THE QUIJOTE EXPERIMENT: PROSPECTS FOR CMB B-MODE POLARIZATION DETECTION AND FOREGROUNDS CHARACTERIZATION

F. POIDEVIN$^{1,6}$, J.A. RUBINO-MARTIN$^{1,6}$, R. GENOVA-SANTOS$^{1,6}$, R. REBOLO$^{1,6,7}$, M. AGUIAR$^1$, F. GOMEZ-RENASCO$^1$, F. GUIDI$^{1,6}$, C. GUTIERREZ$^{1,6}$, R. J. HOYLAND$^1$, C. LOPEZ-CARABALLO$^{1,6,8}$, A. ORIA CARRERAS$^1$, A. E. PELAEZ-SANTOS$^{1,6}$, M. R. PEREZ-DE-TAORO$^{1,6}$, B. RUIZ-GRANADOS$^{1,6}$, D. TRAMONTE$^{1,6}$, A. VEGA-MORENO$^1$, T. VIERA-CURBELO$^1$, R. VIGNAGA$^{1,6}$, E. MARTINEZ-GONZALEZ$^2$, R. B. BARREIRO$^2$, B. CASAPONSA$^2$, F. J. CASAS$^2$, J. M. DIEGO$^2$, R. FERNANDEZ-COBOS$^2$, D. HERRANZ$^2$, M. LOPEZ-CANIEGO$^2$, D. ORTIZ$^2$, P. VIELVA$^2$, E. ARTAL$^3$, B. AJA$^3$, J. CAGIGAS$^3$, J. L. CANO$^3$, L. DE LA FUENTE$^3$, A. MEDIAVILLA$^3$, J. V. TERAN$^3$, E. VILLA$^3$, L. PICCIRILLO$^4$, C. DICKINSON$^4$, K. GRAINE$^4$, S. HARPER$^4$, M. MCCULLOCH$^4$, S. MELHUISH$^4$, G. PISANO$^4$, R. A. WATSON$^4$, A. LASENBY$^{5,9}$, M. ASHDOWN$^{5,9}$, Y. PERROTT$^5$, N. RAVALI-GHODS$^5$, D. TITTERINGTON$^5$ and P. SCOTT$^5$

$^1$ Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Canary Islands, Spain
$^2$ Instituto de Física de Cantabria (CSIC-Universidad de Cantabria), Avda. de los Castros s/n, 39005 Santander, Spain
$^3$ Departamento de Ingeniería de COMunicaciones (DICOM), Laboratorios de I+D de Telecomunicaciones, Universidad de Cantabria, Plaza de la Ciencia s/n, E-39005 Santander, Spain
$^4$ Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, U.K
$^5$ Astrophysics Group, Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK
$^6$ Departamento de Astrofísica, Universidad de La Laguna (ULL), 38206 La Laguna, Tenerife, Spain
$^7$ Consejo Superior de Investigaciones Científicas, Spain
$^8$ Departamento de Física, Universidad de la Serena, Av. Cisternas 1200, La Serena, Chile
$^9$ Kavli Institute for Cosmology, Madingley Road, Cambridge, CB30HA

QUIJOTE (Q-U-I JOint TEnerife) is an experiment designed to achieve CMB B-mode polarization detection and sensitive enough to detect a primordial gravitational-wave component if the B-mode amplitude is larger than $r = 0.05$. It consists in two telescopes and three instruments observing in the frequency range 10-42 GHz installed at the Teide Observatory in the Canary Islands, Spain. The observing strategy includes three raster scan deep integration fields for cosmology, a nominal wide survey covering the Northern Sky and specific raster scan deep integration observations in regions of specific interest. The main goals of the project are presented and the first scientific results obtained with the first instrument are reviewed.
1 Introduction

Over the last decades, astronomers have measured with unprecedented precision many of the parameters that describe the current Cosmological Model. Several experiments focus on the Cosmic Microwave Background (CMB) and its anisotropies, that originated about 380,000 years after the Big Bang. Analyses of the CMB suggest that, at a very early time, an exponentially accelerated expansion of the Universe occurred. This inflationary scenario can solve most of the problems that haunted the classical Big Bang scenario. A prediction from inflation is that during the accelerated expansion, the quantum fluctuations in the dominant scalar field would have grown into macroscopic density fluctuations (i.e., scalar fluctuations, which have been measured) and a background of gravitational waves (GWB), (i.e., tensor fluctuations). Theoretical models predict a B-mode whose amplitude is defined by the ratio of the tensor-to-scalar fluctuations and quantified with the parameter $r$, constrains the expansion rate at that time providing a unique measure of the energy scale of inflation. The GWB would have left a characteristic imprint on the polarization of the CMB photons at last scattering. This imprint can in principle be characterized by estimating the parameter $r$ from the analysis of polarization maps. This is an extremely challenging multi-disciplinary task which requires very high sensitivity experiments and a full understanding of the polarization properties of the astrophysical signals emitted in our Galaxy and beyond.

2 Prospects For CMB B-Mode Polarization Detection

Several experiments investigate the temperature and polarization properties of the CMB radiation. Until very recently, limits on the B-mode amplitude came from the analysis of the angular power spectrum in temperature: Planck+WMAP+HighL ($r < 0.11$ at the 95% Confidence Level or C.L.) $^5$, SPT+WMAP+H0+BAO ($r < 0.17$ at the 95% C.L.) and WMAP alone: $r < 0.36$, at 95% C.L. $^6$. Improvement on such estimates have be obtained by the analysis of the CMB angular power spectrum in polarization. One constraint has come from the BICEP/Keck and Planck collaboration with $r < 0.12$ (95% C.L.) $^9$. The Planck collaboration alone reports an upper bound on the tensor-to-scalar ratio $r < 0.11$ (95% C.L.) $^8$. The BICEP/Keck Array cosmic microwave background polarization experiments have recently reported the currently most stringent constraints on the tensor-to-scalar ratio to date with $r < 0.09$ from B-modes alone, and $r < 0.07$ in combination with other datasets $^{10}$. The POLARBEAR collaboration reports an improved measurements of the CMB B-mode polarization power spectrum and rejects the null hypothesis of no B-mode polarization detection at a confidence level of $3.1\sigma$ over angular multipoles $500 \leq l \leq 2100$ $^{11}$.

The QUIJOTE $^{12,13}$ (Q-U-I JOint TEnerife) is an experiment designed to achieve B-mode polarization detection and sensitive enough to detect a primordial gravitational-wave component if the B-mode amplitude is larger than $r = 0.05$. The other main science driver of this experiment is to characterize the polarization of low-frequency foregrounds, mainly the synchrotron emission and the Anomalous Microwave Emission (AME), so that these signals can be removed from the primordial maps to a level that will permit reaching the previous sensitivity on $r$ for cosmology.

3 The QUIJOTE Experiment

The QUIJOTE experiment is a collaboration between the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria and DICOM University of Cantabria, in Spain, and the Universities of Cambridge and Manchester, in the UK. It consists of two telescopes and three linear polarimetry instruments covering respectively the frequencies 10-20, 31 and 42 GHz. The experiment is located at Izaña, near the Teide Volcano, in the Tenerife island (Spain) at an altitude of 2400 meters over the sea level at longitude, latitude position $28.3^\circ$N, $16.5^\circ$W. The
Figure 1 – QUIJOTE telescope 1 in its enclosure at the Teide Observatory.

Izaña site is well suited for such an experiment as it has been a test bed for previous CMB experiments starting from the Tenerife experiment in 1984\textsuperscript{14}.

The development of the project includes two phases. In the first phase the first QUIJOTE telescope (QT1) was installed and the first two instruments were built. The first instrument, the Multi-Frequency Instrument (MFI) observing in the frequency range 10-20 GHz had its first light on November 2012 and has been operating for almost 5 years now. In the current and second phase the second telescope (QT2) that was installed on July 2014 has been tested and is operational. The second instrument, the Thirty-Gigahertz Instrument, or TGI, made of 30 receivers observing at 31 GHz has been built and already started its commissioning phase. The third instrument, the Fourty-Gigahertz Instrument, or FGI, observing a frequency centred at 42 GHz, has been built and is currently in the integration phase. Half of the pixels of the TGI and half of the pixels of the FGI are currently being mounted on the same cryostat, to be installed at the QT2. The first light of this combination of receivers and the commissioning phase of half of the FGI should start before end of 2017.

3.1 The QUIJOTE Telescopes

The two QUIJOTE telescopes, QT1 (see Figure 1) and QT2, have altazimuthal mounts with crossed-dragonened designed. The primary (parabolic) and secondary (hyperbolic) mirrors have apertures of 2.25 m and 1.90 m, respectively. Each telescope has a maximum azimuthal speed of 0.25 Hz or 15 rpm and can point at a minimum elevation of 30°. The data obtained from the QT1 with the MFI show a high symmetric beam with ellipticity $> 0.98$ with very low far sidelobes ($\leq -40$dB) and polarization leakage ($\leq -25$dB).

3.2 The Multi-Frequency Instrument: MFI

The first instrument of the QUIJOTE experiment is the Multi-Frequency Instrument, or MFI\textsuperscript{15}. It is operating in four frequency bands centred at 11.2, 12.9, 16.7 and 18.7 GHz and is operative from November 2012. It is made of four horns, two of them operating in the frequency range 10-14 GHz and the two other ones operating in the frequency range 16-20 GHz. The modulation of the polarization is operated by a mechanically rotating half-wave plate. The sensitivities are of order 400-600 $\mu$K/s$^{1/2}$ per channel. Each horn has 4 channels operating at one of the two frequencies and their combinations permits to recover the I, Q and U Stokes parameters at each frequency. The FWHMs are in the range 0.62° - 0.87°. Since its first light the MFI has been...
performing routine observations covering large sky areas. Some parts of the instrument are shown in Figure 2.

### 3.3 The Thirty and the Forty GHz Instruments: TGI and FGI

The TGI is a detector including 30 pixels centred at a frequency of 31 GHz with a bandwidth of 10 GHz. Thirty similar feedhorns or pixels have been designed with linear polarimetry capability. Each pixel is made of 4 channels providing data to the acquisition system. The polarization modulation is obtained by combining two phase-switches, each of them having two different possible phase states, i.e. $0^\circ/90^\circ$ and $0^\circ/180^\circ$, respectively. High frequency modulation allows to get almost simultaneous measurements of $I$, $Q$ and $U$ on the sky and to get rid of many systematics. The FGI has a design similar to the one of the TGI with a center frequency of 41 GHz in a bandwidth of 12 GHz and the two instruments can share a common cryostat. The acquisition system has been designed to be operational with the two type of pixels. A schematic view of the TGI receiver is shown in Figure 2.

### 4 Observation strategy

The QUIJOTE experiment will take advantage of the combination and sensitivity of its three instruments to characterize the nature of the CMB emission in intensity and in polarization toward 3 fields dedicated to cosmology. The data obtained with the MFI, TGI and FGI will be combined with the Planck and WMAP data and allow a state-of-the-art characterization of the foregrounds between 10 and 42 GHz to produce CMB maps at 31 GHz and 42 GHz. For this purpose the role of the MFI is fundamental in the sense that it will allow to disentangle the
contributions of the Free-Free, of the AME and Synchrotron components from the thermal dust component in the frequency range 10-20 GHz. The core science program includes observations toward three fields dedicated to cosmology and a wide survey. Additional fields out of the core science program are dedicated to targets of specific science interest. A view of the sky covered from the Teide Observatory including the wide survey, the 3 cosmology fields and some of the other targets of interest is given in Figure 4.

4.1 Cosmology Fields

The observing strategy includes deep integration fields obtained with raster scan mode toward three fields dedicated to cosmology. The three fields cover a total of about 3000 deg$^2$. From its first light in November 2012 a total of about 4000 hours of observations have been obtained with the MFI toward those three fields. Given the expected nominal sensitivities to be reach by the TGI and the FGI, a sensitivity on the tensor-to-scalar ratio of $r = 0.1$ (at 95% C.L.) should be obtained after one effective year of observations with the TGI toward the total area of the three cosmology fields. A sensitivity of $r$ of 0.05 (at 95% C.L.) will necessitate the combination of 3 effective years of observations with the FGI and 2 effective years of observations with the FGI.

4.2 Wide survey and Galactic Foregrounds Characterization

One of the main science driver of the QUIJOTE experiment with the MFI is to characterize the properties of the synchrotron emission, i.e. the large scale magnetic field, spectral index, curvature of the index and polarization properties, and to characterize the properties of AME which may be a polarization CMB contaminant. In order to do so the observing strategy includes a wide survey of about 20,000 deg$^2$ obtained from observations in nominal mode, i.e., observations obtained over blocks of about 24 hours at constant elevations (EL= 30°, 40°, 50°, 60°, 65°, 70°, 75° and 80°) at a scanning speed of 2 rpm that have accumulated a total of about 6800 hours.

The wide survey is part of the Radioforeground Project\(^a\), one of the H2020-COMPET-2015 selected project within the European Union’s Horizon 2020 research and innovation programme. In addition to the physics results and new knowledge it is going to produce (as mentionned above), it is planned to provide a complete and statistically significant multi-frequency catalogue of radio sources in both temperature and polarization as well as specific (open source) software.

\(^a\) [http://www.radioforegrounds.eu](http://www.radioforegrounds.eu)
tools for data processing, data visualization and public information. A preliminary wide survey map obtained with a total of 700 hours of observations at 11 GHz with the MFI is shown in Figure 5.

4.3 Observations dedicated to specific regions of interest

A series of specific fields of interest has been defined which are observed in raster scan mode in order to complement the wide survey with deeper integrations. These fields include Galactic region like the Fan region, a region toward which a large uniform magnetic field is probed which origin is still not understood. A series of molecular clouds that have been studied by the Planck collaboration and are sources where the AME emissivity was detected with high significance. This observation program includes the Taurus molecular cloud and is part of the PolAME project dedicated to the study of AME properies in cold molecular clouds supported by the Marie Sklodowska-Curie European Union’s Horizon 2020 research and innovation programme. Other regions of scientific interest are the Galactic center and the Haze regions, 3C58 and M31. The Perseus molecular cloud complex region, the W43 and W47 molecular cloud regions as well as the Super Novae Remnants (SNRs) W44, W51, IC443 and W63 have also been observed.

5 First Scientific Results

5.1 The Perseus Molecular Cloud Complex

The first scientific results obtained with the MFI are from the analysis of 194 hours of observations towards the well studied Perseus molecular cloud complex over an area of about 250 deg². The flux densities obtained with the MFI in the frequency range 10-20 GHz nicely complete the WMAP measurements and allow a full characterization of the AME component which would not be possible otherwise. The upper limits on the fraction of polarization of the total intensity components derived from the Spectral Energy Distributions (SEDS) analysis of G159.6-18.5 are \( \pi < 6.3\% \) and \( \pi < 2.8\% \) at 12 and 18 GHz, respectively, which means upper

---

\(^b\) [http://www.iac.es/proyecto/polame/](http://www.iac.es/proyecto/polame/)
Figure 6 – Left: TMC map at 11 GHz obtained with the MFI on QT1. Middle: same as left but at a frequency of 13 GHz. Right: same as left and middle but at a frequency of 22.7 GHz as obtained by the WMAP.

limits $\pi_{\text{AME}} < 10.1\%$ and $\pi_{\text{AME}} < 3.4\%$ on the fraction of polarization associated with the AME components.

5.2 The W43, W44 and W47 SNRs

A total of 210 hours observations have been obtained along the Galactic Plane toward the area $24^\circ < l < 45^\circ$, $|b| < 8^\circ$. Combined with the WMAP data the frequency range covered by the MFI is crucial to confirm the presence of AME towards the two molecular cloud complexes W43 (at 22$\sigma$) and W47 (at 8 $\sigma$). The most stringent constraints ever obtained on the polarisation fraction of the AME are obtained from the analysis of the polarised flux of W43 and show $\pi_{\text{AME}} < 0.39\%$ (95 per cent C.L.) from the QUIJOTE 17 GHz data, and $\pi_{\text{AME}} < 0.22\%$ from WMAP 41 GHz data. The estimated spectral index of the synchrotron emission in W44 is, $\beta_{\text{sync}} = 0.62 \pm 0.03$, in good agreement with the value inferred from the intensity spectrum once a free–free component is included in the fit. The change in the polarisation angle associated with Faraday rotation in the direction of W44 corresponds to a rotation measure of $404 \pm 49$ rad /m$^2$.

5.3 The Taurus Molecular Cloud

A total observing time of about 423 hours has been obtained towards the Taurus Molecular Cloud (TMC). The maps obtained at 11 GHz and 13 GHz shown in Figure 6 can be compared to the WMAP map at 22.7 GHz. The analysis of the SED on the high column density regions of the TMC shows a clear detection of AME in the TMC in the frequency range 10-60 GHz. These results are presented and discussed in 20.

6 Conclusions

The QUIJOTE is a fruitfull experiment starting to provide unique measurements of the Northern Hemisphere Sky in the frequency range 10-20 GHz with its first instrument the MFI. The results provided by the MFI are strategical to understand the properties of the free-free, AME and of the synchrotron radiation so that they can be properly removed from the CMB polarization map that are going to be provided by the TGI and FGI. Given the expected nominal sensitivities to be reach by these two instruments, a sensitivity on the tensor-to-scalar ratio of $r = 0.05$ (at 95% C.L.) will need the combination of 3 effective years of observations with the FGI and 2 effective years of observations with the FGI.
Acknowledgments

The QUIJOTE experiment is being developed by the Instituto de Astrofísica de Canarias (IAC), the Instituto de Física de Cantabria (IFCA), and the Universities of Cantabria, Manchester and Cambridge. Partial financial support is provided by the Spanish Ministry of Economy and Competitiveness (MINECO) under the projects AYA2007-68058-C03-01, AYA2010-21766-C03-02, AYA2014-60438-P, and also by the Consolider-Ingenio project CSD2010-00064 (EPI: Exploring the Physics of Inflation). This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 687312 (RADIOFOREGROUNDS) and number 658499 (PolAME). FP is a Marie Sklodowska-Curie fellow from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 658499 (PolAME).

References

1. J. A. Rubiño-Martín and the VSA collaboration, 2003, MNRAS, 341, 1084.
2. Hinshaw, G.F., et.al., 2013, ApJS., 208, 19H.
3. Planck collaboration 2016, A&A, 594, A11
4. Guth, A. H., Physical Review D (Particles and Fields), Volume 23, Issue 2, 15 January 1981, pp.347-356
5. Planck Collaboration 2014 A&A 571, A22
6. Keisler et al. 2011, ApJ, 743, 28
7. BICEP2 collaboration - Ade et al., 2014, Physical Review Letter 112, 241101
8. Planck collaboration 2016, A&A, 594, A20
9. BICEP2/Keck and Planck Collaborations, 2015, Phys. Rev. Lett. 114, 101301
10. BICEP/Keck collaboration, APS April Meeting 2017, abstract number Y5.008
11. The POLARBEAR collaboration 2017, arXiv:1705.02907
12. J. A. Rubiño-Martín and the QUIJOTE collaboration, 2010 ASSP..14..127R
13. J. A. Rubiño-Martín and the QUIJOTE collaboration, Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18-22, 2016, in Bilbao, Spain, p. 99-107.
14. Hancock, S.; Davies, R. D.; Lasenby, A. N.; Guiterrez de La Cruz, C. M.; Watson, R. A.; Rebolo, R.; Beckman, J. E., 1994, Nature V.367, NO.6461/JAN27, P. 333.
15. M. R. Pérez-de-Taoro and the QUIJOTE collaboration. Proceedings of the SPIE, Volume 9906, id. 99061K 8 pp. (2016).
16. Hill et al. 2017, MNRAS, 467, 4631.
17. Planck collaboration 2014 A&A 565, A103.
18. R. Génova-Santos and the QUIJOTE collaboration, 2015, MNRAS, 452, 4169.
19. R. Génova-Santos and the QUIJOTE collaboration, 2017, MNRAS, 464, 4107.
20. F. Poidevin and the QUIJOTE collaboration, 2018, In prep.