The QUIJOTE-CMB Experiment: studying the polarisation of the Galactic and Cosmological microwave emissions

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ABSTRACT

The *QUIJOTE* (Q-U-I JOint Tenerife) *CMB* Experiment will operate at the Teide Observatory with the aim of characterizing the polarisation of the CMB and other processes of Galactic and extragalactic emission in the frequency range of 10–40 GHz and at large and medium angular scales. The first of the two QUIJOTE telescopes and the first multi-frequency (10–30 GHz) instrument are already built and have been tested in the laboratory. *QUIJOTE-CMB* will be a valuable complement at low frequencies for the *Planck* mission, and will have the required sensitivity to detect a primordial gravitational-wave component if the tensor-to-scalar ratio is larger than $r = 0.05$.

Keywords: cosmic microwave background, polarisation, cosmological parameters, early Universe, telescope, instrumentation

1. INTRODUCTION

The study of the Cosmic Microwave Background (CMB) anisotropies is one of the most powerful tools in modern cosmology, and it has played a crucial role in our understanding of the Universe. With the latest results from WMAP satellite,[1] and with the information provided by ground-based experiments such as VSA,[2] ACBAR,[3] CBI,[4] SPT[5] or ACT,[6] it has been possible to determine cosmological parameters with accuracies better than five per cent.[7] *Planck* satellite, launched in May 2009, is expected to improve the accuracy on the determination of the cosmological parameters, reaching precisions of less than a percent.[8]

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Until now, the majority of the CMB constraints are obtained from intensity measurements. However, the CMB contains a wealth of information encoded in its polarisation signal. Since the first detection of polarisation by the DASI experiment,[9] other experiments have provided measurements of the angular power spectrum of the polarisation.[10–17] Despite their relatively poor signal-to-noise ratio, they still show excellent agreement with the predictions of the standard ΛCDM model.

The standard theory predicts that the CMB is linearly polarized, the physical mechanism responsible for its polarisation being Thomson scattering during the recombination or reionization epochs. Thus, the polarisation state on any direction $\hat{n}$ on sky can be well described by the two Stokes parameters Q and U. Full-sky maps of these two parameters can be decomposed into complex spin-2 harmonics

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell m} a_{\pm 2,\ell m}\ {}_{\pm 2}Y_{\ell m}(\hat{n}), \tag{1}$$

However, in practice these coefficients ($a_{\pm 2,\ell m}$) are not used in CMB studies to describe full-sky polarisation maps. Instead, these polarisation maps are decomposed in terms of two scalar components usually called a E-field (gradient) and a B-field (rotational),[18, 19] and which are given by the coefficients

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2}, \qquad a_{B,\ell m} = -\frac{a_{2,\ell m} - a_{-2,\ell m}}{2i} \tag{2}$$

From here, the angular power spectra can be written as

$$C_\ell^{XY} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{m=+\ell} a^*_{X,\ell m} a_{Y,\ell m} \tag{3}$$

where X and Y can take the values T, E, or B. Thus, in addition to the temperature power spectrum TT (C_ℓ^{TT}), we have three parity-independent angular power spectra to describe the polarisation field: the cross-correlation of temperature T and E mode, TE (C_ℓ^{TE}); and the auto-correlation of the E and B modes, EE (C_ℓ^{EE}) and BB (C_ℓ^{BB}), respectively. All the other combinations (TB and EB) are expected to be zero for the CMB field.

The importance of this decomposition is connected with the physics of generation of the CMB anisotropies. If the fluctuations in CMB intensity are seeded by scalar perturbations (i.e fluctuations in the density alone), one would only expect primordial E modes in the CMB polarisation. However, vector and tensor perturbations, like those due to gravitational waves (GW) in the primordial Universe,[20] are mechanisms that could generate primordial B-modes in the polarisation on large angular scales. Therefore, if we can measure these modes, we may have a unique way to carry out a detailed study of the inflationary epoch. In particular, the energy scale V at which inflation occurred can be expressed in terms of r, the ratio of tensor to scalar contributions to the power spectrum, as[21]

$$r = 0.001\left(\frac{V}{10^{16}\ \mathrm{GeV}}\right)^4 \tag{4}$$

Based on BB upper limits alone, the best current constraint on the inflationary GW background is[15] $r \leq 0.72$ (95% C.L.). When combining this information with the measurements of the other three CMB power spectra (TT, TE and EE), the WMAP data[16] alone gives $r \leq 0.36$ (95% C.L.). Finally, when BAO and SNIa constraints are included,[7] we have $r \leq 0.2$ (95% C.L.). These numbers translate into a constraint of $\lesssim 4 \times 10^{16}$ GeV.

Because of the importance of detecting primordial gravitational waves,[22, 23] there is a huge interest to develop experiments to measure (or constrain) the amplitude of B-modes power spectrum of the CMB polarisation. Here we present one of these efforts.

The *QUIJOTE* (Q-U-I JOint TEnerife) *CMB Experiment*[24] is a scientific collaboration between the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria, the IDOM company, and the universities of Cantabria, Manchester and Cambridge, with the aim of characterizing the polarisation of the CMB, and other galactic and extragalactic physical processes in the frequency range 10–40 GHz and at angular scales larger than 1 degree. Updated information can be found on the project website.[25]

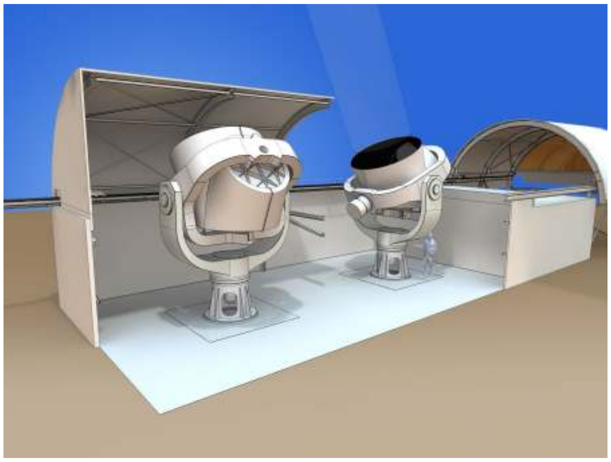

Figure 1. A 3D drawing of the *QUIJOTE-CMB* experiment dome and the two telescopes.

2. PROJECT BASELINE

The *QUIJOTE-CMB* experiment consists of two telescopes and three instruments (see Fig. 1), which will observe in the frequency range 10–40 GHz with an angular resolution of ~ 1 degree, from the Teide Observatory (2400 m) in Tenerife (Spain). Experience over more than 27 years[26] with several CMB experiments (Tenerife Experiment, JBO-IAC Interferometer, COSMOSOMAS, Very Small Array) shows that this is an excellent place for CMB observations. The project has two phases already funded:

- *Phase I.* Construction of the first *QUIJOTE-CMB* telescope (QT1) and two instruments which can be exchanged in the QT1 focal plane. The first instrument (MFI) is a multichannel instrument providing the frequency coverage between 10 and 20 GHz, and it will start commissioning during the summer of 2012. The second instrument (TGI) will consist of 31 polarimeters working at 30 GHz, and it is expected to start operations at the end of 2013. This phase also includes a two-element interferometer operating at 30 GHz, which will be used as a "source-subtractor" facility to monitor and correct the contribution of polarized radio-sources in the final *QUIJOTE-CMB* maps.
- *Phase II.* Construction of the second *QUIJOTE-CMB* telescope (QT2), and a third instrument (FGI) with 40 polarimeters working at 40 GHz.

There are also plans for a future *Phase III* of the project, which considers the construction of a new instrument with at least 100 receivers at W-band. However, this third phase is not funded yet.

Table 1 summarizes the basic (nominal) characteristic of these three instruments in phases I and II. The noise equivalent power (NEP) for one stabilized polarimeter channel is defined here as

$$\mathrm{NEP} = \sqrt{2}\frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu \; N_{chan}}}, \tag{5}$$

where T_{sys} stands for the total system temperature, $\Delta\nu$ is the bandwidth and N_{chan} is the number of channels (computed here as the number of horns times the number of output channels per horn). From here, the noise sensitivity is obtained as $\mathrm{NEP}/\sqrt{t}$, being t the integration time. We note that the system temperature (T_{sys}) values appearing in Table 1 have several contributions: the receiver contribution; the estimated contribution of the opto-mechanics; the spillover contribution (i.e., the background contribution when the instrument is placed in the focal plane of the telescope); the atmospheric contribution at the considered frequency; and the CMB contribution (2.7 K).

Table 1. Nominal characteristics of the three *QUIJOTE-CMB* instruments: MFI, TGI and FGI. Sensitivities are referred to Stokes Q and U parameters. See text for details.

	MFI					TGI	FGI
Nominal Frequency [GHz]	11	13	17	19	30	30	40
Bandwidth [GHz]	2	2	2	2	8	8	10
Number of horns	2	2	2	2	1	31	40
Channels per horn	4	4	4	4	2	4	4
Beam FWHM [°]	0.92	0.92	0.60	0.60	0.37	0.37	0.28
$T_{\rm sys}$ [K]	25	25	25	25	35	35	45
NEP [μK $s^{1/2}$]	280	280	280	280	390	50	50
Sensitivity [Jy $\rm s^{1/2}$]	0.30	0.42	0.31	0.38	0.50	0.06	0.06

Figure 2. Left: *QUIJOTE-CMB* enclosure at the Teide Observatory. Right: Inside the *QUIJOTE-CMB* dome, before the installation of QT1.

3. EXPERIMENT DESCRIPTION

3.1 Telescopes and Enclosure

The *QUIJOTE-CMB* experiment consists of two telescopes (hereafter QT1 and QT2) that will be installed inside a single enclosure at the Teide Observatory. The enclosure and the building hosting the control room were finished in June 2009 (see Fig. 2).

The layout of both QT1 and QT2 telescopes is based on an altazimuth mount supporting a primary (parabolic) and a secondary (hyperbolic) mirror disposed in an offset Gregorian Dracon scheme, which provides optimal cross-polarisation properties (designed to be ≤ -35 dB) and symmetric beams. Each primary mirror has a 2.25 m projected aperture, while the secondary has 1.89 m. The system is under-illuminated to minimize side-lobes and ground spillover. Each telescope is mounted on its own platform that can rotate around the vertical axis at a maximum frequency of 6 rpm (i.e., 36 deg $\rm s^{-1}$).

The telescope control software for QT1 was implemented during 2009, and the different observing modes (raster, scanning, tracking, etc.) have been tested.[27] The construction scheme, as well as the fabrication techniques for QT1 have been already presented.[28] We note that the QT1 mirrors have been designed to operate up to 90 GHz (i.e., rms $\leq 20\,\mu$m and maximum deviation of $d = 100\,\mu$m). However, QT2 has been specified to have a better surface accuracy, so the telescope could in principle operate up to 200 GHz.

The installation of QT1 at the Teide Observatory took place during May 2012 (see Fig. 3).

3.2 Instruments

3.2.1 Multi-frequency Instrument (MFI)

This is a multi-channel instrument with five independent sky pixels: two operate at 10–14 GHz; the other two at 16–20 GHz, and finally a central polarimeter at 30 GHz that is being used as a demonstrator of the second

Figure 3. Left: QT1 at the IAC workshop (June 2009). Right: Installation of QT1 at the Teide Observatory (May 3rd, 2012).

instrument during the laboratory tests and commissioning phase. The main science driver for the MFI is the characterization of the Galactic emission. A complete description of the MFI and the details on the software are presented elsewhere.[27,29] Here, we only provide the basic aspects of the instrument (see Fig. 4).

The optical arrangement includes five conical corrugated feedhorns (designed by the University of Manchester). Each horn feeds a novel cryogenic on-axis rotating polar modulator which can rotate at speeds of up to 1 Hz. We consider two possible operational modes: either continuous rotation of the polarimeters, or discrete changes of the positions of the motors in steps of 22.5° (note that the polar modulation occurs at four times the rotation angle). The orthogonal linear polar signals are separated through a wide-band cryogenic Ortho-Mode-Transducer (OMT) before being amplified through two similar LNAs (a Faraday-type module in the case of 30 GHz). These two orthogonal signals are fed into a room-temperature Back-End module (BEM) where they are further amplified and spectrally filtered before being detected by square-law detectors. All the polarimeters except the 30 GHz receiver have simultaneous "Q" and "U" detection i.e. the 2 orthogonal linear polar signals are also correlated through a 180° hybrid and passed through two additional detectors. The band passes of these lower frequency polarimeters have also been split into an upper and lower band which gives a total of 8 channels per polarimeter (see Table 1).

The FEM for the low frequency channels was built by the IAC. The receivers for these channels use MMIC 6-20 GHz LNAs (designed by S. Weinreb and built in Caltech). The gain for these amplifiers is approximately 30 dB, and the noise temperature is less than 9 K across the band. The 30 GHz FEM was built at the University of Manchester, and the design used an existing Faraday module (same as the one used for OCRA-F*). The BEM for the 30 GHz instrument was built by DICOM, with collaboration of IFCA at the simulation level. The cryogenics and the mechanical systems were provided by the IAC.

3.2.2 Thirty-GHz Instrument (TGI)

This instrument will be mainly devoted to primordial B-mode science. TGI will be fitted with 31 polarimeters working in the range of 26-36 GHz. After the laboratory tests with the 30 GHz polarimeter of the MFI, we found

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*OCRA-F: `http://www.jodrellbank.manchester.ac.uk/research/ocra/ocraf.html`.

Figure 4. Left: Close view of the MFI, during the integration phase (May 2011). Center: Integration of the MFI in the QT1 focal plane (December 2011). Right: MFI already installed at the QT1 focal plane (January 2012). The electronic boxes controlling the telescope and the instrument are also installed.

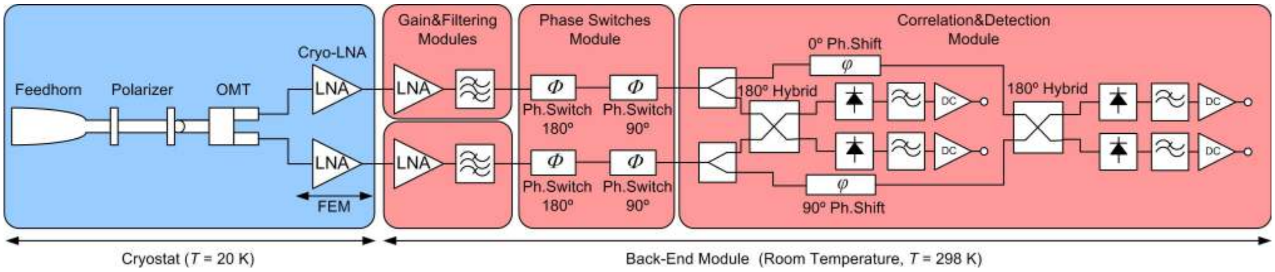

Figure 5. Configuration of each of the 31 receivers of the TGI, in the *QUIJOTE-CMB* experiment.

that the MFI design, based on the spinning polar modulators in a cryogenic environment, is not appropriate for the long-term operations required for the TGI. Thus, we have modified the receiver configuration by replacing the rotating polar modulator with a fixed polarizer. The current new design is presented in Fig. 5. It includes a fixed polarizer and 90° and 180° phase switches to generate four polarisation states to minimize the different systematics in the receiver. A detailed description of the system has been already presented.[30]

3.2.3 Forty-GHz Instrument (FGI)

Also devoted to primordial B-mode science, the FGI will be fitted with 40 polarimeters working at 40 GHz. The conceptual design of a polarimeter chain for the FGI is identical to the one used for the TGI (see Fig. 5).

3.3 Source subtractor facility

An upgraded version of the VSA source subtractor (VSA-SS) facility,[31] which is being carried out by the Cavendish Laboratory and the University of Manchester, will be used to monitor the contribution of polarized radio-sources in the *QUIJOTE-CMB* maps. The VSA-SS is a two element interferometer, operating at 30 GHz, with 3.7 m dishes and a separation of 9 m (see Fig. 6). The VSA-SS system only measured one linear polarisation of the incoming radiation, so it is being upgraded to include a half-wave plate (HWP) in front of each of the antennas in order to allow for successive measurements of Stokes Q and U. Here, we use a dielectrically embedded mesh-HWP designed and produced at the University of Manchester (see right panel of Fig. 6).

Using the method described by Tucci et al. (2004)[32] to simulate the polarisation properties of radio sources at the *QUIJOTE-CMB* frequencies, we have estimated that in order for the residual source contribution to our measurements be equal to or smaller than the expected B-mode signal for the case of $r = 0.1$ at 30 GHz, we must remove the effects of all sources whose Stokes I intensity is higher than 300 mJy (see Fig. 7). Our strategy is therefore to measure the 30 GHz Stokes I intensity of known radio sources (e.g., from the GB6 catalogue) and then measure the polarisation of those that we find have Stokes I greater than 300 mJy. The total number of sources to be monitored in the whole *QUIJOTE-CMB* surveyed area will be around 500. The expected polarised flux sensitivity per source of the VSA-SS is 2–3 mJy.

An upgrade of this VSA-SS facility to operate at 40 GHz during the Phase II of the project is currently under discussion.

Figure 6. Left: One of the two antennas of the VSA source subtractor. This facility will be re-used to measure the polarisation of radio sources to correct the *QUIJOTE-CMB* 30 GHz maps. Right: Picture of the HWPs used for the VSA-SS.

4. SCIENCE GOALS AND SCIENCE CASES

4.1 Core science

The *QUIJOTE-CMB* experiment has two primary scientific goals:

- to detect the imprint of gravitational B-modes if they have an amplitude $r \geq 0.05$;
- to provide essential information of the polarisation of the synchrotron and the anomalous microwave emissions from our Galaxy at low frequencies (10–40 GHz).

For these scientific objectives, *QUIJOTE-CMB* will conduct two large surveys in polarisation (i.e., Stokes Q and U maps):

i) a shallow "Galactic" survey. It will cover around 10 000 deg^2 of sky. It is expected to be finished after 2–3 months of effective observing time with each instrument, reaching sensitivities of ~ 10–$15\,\mu$K per one degree beam in the Stokes Q and U maps with the MFI (11–19 GHz), and $\lesssim 3\,\mu$K per beam with the TGI and FGI at 30 and 40 GHz.

ii) a deep "Cosmological" survey. It will cover around 3 000 deg^2. Here, we shall reach sensitivities of ~ 3–$4\,\mu$K per one degree beam after one year of effective observing time with the MFI (11–19 GHz), and $\lesssim 1\,\mu$K per beam with TGI and FGI at 30 and 40 GHz.

According to these nominal sensitivities, *QUIJOTE-CMB* will provide one of the most sensitive 11–19 GHz measurements of the polarisation of the synchrotron and anomalous emissions on degree angular scales. This information is extremely important given that B-modes are known to be sub-dominant in amplitude as compared to the Galactic emission,[33] as illustrated in Fig. 7. The *QUIJOTE-CMB* maps will also constitute an unique complement of the *Planck* satellite[†], helping in the characterization of the Galactic emission. In particular, the combination of *Planck* and *QUIJOTE-CMB* will allow us: (a) to determine synchrotron spectral indices with high accuracy, and to fit for curvature of the synchrotron spectrum to constrain CR electron physics;[34] (b) to study the large-scale properties of the Galactic magnetic field;[35] or (c) to assess the level of a possible contribution of polarized anomalous microwave emission.[36, 37]

Using the MFI maps from the deep survey, we plan to correct the high frequency *QUIJOTE-CMB* channels (30 and 40 GHz) to search for primordial B-modes. As an illustration, Fig. 8 presents two cases. The left panel shows the scientific goal for the angular power spectrum of the E and B modes after 1-year of effective observing time, assuming a sky coverage of 3 000 square degrees, with the TGI only. In this particular case, the final noise

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[†] *Planck*: `http://www.rssd.esa.int/index.php?project=Planck`

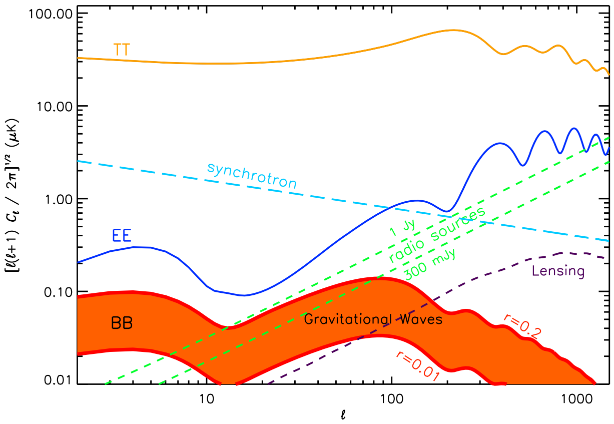

Figure 7. Expected foreground contamination in the 30 GHz *QUIJOTE-CMB* frequency band. It is shown the contribution of polarized synchrotron emission and radio-sources for the case of subtracting sources down to 1 Jy in total intensity (upper dashed line for radio-sources) and 300 mJy (lower dashed-line). The physical models for these emissions are described in.[33] The shaded red area shows the expected level of primordial gravitational waves for r in the range 0.01–0.2.

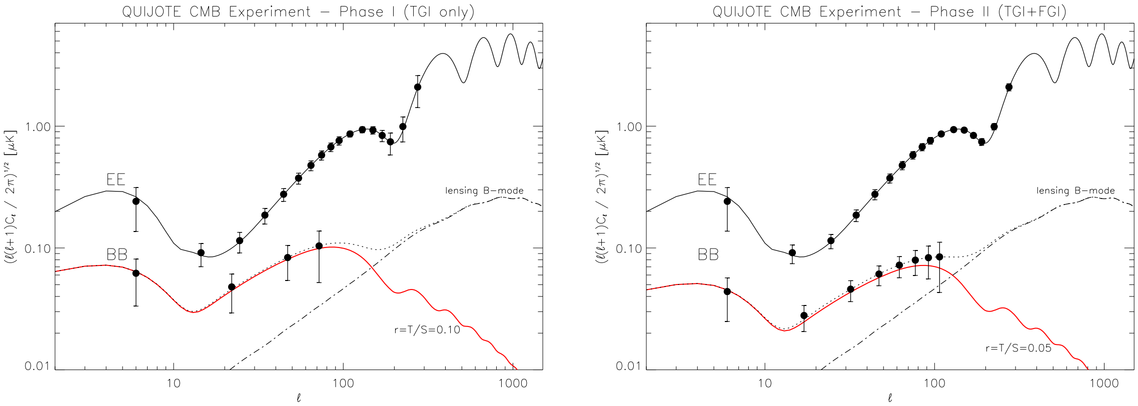

Figure 8. Left: Example of the *QUIJOTE-CMB* scientific goal after the Phase I of the project, for the angular power spectrum of the CMB E and B mode signals. It is shown the case for 1 year (effective) observing time, and a sky coverage of $\sim 3,000\,\mathrm{deg}^2$. The red line corresponds to the primordial B-mode contribution in the case of $r = 0.1$. Dots with error bars correspond to averaged measurements over a certain multipole band. Right: Same computation but now for the *QUIJOTE-CMB* Phase II. Here we consider 3 years of effective operations with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to $r = 0.05$.

level for the 30 GHz map is $\sim 0.5\,\mu$K/beam. The right panel shows the scientific goal for the *QUIJOTE-CMB* Phase II. Here, we consider 3 years of effective observing time with the TGI, and 2 years with the FGI. Note that, once the two instruments (FGI and TGI) are available, they can be operated simultaneously, as we will have two telescopes. Finally, we stress that the computations presented in Fig. 8 correspond to the optimal situation in which the foreground removal leaves a negligible impact on the power spectrum. More realistic estimates will be published in a future paper.

4.2 Non-core science

Apart from the scientific goals described in the previous section, we have identified a number of secondary science projects. The characteristics of *QUIJOTE-CMB* make it a suitable experiment for performing (relatively-short) observations in specific regions that would allow us to tackle scientific objectives different to those for which it was conceived. Some of these possible projects are:

i) Study of the polarisation of Galactic regions and extragalactic sources. One of the main science drivers of *QUIJOTE-CMB* is to characterize the polarisation of the large-scale synchrotron emission from our Galaxy.

However, it is also interesting to study this polarisation in specific Galactic regions, and also in extragalactic regions like M31, or in some of the 22 polarized sources detected in WMAP data.[38] This could be done either with the MFI or with the polarized source subtractor, depending on the angular resolution.

ii) Study of the North Polar Spur. This a huge feature, visible mainly in radio wavelengths, which covers about a quarter of the sky and extends to high Galactic latitudes. Two main hypotheses have been proposed for its origin, namely a superbubble inflated by stellar winds and supernovae activity from the Scorpius-Centaurus OB association, on one hand, and an interaction between the loop I superbubble and the local superbubble.[39] *QUIJOTE-CMB* data in this region may help to disentangle these two hypotheses.

iii) Study of the polarisation of the anomalous microwave emission (AME) in the Perseus molecular cloud and in other bright Galactic clouds. Apart from the synchrotron, it is also mandatory to have a good characterization of the AME polarisation in order to assess what level of contamination current and future B-modes experiments will suffer. At present, only upper limits of the polarisation percentage have been obtained;[40] these stand at ∼1% at the 95% C.L. We estimate that 35 h of observations with the 30 GHz channels of the MFI on Perseus could allow us to obtain a ∼1% upper limit at the 99% C.L. Other possible targets include the ρ-Ophiuchi molecular cloud,[41] the dark nebula LDN1622 or the Pleiades reflection nebula.[42] These *QUIJOTE-CMB* measurements will provide a unique tool to understand the physical mechanism responsible for the AME, helping to distinguish between the electric dipole and the magnetic dipole radiation models.[43, 44]

iv) Study of the WMAP haze in polarisation. This is an excess of microwave emission towards the centre of the Galaxy that was found at 23 GHz in WMAP data, with a significantly flatter spectrum than synchrotron, and which has recently been shown to have a Gamma-ray counterpart in Fermi data.[45] This is a burning subject at the moment, mainly owing to one of the proposed hypotheses for its origin, which is based on hard synchrotron radiation driven by relativistic electrons and positrons produced in the annihilations of one (or more) species of dark matter particles.[46] *QUIJOTE-CMB* data could have an important contribution here, as it could allow us to measure, or to constrain the expected level of polarisation of this synchrotron emission.

v) Study of the polarisation of the WMAP cold spot. This is a non-Gaussian feature in the CMB, in the form of an extremely extended and cold region, which was found in WMAP data.[47] After several considerations, it was proposed as a possible scenario for its origin the presence of a texture, a kind of topological defect which is predicted to occur in the primordial Universe. If this hypothesis were correct, a lack of polarisation would be expected in this region as compared with typical values of the primordial CMB. Therefore, the *QUIJOTE-CMB* data could help to disentangle the Gaussian and the texture hypotheses. In particular, it has been estimated[48] that these data would be able to reject the Gaussian hypothesis with a significance of ∼1%.

5. PROJECT STATUS AND TIMELINE

QT1 is already installed at the Teide Observatory, and is now in the commissioning process. Immediately after this, the MFI will be commissioned, probably during this summer (2012). In parallel, the commissioning phase of the source-subtractor facility will take place.

We expect to install the QT2 at the end of 2013. Concerning the other two instruments, the TGI will be installed in the focal plane of the QT2, and will be commissioned by the end of 2013. The TGI will be available by the end of 2014. Note that once the TGI is operative, the FGI will be permanently installed in QT1, while the TGI will be placed in QT2.

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