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The QUIJOTE experiment: project status and first scientific results

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Abstract

We present the current status of the QUIJOTE (Q-U-I JOint TEnerife) experiment, a new polarimeter with the aim of characterizing the polarization of the Cosmic Microwave Background, and other galactic or extra-galactic physical processes that emit in microwaves in the frequency range 10–42 GHz, and at large angular scales (around 1 degree resolution). The experiment has been designed to reach the required sensitivity to detect a primordial gravitational wave component in the CMB, provided its tensor-to-scalar ratio is larger than $r \sim 0.05$. The project consists of two telescopes and three instruments which will survey a large sky area from the Teide Observatory to provide I, Q and U maps of high sensitivity. The first QUIJOTE instrument, known as Multi-Frequency Instrument (MFI), has been surveying the northern sky in four individual frequencies between 10 and 20 GHz since November 2012, providing data with an average sensitivity of $80\,\mu$K beam^{-1} in Q and U in a region of 20,000 square-degrees. The second instrument, or Thirty-GHz Instrument (TGI), is currently undergoing the commissioning phase, and the third instrument, or Forty-GHz Instrument (FGI), is in the final fabrication phase. Finally, we describe the first scientific results obtained with the MFI. Some specific regions, mainly along the Galactic plane, have been surveyed to a deeper depth, reaching sensitivities of around $40\,\mu$K beam^{-1}. We present new upper limits on the polarization of the anomalous dust emission, resulting from these data, in the Perseus molecular complex and in the W43 molecular complex.

1 Introduction

The QUIJOTE experiment[1] is a scientific collaboration between the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria, the universities of Cantabria, Manchester and Cambridge, and the IDOM company. The project consists of two telescopes and three instruments [15], covering the frequency range 10–40 GHz with an angular resolution of $\sim 0.9°$ at 11 GHz, and located at the Teide Observatory (2400 m) in Tenerife (Spain). This site provides excellent atmospheric conditions for CMB observations, as demonstrated by many previous experiments since mid 80s [8, 3, 19]. Indeed, the data obtained with the first QUIJOTE instrument throughout the first three years of operations show that the zenith atmosphere temperature is on average ~ 2 K at 11 GHz and $\sim$ 4–6 K at 19 GHz, while the PWV column density is typically between 2 and 4 mm.

The project has two phases. In the first phase we installed the first QUIJOTE telescope (QT1) and we built two instruments. The first one is a multi-frequency instrument (MFI) [9], observing at four frequency bands (11, 13, 17 and 19 GHz), which had the first light in November 2012. The second instrument of QUIJOTE, or thirty-gigahertz instrument (TGI) [10], consists of 31 receivers at 30 GHz, and it is now in the commissioning phase. The

[1]QUIJOTE web page: http://www.iac.es/project/cmb/quijote

Figure 1: The QUIJOTE experiment at the Teide Observatory. The image shows the first QUIJOTE telescope (QT1) in the back, and the second telescope (QT2) in the front. Image taken by Daniel Lopez.

second phase of QUIJOTE includes a second telescope (QT2), which was already installed at the Teide Observatory in July 2014, and a third instrument at 42 GHz, the forty-gigahertz instrument (FGI), which is now in the integration phase. This second phase is mainly funded by the Consolider 2010 project entitled "Exploring the Physics of Inflation" (EPI[2]). Figure 1 shows a photo of the QUIJOTE enclosure and the two telescopes at the Teide Observatory.

The main science driver of QUIJOTE is to perform observations of the CMB polarization to constrain the "B-mode" signal down to the level of $r = 0.05$ after three years of operations. A secondary goal is to characterize the low-frequency polarized foregrounds, mainly synchrotron emission and the AME, so that this signal can be characterized and removed from the frequency maps of future CMB experiments.

2 Project status: telescopes and instrumentation

The QUIJOTE telescopes are based on an offset crossed-Dragone design, with projected apertures of 2.25 and 1.89 m for the primary and secondary mirrors, respectively. QT1 is in operations since November 2012, and QT2 was installed in July 2014. A detailed description of the two units can be found in [7] for the QT1, and [18] for the QT2. The data from the QT1 shows that we have highly symmetric beams (ellipticity > 0.98) with very low sidelobes (≤ -40 dB) and polarization leakage (≤ -25 dB). We note that a surface roughness of 2 μm and 1.6 μm was achieved for the mirrors of the QT1 and QT2, respectively, and the final overall shape of those mirrors was below 200 μm rms error with respect to the theoretical

[2] Web page: http://www.epiconsolider.es/

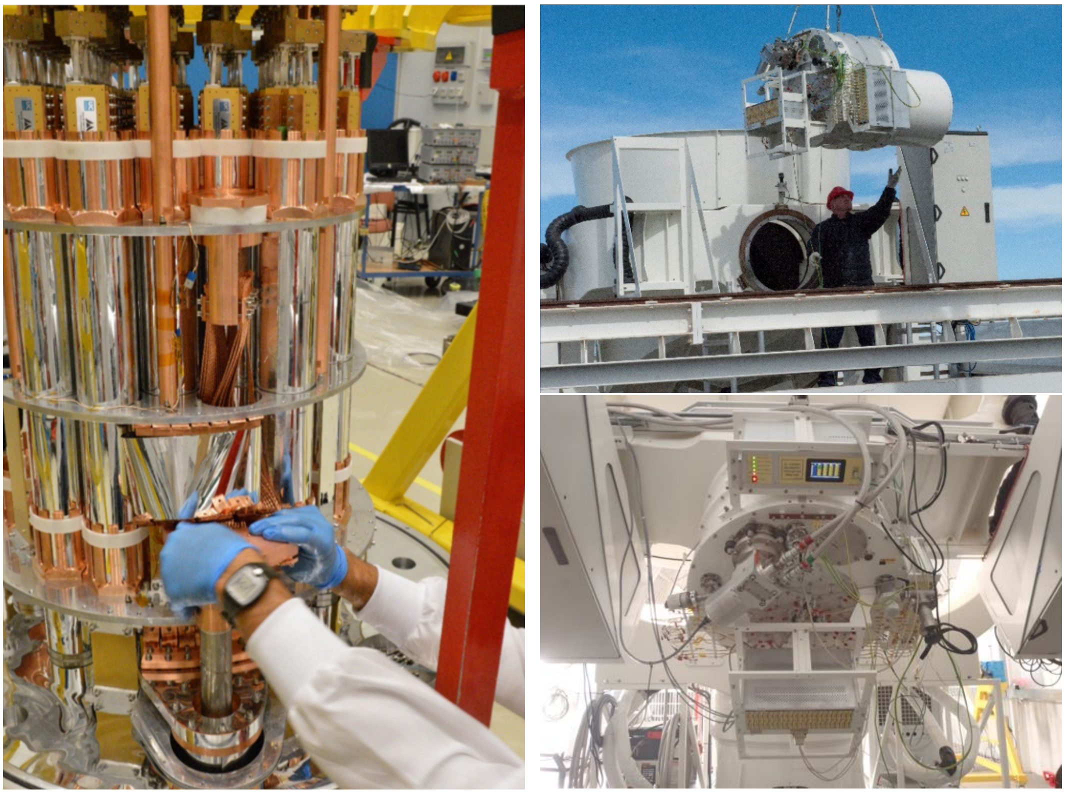

Figure 2: Left: TGI during the AIV phase. Right: TGI being installed in the QT2 focal plane on April 20th, 2016 (top), and a close view of the TGI with three pixels connected to the Back-End-Module (May 2016).

optical surface, so in principle both units could operate at higher frequencies (e.g. up to 200 GHz).

The first QUIJOTE instrument (MFI) has been in operations since November 2012. It has four horns covering the frequency range 10–20 GHz. The detectors are fitted with MMIC low-noise amplifiers (noise temperatures better than 10 K), providing instantaneous (polarization) sensitivities of $\sim 650\,\mu\mathrm{K\,s}^{1/2}$ in four individual bands with nominal frequencies 11, 13, 17 and 19 GHz. The measured beam FWHMs are 0.87° for the two lower frequencies, and 0.65° for the two high-frequency bands. The polarization is measured with stepped polar modulators, with a design based on a turnstile junction implemented in waveguide. These modulators have a high performance, with return losses below -20 dB, insertion losses below -0.15 dB, and isolation below -40 dB across the full band ($\Delta\nu = 2$ GHz). These elements constitute a powerful tool to reject systematic effects.

The TGI and FGI instruments share the same cryostat, which is designed to contain up to 31 polarimetric chains (see Figure 2). TGI pixels cover the band 26–36 GHz with an expected array sensitivity of $\sim 50\,\mu\mathrm{K\,s}^{1/2}$ [10]. The FGI pixels have a central frequency of 42 GHz with a bandwidth of 12 GHz, and an expected sensitivity of $\sim 60\,\mu\mathrm{K\,s}^{1/2}$ for the full

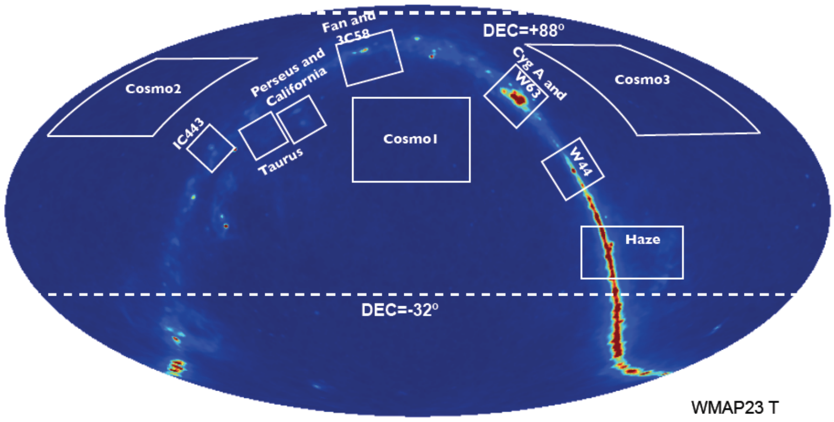

Figure 3: The location of the QUIJOTE fields, displayed on top of the WMAP 23 GHz intensity map in equatorial coordinates. Horizontal lines show the range covered by the QUIJOTE wide survey. We also show the location of the QUIJOTE cosmological fields and some of the Galactic regions (see Table 1).

array. Instead of the mechanical modulation solution adopted for the MFI, both TGI and FGI instruments are based on a polarizer opto-mechanic element designed and manufactured for each frequency. The combination of two phase-switches with two possible phase states, one at $0°/90°$ and other at $0°/180°$, generates four polarization states. The current status of the TGI cryomechanics is described in [17]. At the moment, the TGI is in commissioning phase with 27 polarimeters.

Updated information on the QUIJOTE instruments and telescopes can be found in [13, 14].

3 First scientific results

The MFI instrument has been operating for almost four years. A summary of all the observations carried out with the instrument is presented in Table 1. The location of those regions is shown in Figure 3. Most of the observations are dedicated to two main polarization surveys, which constitute the core science programs:

i) A wide Galactic survey. It covers around $20,000\,\mathrm{deg}^2$, aiming for a final sensitivity of $\sim 25\,\mu\mathrm{K\,beam}^{-1}$ at 11, 13, 17 and 19 GHz (MFI), $\sim 4\,\mu\mathrm{K\,beam}^{-1}$ at 30 GHz (TGI) and $\sim 6\,\mu\mathrm{K\,beam}^{-1}$ at 40 GHz (FGI). Currently, we have accumulated around 9 months of data with the MFI. The preliminary maps for individual horns, and considering data at elevations $EL > 60°$, have sensitivities of $\sim 80\,\mu\mathrm{K\,beam}^{-1}$ in Q and U (see Figure 4).

ii) A deep "cosmological" survey. It covers $\sim 3,000\,\mathrm{deg}^2$ in three separated fields (COSMO1, COSMO2, COSMO3). Here, we shall obtain a sensitivity of $\sim 5\,\mu\mathrm{K\,beam}^{-1}$ after 2 years of observations with the MFI, and $\sim 1\,\mu\mathrm{K\,beam}^{-1}$ with the TGI (30 GHz) and with the FGI (40 GHz). Currently, we have 5.4 months of data with the MFI.

Table 1: Summary of MFI observations. After almost four years of scientific operations, we have accumulated 17,110 h of observations, which corresponds to approximately 50 % observing efficiency. For those regions already presented in a QUIJOTE collaboration paper, the last column indicates the corresponding reference.

Region(s)	Integration time (h)	Refs.
Wide survey (EL= $30°, 40°, 50°, 60°, 65°, 70°, 75°, 80°$)	6760	
Cosmological fields (COSMO1, COSMO2, COSMO3)	3900	
Calibrators (Crab, Cass-A, Jupiter, sky dips)	1395	
Galactic center and Haze	830	
Perseus	760	[4]
Fan region and 3C58	504	
Taurus	450	
SNRs (W44, W51, IC443, W63)	973	[5]
Others	1500	

These QUIJOTE maps will provide valuable information about the polarization properties of the synchrotron emission (e.g., spectral index, curvature of the index, cosmic-rays electron physics, large scale Galactic magnetic field), as well as the polarization properties of the anomalous microwave emission (AME) [11, 16], and will constitute an excellent complement to the Planck maps at low frequencies. This information could be used to improve our understanding of the radio-foregrounds[3], and might be of importance for future CMB polarization experiments (see e.g., [2]). In the case of the QUIJOTE project, the MFI maps from the deep cosmological survey will allow us to correct the TGI and FGI maps from those emissions, leaving residual signals below the instrumental noise sensitivities. According to the forecasted sensitivities, after 1 year of effective observing time over $3,000\,\mathrm{deg}^2$ with the TGI we should reach a sensitivity on the tensor-to-scalar ratio of $r = 0.1$ (at the 95 % C.L.). The combination of 3 years of effective integration time with the TGI and 2 years with the FGI would allow to reach $r = 0.05$ at the same confidence level.

In addition to the core science program, Table 1 shows that a significant fraction of the time was invested in observing different Galactic fields related to the QUIJOTE non-core science program [15, 6]. Some of these topics are:

i) Study of the polarization of the anomalous microwave emission (AME). We observed the Perseus molecular complex [4], and derived upper limits on the AME polarization from G159.6-18.5 of $\Pi < 6.3\,\%$ and $\Pi < 2.8\,\%$ at 12 and 18 GHz respectively, a spectral range that had not been covered before in polarization. More recently, we have studied the W43 molecular complex and we set upper limits on the AME polarization of $\Pi < 0.39\,\%$ (95 %C.L.) from QUIJOTE 17 GHz, and $\Pi < 0.22\,\%$ per cent from WMAP 41 GHz data. These values are the most stringent constraints ever obtained on the polarization fraction of the AME [5].

[3]RADIOFOREGROUNDS project: http://www.radioforegrounds.eu.

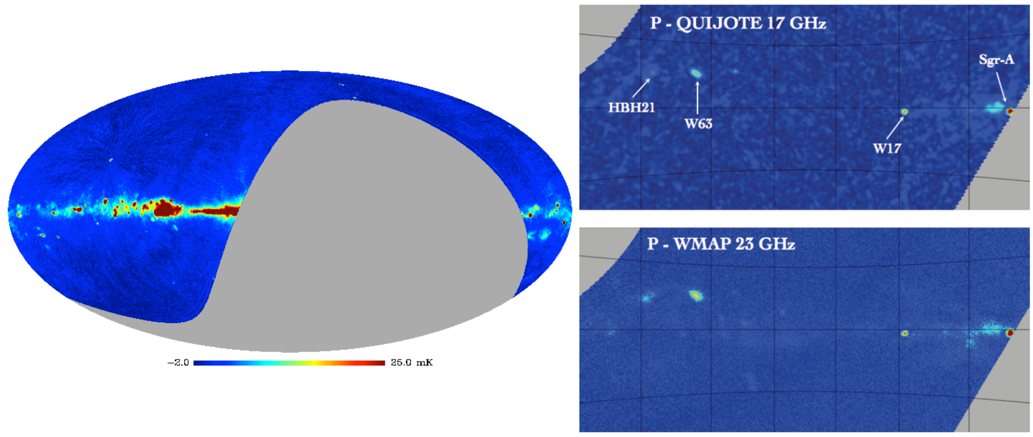

Figure 4: Left: Preliminary map of the wide survey at 11 GHz, in galactic coordinates. We used a subset of observations at elevations above 60°. Right: Preliminary map of the polarized intensity ($P = \sqrt{Q^2 + U^2}$) at 17 GHz, compared to WMAP P at 23 GHz. The QUIJOTE 17 GHz maps (FWHM= 0.6°) were degraded to the WMAP 23 GHz angular resolution (0.82°) for a better comparison.

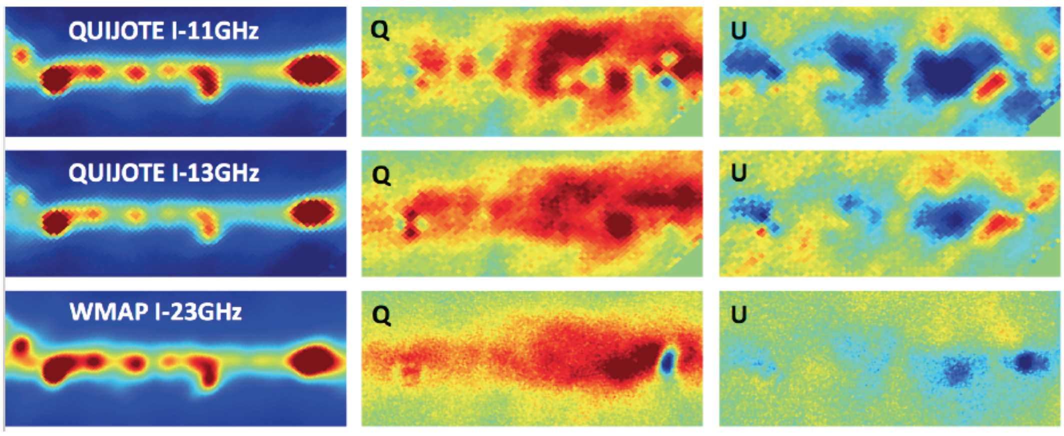

Figure 5: Preliminary Galactic plane (20° × 6°) maps centered at $l = 8°$, as seen by QUIJOTE-11 GHz, QUIJOTE-13 GHz and WMAP 23 GHz. We present Stokes I (left column), Stokes Q (center), and Stokes U (right column) maps. The QUIJOTE maps correspond to four days of total observing time.

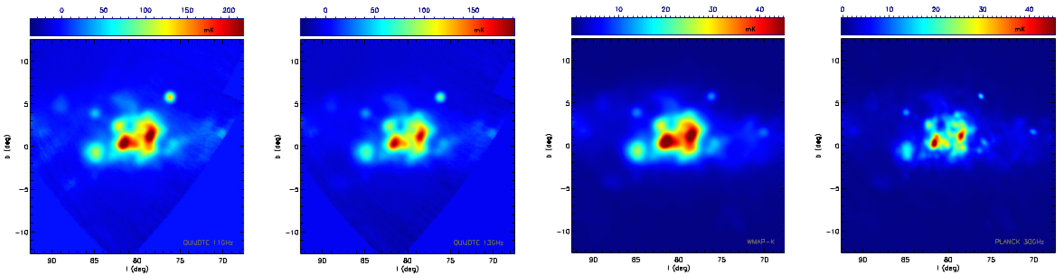

Figure 6: Preliminary QUIJOTE intensity maps ($25° \times 25°$) of the Cygnus region, as seen by QUIJOTE at 11 and 13 GHz, compared to WMAP 23 GHz and Planck 30 GHz. The two strongest polarized sources in this region are the SNR W63 and Cygnus-A. The later appears to be polarized at 11 GHz at the level of 8 %, due to the Laing-Garrington effect (see e.g. [12]).

ii) Study of the WMAP Haze and the Galactic center in polarization. The Galactic haze is an excess of microwave emission in a region around the Galactic center, initially found in WMAP data and later confirmed by the Planck satellite, and which apparently has a gamma-ray counterpart in Fermi data [1]. Figure 5 shows our preliminary QUIJOTE 11 and 13 GHz maps ($20 \times 6\,\mathrm{deg}^2$) of the Galactic plane around the Galactic center, and compared to WMAP data.

iii) Study of the polarization of the synchrotron emission. We have completed observations in several diffuse regions like the Fan, and in some individual compact objects, like in the SNR W44 [5], or the SNR W63, which is located inside the Cygnus region, around $l = 80°$ (see Figure 6).

4 Future plans

The commissioning phase of the full TGI instrument is now taking place. The preliminary results from the first commissioning measurements with three pixels of the TGI, which were done last June 2016, show: a good quality of the main beam, which is highly symmetrical and Gaussian, and with the first sidelobes well below 25 dB; a system temperature of $T_{\rm sys} \approx 36\,\mathrm{K}$ as expected; an atmospheric temperature of $T_{\rm atm}(\mathrm{zenith}) = 5\,\mathrm{K}$ when pwv is around 3 mm; knee frequencies around 20 mHz for polarization measurements; and extrapolated array sensitivities of $\sim$ 50–60 $\mu\mathrm{K\,s}^{1/2}$. The first FGI pixels are being integrated now, and their commissioning phase is expected for the first half of 2017.

Finally, we are also exploring the possibility of building a replica of a QUIJOTE telescope in the southern hemisphere. In collaboration with the Wits University (ZA), a prototype of a MFI pixel is being manufactured, and will be tested at the 7.6 m telescope at HartRAO[4] during 2017.

[4] HartRAO: http://www.hartrao.ac.za/.

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