] Aumont J., Macías-Pérez J.-F., Ritacco A., *et al.* *A&A* **634**, A100 (2020)
- [8] Ritacco A., Macías-Pérez J.-F., Ponthieu N., *et al.* *A&A*, **616**, A35 (2018)
- [9] Perotto L., Ponthieu N., Macías-Pérez J.-F., *et al.*, *Astron. Astrophys.* **637**, A71 (2020)
- [10] Adam R. *et al.*, *Astron. Astrophys.* **609**, A115 (2018)
- [11] Calvo M. *et al.*, *Journal of Low Temperature Physics*, **184**, 816 (2016)
- [12] Bourrion O. *et al.*, *Journal of Instrumentation*, **11**, 11001 (2016)