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Authors	TROMBETTI, Tiziana; BURIGANA, CARLO; VALENZIANO, LUCA
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Square Kilometre Array and cosmic microwave background spectral distortions

Tiziana Trombetti
INAF–IASF Bologna,
Via Piero Gobetti 101, I–40129 Bologna, Italy
Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara,
Via Giuseppe Saragat 1, I–44122 Ferrara, Italy
E-mail: trombetti@iasfbo.inaf.it

Carlo Burigana
INAF–IASF Bologna,
Via Piero Gobetti 101, I–40129 Bologna, Italy
Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara,
Via Giuseppe Saragat 1, I–44122 Ferrara, Italy
INFN, Sezione di Bologna, Via Irnerio 46, I–40126, Bologna, Italy
E-mail: burigana@iasfbo.inaf.it

Luca Valenziano
INAF–IASF Bologna,
Via Piero Gobetti 101, I–40129 Bologna, Italy
E-mail: valenziano@iasfbo.inaf.it

The Square Kilometre Array (SKA) is a new technology (large array) radio-telescope that, owing to its extremely high sensitivity and resolution, will allow to investigate different cosmological and astrophysical topics. In this work, we discuss the possible contribution of the SKA in combination with future cosmic microwave background experiments in probing various types of dissipation processes relevant at different cosmic epochs.

Keywords: Cosmology: cosmic background radiation; reionization; radiation mechanisms: general.

1. Theoretical and observational framework

The cosmic microwave background (CMB) spectrum emerges from the thermalization epoch, at $z \sim 10^6 - 10^7$, with a blackbody (BB) shape thanks to the high efficiency of interaction processes in the cosmic plasma able to re-establish the matter-radiation thermal equilibrium even in the presence of a significant departure. After this phase and passing through the recombination epoch, the thermodynamical equilibrium is no longer ensured since the reduced interaction of CMB photons with the plasma, because of the expansion of the Universe and the decrease of electron and photon number densities and temperatures.

The distorted spectra mainly depends on the fractional amount of energy exchanged during the interaction, the epoch and type of the heating or cooling process, and the baryon density. Theoretically, the departure from a perfect BB is predicted by three main unavoidable mechanisms:[1]

(*i*) cosmological reionization and related electron heating, which produce physically correlated Comptonization distortion characterized by an (energy) Comptonization parameter, $y \approx 10^{-7} - 10^{-6}$, proportional to the fractional energy exchanged in the interaction, $\Delta\varepsilon/\varepsilon_i \simeq 4y$, and free-free (FF) distortion;

(*ii*) dissipation of primordial perturbations at small scales, damped by photon diffusion and thus invisible in CMB anisotropies, which produces mainly BE-like distorted spectra characterized by a positive chemical potential $\mu_0 \simeq 1.4\Delta\varepsilon/\varepsilon_i \approx 10^{-9} - 10^{-7}$;

(*iii*) BE condensation of CMB photons by colder electrons associated with the matter temperature decrease in the expanding Universe relatively faster than that of radiation gives $\mu_0 \approx -3 \times 10^{-9}$.

The photon occupation number and its evolution at different frequencies and times is described by the complete kinetic Boltzmann equation, very well approximated in terms of the Kompaneets equation. The FF signal associated with cosmological reionization is the most relevant type of low-frequency global spectral distortion (see Figure 1). Indeed, the FF term is proportional to the square of baryon density and the structure formation process implies a rate amplification by a factor $\simeq 1 + \sigma^2$ (being σ^2 the matter distribution variance) with respect to the case of homogeneous plasma.[3]

Recent limits on CMB spectral distortions and constraints on energy dissipation processes in the plasma[4] ($|\Delta\varepsilon/\varepsilon_i| \lesssim 10^{-4}$ at 95% C.L., the exact value depending on the dissipation epoch and on considering a single process or two different processes jointly) are mainly set by the FIRAS instrument on board the NASA COBE[a] satellite[5] in the wavelength range between 1 cm and 0.5 mm. The measured monopole of the background radiation resulted compatible with a BB spectrum[6] at the current temperature of $T_0 = (2.72548 \pm 0.00057)$ K, because of the Universe expansion, a value that well accounts also for the main (Doppler effect) dipole[b] induced by the solar system velocity ($v \simeq 369\,\mathrm{km/s}$) relative to the CMB restframe.

High accuracy CMB spectrum space experiments, such DIMES[9] ($0.5 \lesssim \lambda \sim 15$ cm) and FIRAS II[10] ($\lambda \lesssim 1$ cm), were proposed to constrain energy exchanges up to 100 times better than FIRAS. Dissipation processes at early times ($z \gtrsim 10^5$), like the ones DIMES is able to probe, result in Bose-Einstein (BE)-like distortions,[11] while late epochs mechanisms ($z \lesssim 10^4$) before or after the recombination era generate Comptonization and FF distortions.[12] New space missions were proposed to investigate the cosmic origin and its evolution by observing CMB temperature and polarization anisotropies with ∼ degree resolution, as in PIXIE[13] and LiteBird,[c] or

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[a] `http://lambda.gsfc.nasa.gov/product/cobe/`

[b] The analysis of the dipole term frequency dependence can be also exploited to study CMB spectral distortions.[7,8]

[c] `http://litebird.jp/eng/`

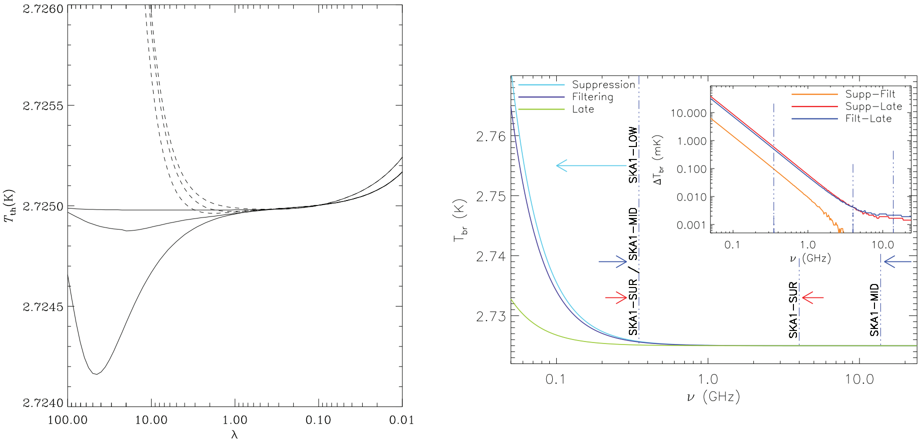

Fig. 1. Left panel: distorted spectra in equivalent thermodynamic temperature vs. λ (cm) with late energy injection $\Delta\varepsilon/\varepsilon_i \simeq 4y = 5 \times 10^{-6}$ plus an early/intermediate energy injection $\Delta\varepsilon/\varepsilon_i = 5 \times 10^{-6}$ (~ 20 times smaller than current upper limits) at the "time" Comptonization parameter $y_h = 5, 1, 0.01$ (bottom to top; the cases at $y_h = 5$ and 1 are very similar at short λ; solid lines) plus a FF distortion with $y_B = 10^{-6}$ (dashes). $y_h = y$, but assuming electron temperature equal to the radiation one and computing the integral from the energy injection time to the current time. Right panel: FF distortion in SKA2 frequency range by two astrophysical reionization histories (a *late* phenomenological model is also displayed for comparison). Inset: models absolute differences; vertical lines: ranges of SKA1 configurations. From Ref. 2.

with arcmin resolution, as in COrE,[14] [d] PRISM,[15] [e] and COrE+, or in combination with spectrum measurements as in the case of PIXIE and PRISM.

Improved absolute temperature measures will strengthen the constraints on CMB spectrum affected by (pre-recombination) decaying and annihilating particles,[16,17] by superconducting cosmic strings electromagnetic radiation,[18] by energy injection of evaporating primordial black holes.[19] Spectral distortions could constrain non evaporating black-holes spin,[20] small scale magnetic fields,[21] vacuum energy density decay,[22] axions.[23]

2. The Square Kilometre Array

The Square Kilometre Array (SKA) is a huge, new technology radio telescope that, with an extension of ~ 3000 km and a collecting area of ~ 1 km^2, has been designed to provide a significant breakthrough in the knowledge of the Universe.[25] Moreover, its extremely high sensitivity and resolution can contribute to set new constraints on CMB spectral distortions and dissipation processes beyond current limits. SKA will observe in the radio band with different antenna concepts and a continuous frequency coverage from 50 MHz to 14 GHz, allowing all-sky surveys and redshift depth observations.[26] The project will consist of two consecutive phases, the Phase 1

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[d] `http://www.core-mission.org/`
[e] `http://www.prism-mission.org/`

(SKA1), able to perform HI intensity mapping surveys and the Phase 2 (SKA2), that will allow to carry out a wide HI galaxy redshift survey, the biggest spectroscopic survey of ∼1 billion of galaxies. A future, third phase, if feasible, should extend the frequency domain up to ∼ 30 GHz.

Each antenna design will consist of sub-arrays, which can be divided into the SKA LOW, MID, SUR arrays.[27] The SKA1 will host most of the low frequency aperture arrays (SKA1-LOW), a small part of the middle frequency (SKA1-MID) dishes, and the survey aperture arrays (SKA1-SUR), that should be deferred. During the Phase 2 the total array will be completed. In Table 1 we report the main observational characteristics of the three main sub-arrays described above.[28]

Table 1. SKA main parameters

	SKA1-LOW	SKA-MID	SKA1-SUR
Frequency Range (GHz)	0.05-0.35	0.35-14	0.65-1.67
Fiducial Frequency (GHz)	0.11	1.67	1.67
Resolution (arcsec)	7	0.25	0.9
FoV (deg^2)	20.77	0.49	18
Continuum Sensitivity (μJy-hr$^{-1/2}$)	3.36	0.75	3.72

Since radio-continuum surveys play an important role in many relevant research fields, various reference surveys have been taken into account as the top priority SKA continuum science cases.[29] The Ultra Deep Survey devoted to trace the Star Formation History of the Universe (SFHU) and the SKA1 extremely high sensitivity at the μJy level and resolution over wide areas (0.5" or lower at ∼ 1GHz) will allow the disentangling of the single radio source populations down to very faint fluxes. Assuming 1 GHz as a reference frequency, the flux limit will be 0.05, 0.2, 1, μJy/beam for the Ultra Deep (1 deg^2 sky coverage), Deep (10–30 deg^2) and Wide (1–5 $\times 10^3$ deg^2) survey, respectively.

3. SKA contribution to future CMB spectrum experiments

SKA high sensitivity and resolution can also be used to model the contribution from Galactic emissions and extragalactic foreground, a fundamental step to accurately observe these kinds of distortions. Extragalactic source contribution is small compared to Galactic radio emission, currently the major astrophysical problem in CMB spectrum experiments, but, differently from the Galactic emission, it cannot be subtracted from the CMB by exploiting its angular correlation properties because of the limited resolution of experiments devoted to CMB monopole temperature, particularly at low frequencies. A direct radio background estimate from precise number counts will certainly improve the robustness of thesekind of analyses. Exploiting the recent differential number counts at 0.153 GHz,[30] 0.325 GHz,[31] 1.4 GHz,[32] and 1.75 GHz[33] it is possible to evaluate the contribution T_b to the radio background from extragalactic sources in various ranges of flux densities. These signals can be significant at the accuracy level potentially achievable with future experiments. Subtracting sources brighter than several tens of nJy, the background results less than $\sim 1\,\mathrm{mK}$ at $\nu \gtrsim 1\,\mathrm{GHz}$, but greater than $\sim 10\,\mathrm{mK}$ below $0.3\,\mathrm{GHz}$. The minimum source detection threshold is given by the source confusion noise. The finite angular extension of faint galaxies, $\theta \sim 1''$, implies a "natural confusion limit" $\sim 10\,\mathrm{nJy}$ at $\nu \sim 1.4\,\mathrm{GHz}$, not a relevant limitation for deep surveys. At $1\,\mathrm{GHz} \lesssim \nu \lesssim$ some GHz ($\lambda \approx 1\,\mathrm{dm}$) the signal amplitudes found for CMB distorted spectra well below FIRAS constraints are significantly larger than the estimates of the background from extragalactic sources fainter than some tens of nJy. At decreasing frequencies FF distortion amplitude increases but, at the same time, source confusion noise may represent a serious problem, possibly preventing the achievement of the faint detection threshold necessary to have a source contribution to the background significantly less than the CMB distortion amplitude.

Moreover, SKA will trace the neutral hydrogen distribution and the neutral-to-ionized transition state at the reionization epoch through the 21-cm line.[34] It could trace the development of ionized material directly by looking for FF emission from ionized halos. The expected signal can be derived by reionization models through both semi-analytical methods[35] and numerical simulations.[36] Dedicated high resolution sky areas observations allow to distinguish FF distortion by ionized halos rather than by diffuse ionized IGM. SKA should be able to detect up to $\sim 10^4$ individual FF emission sources with $z > 5$ in 1 deg^2 discerning ionized halos or diffuse ionized IGM FF distortions.

In conclusion, SKA precise number counts, particularly at frequencies from $\sim$ 1 to few GHz, will be crucial for a precise analysis of CMB spectral distortion experiments, while the precise mapping of individual halos represents an interesting goal for the excellent imaging capabilities of SKA.

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