SEARCH FOR DISTORTIONS IN THE SPECTRUM OF THE COSMIC MICROWAVE RADIATION

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We present preliminary results of TRIS, an experiment dedicated to the search of deviations from a pure Planckian distribution in the spectrum of the Cosmic Microwave Background at frequencies close to 1 GHz.

1 Introduction

According the Standard Model the expected spectrum of the Cosmic Microwave Background (CMB) is an equilibrium, (blackbody), spectrum therefore a plot of measured values of the CMB thermodinamic temperature versus frequency should be perfectly flat. At the second order level we expect however deviations from equilibrium (distortions) because a variety of processes which accompanied the evolution of the Universe (e.g. turbulence dissipation, particle annihilation and so on) may have disturbed it injecting energy which, through matter - radiation interactions, modify the photon distribution. Subsequent interactions gradually redistribute the photons and, under proper conditions, completely cancel the distortions (see for instance [1]). The entire process, described by the Kompaneets Equation [2], has been studied by many authors (e.g. [3, 4, 5]) What remains and we see today depends on the epoch when the energy was injected. Marking the epoch of the energy injection by the red shift parameter $Z$ three scenarios are possible:

i) $Z \geq 10^7$: at that epoch the velocity of the matter radiation interactions was so high that the expanding Universe was a sequence of equilibrium states. The energy $\Delta E$ injected at that epoch was therefore redistributed over the entire spectrum and the Planck distribution reestablished almost immediately. No distortion is therefore expected today;
ii) $10^7 \geq Z \geq 10^4$: the reaction velocity and the time elapsed since the energy injections are insufficient to reestablish equilibrium but enough to produce a Bose Einstein semiequilibrium condition, characterized by the chemical potential $\mu$, proportional to the fraction $\Delta E/E$ of energy injected, and by the Comptonization parameter $y$. Therefore if energy injections occurred at $10^7 \geq Z \geq 10^4$, today we should see distortions, among which particularly interesting are distortions at frequencies close to 1 GHz: a deep in the distribution of $T_{\text{CMB}}$ versus $\nu$ (see for instance [3, 4]). The precise frequency of the deep depends on the barion density $\Omega_b$.

iii) $Z \leq 10^4$: after recombination the matter radiation-interactions were drastically reduced, therefore distortions produced at $Z \leq 10^4$ remain and keep track of the process which generated them.

The effective scenario one observes can be very complicated being the combination of a variety of processes which injected energy at different epochs. It is however worth studying and try to detect distortions, unique probes of the conditions existing in the Universe up to $Z \simeq 10^6 - 10^7$, well before the condensations we see today began to form.

2 Measurements of the CMB spectrum

The most accurate measurement of the CMB spectrum was made ten years ago [6, 7] with FIRAS, an absolute radiometer on board the COBE satellite. It shows that between 60 and 600 GHz an extremely good description of the CMB spectrum is given by the spectrum of a blackbody with a temperature $T_{\text{CMB}} = (2.725 \pm 0.002) \text{K}$. Deviations from the plankian shape, if present, are $\leq 0.005\%$. Outside the 60 - 600 GHz frequency range explored by FIRAS the measured values of $T_{\text{CMB}}$ are less accurate. Here in fact we are far from the maximum of the CMB brightness distribution, therefore the importance of the foregrounds (galactic synchrotron and blend of unresolved extragalactic sources on the low frequency side, dust emission at high frequencies) is higher. Moreover all the observations were made in worse conditions than in space, on a dedicated satellite.

Above 600 GHz observations were extended with a rocket borne radiometer which set an upper limit of 3 K to $T_{\text{CMB}}$ at 900 GHz [9].

\footnote{It has been suggested recently (8) that the blackbody reference used by FIRAS to calibrate its system had deviations from the distribution the assumed by the observers. Even if this fact will be confirmed the FIRAS results will remain the most accurate in literature.}
Below 60 GHz all the observations were made with radiometers installed at ground level or on stratospheric balloons, therefore data are contaminated by the emission of the earth atmospheric layer above the radiometer and by the fraction of the environment radiation the antennae pick up through side and back lobes. In this frequency range the 2.5 - 90 GHz interval was studied 20 years ago by the White Mt. collaboration, using absolute radiometers with geometrically scaled antennae \cite{10}. The White Mt results, combined with independent observations at balloon altitudes \cite{11}, set a 1% upper limit to deviations from the Planck distribution between \(\simeq 10 \, GHz\) and 60\(GHz\) and a 10% upper limit between 3 and 10 GHz.

Below 5\(GHz\) in literature there are more than 20 independent measurements of \(T_{CMB}\), made in about 40 years. They are listed in Table 1. We quote the error bars reported by the observers, it is however worth to note that in some cases these errors probably do not include systematic effects whose importance became evident only recently. The accuracy of these data is definitely lower than the accuracy of the intermediate and high frequency data: neither excludes nor confirms the existence of very large distortions, whose amplitude, below 1 GHz, reach \(\Delta T/T_{CMB}\) up to \(\simeq 0.3 - 0.5\) \cite{12}.

The complete set of measured values of \(T_{CMB}\) tells us that the matter radiation mixture of our Universe was only perturbed by the energy injections which occurred at \(Z < 10^7\). Future detections of large distortions at low frequencies, whose existence has not yet excluded, should not modify this picture. Analysis of the complete set of data (e.g. \cite{13,14}), including the low frequency ones, shows in fact that, no matter if the energy injection occurred at early or late times, the following upper limits hold:

\[
\Delta E/E \leq 10^{-5} \quad \text{and} \quad y \leq 10^{-5}.
\]

3 TRIS experiment

Because the low frequency data can still accommodate large distortions at frequency and a positive detection at frequencies close to 1 GHz of a deep in the distribution of \(T_{CMB}\) versus \(\nu\) would provide direct information on the barionic density in our Universe, a few years ago our group set up TRIS, a system of three absolute radiometers which measure \(T_{sky}\), the absolute temperature of the sky, at 0.6, 0.82 and 2.5 GHz. Fitting the values of the sky temperature measured at three frequencies, at different points on the sky to a model, we expect to be able to disentangle the foregrounds from the back-
Table 1: Measurements of the CMB temperature below 5 GHz

| $\lambda$ (cm) | $\nu$ (GHz) | $T_{\text{CMB}}$ (K) | Ref. | $\lambda$ (cm) | $\nu$ (GHz) | $T_{\text{CMB}}$ (K) | Ref. |
|----------------|-------------|----------------------|------|----------------|-------------|----------------------|------|
| 73.5           | 0.408       | 3.7±1.2              | 15   | 20.9          | 1.44        | 2.5±0.3              | 19   |
| 50.0           | 0.6         | 3.0±1.2              | 16   | 20.7          | 1.45        | 2.8±0.6              | 21   |
| 49.1           | 0.61        | 3.7±1.2              | 15   | 20.4          | 1.47        | 2.27±0.19            | 23   |
| 47.2           | 0.635       | 3.0±0.5              | 17   | 15            | 2.0         | 2.5±0.3              | 19   |
| 36.6           | 0.82        | 2.7±1.6              | 18   | 15            | 2.0         | 2.55±0.54            | 27   |
| 30.0           | 1.0         | 2.5±0.3              | 19   | 13.1          | 2.3         | 2.66±0.77            | 26   |
| 23.44          | 1.28        | 3.45±0.28            | 20   | 12            | 2.5         | 2.71±0.21            | 18   |
| 21.26          | 1.41        | 2.11±0.38            | 21   | 7.9           | 3.8         | 2.64±0.06            | 28   |
| 21.2           | 1.42        | 3.2±1.0              | 22   | 7.35          | 4.08        | 3.5±1.0              | 29   |
| 21             | 1.43        | 2.65±0.32            | 23   | 6.3           | 4.75        | 2.79±0.07            | 30   |

Ground and extract the temperature of the CMB \[31\]. The antennae of the TRIS radiometers were corrugated horns, geometrically scaled, with the same beam ($HPBW = 18^\circ \times 23^\circ$) at the three frequencies. The horns could be aimed at different elevations along the meridian, moreover, when absolute measurements were planned, we cooled the waveguide section to liquid helium temperature $T_{\text{LHe}}$, reducing the thermal noise produced at the system front end. The cryogenic bath used to cool the waveguide housed also a dummy load which provided a stable reference level $T_{\text{ref}} \approx T_{\text{LHe}}$. A second dummy load at ambient temperature provided a warm signal $T_{\text{warm}}$, used for calibrations. Details of the system and its performance are given elsewhere [31].

The three radiometers were installed at Campo Imperatore, a site at 2000 m a.s.l. ($\text{lat.} = 42^\circ N$) near the Gran Sasso underground Laboratory, who provided logistical support. At the beginning of the experiment the level of radio interferences at Campo Imperatore was reasonably low, unfortunately the situation became gradually worse, therefore we were gradually forced to reduce the receiver bandwidth and to move continuously in frequency to overcome the growing level of noise.

The measurements went on a few years and included:

a) absolute measurements of the sky temperature
To first approximation (for complete formulae see [31])

$$T_{sky}(\alpha, \delta) \simeq T_{ant} - T_{gro} - T_{atm}$$

where $T_{ant}$, $T_{gro}$ and $T_{atm}$ are the antenna temperature, the ground contribution and the contribution of the atmosphere, respectively.

$$T_{ant} \simeq [T_{ref} + (S_{sky} - S_{ref}) \frac{T_{warm} - T_{ref}}{S_{warm} - S_{ref}} - T_{amb}(1 - e^{-\tau})]/e^{-\tau}$$

where $S_{sky}$, $S_{ref}$ and $S_{warm}$ are the signals produced respectively by the sky, the cold dummy load and the warm dummy load, with $T_{amb} \simeq T_{ref} \simeq T_{LHe}$ (at Campo Imperatore elevation $T_{LHe}4.0K$)

Absolute measurements were made preferably at night time and repeated at different times throughout the year to get data from different regions of the sky.

b) drift scans. Letting the sky drift through the antenna beam aimed at a fixed elevation along the meridian, we got profiles at constant declination of the sky temperature versus the right ascension. To remove the sun contamination data collected at daytime were eliminated and observation at the same declination were repeated six months apart.

c) measurements of the ground and atmospheric contributions.

The side and back lobes of the horns were minimized adding a band of additional corrugations in the E-plane at the horn aperture. The resulting beam was measured on a geometrically scaled model at 8.4 GHz. The ground contribution was then evaluated convolving the measured beam with a black-body radiator at ambient temperature which filled all the directions below the horizon profile (measured with a teodolite).

The atmospheric contribution was calculated combining models of the atmospheric emission and profiles of atmospheric pressure, humidity and temperature, measured daily by meteorological balloons [32]. Results are shown in Table 3.

4 Extraction of $T_{CMB}$: preliminary results

The sky temperature is a combination
Table 2: Values of the spectral index of the galactic diffuse radiation measured at $\delta = 42^\circ$ between 0.61 and 0.82 GHz

| $\alpha$ | $\gamma$ | $\sigma$ | $\alpha$ | $\gamma$ | $\sigma$ | $\alpha$ | $\gamma$ | $\sigma$ |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0$^h$    | 2.379    | 0.005    | 8$^h$    | 3.034    | 0.003    | 16$^h$   | 2.469    | 0.002    |
| 1$^h$    | 2.515    | 0.009    | 9$^h$    | 3.100    | 0.004    | 17$^h$   | 2.662    | 0.002    |
| 2$^h$    | 2.835    | 0.009    | 10$^h$   | 3.231    | 0.008    | 18$^h$   | 2.693    | 0.002    |
| 3$^h$    | 2.540    | 0.009    | 11$^h$   | 2.983    | 0.011    | 19$^h$   | 2.786    | 0.002    |
| 4$^h$    | 2.438    | 0.005    | 12$^h$   | 2.834    | 0.008    | 20$^h$   | 2.883    | 0.003    |
| 5$^h$    | 2.618    | 0.003    | 13$^h$   | 2.646    | 0.006    | 21$^h$   | 2.658    | 0.002    |
| 6$^h$    | 2.827    | 0.002    | 14$^h$   | 2.393    | 0.005    | 22$^h$   | 2.649    | 0.003    |
| 7$^h$    | 2.973    | 0.002    | 15$^h$   | 2.194    | 0.003    | 23$^h$   | 2.540    | 0.003    |

\[
T_{\text{sky}}(\alpha, \delta, \nu) = T_{\text{CMB}} + T_{\text{gal}}(\alpha, \delta, \nu) \left( \frac{\nu}{\nu_o} \right)^{-\gamma} + T_{\text{egs}}(\nu) \left( \frac{\nu}{\nu_o} \right)^{-\beta} \quad (3)
\]
of the CMB signal and the signal produced by the galactic diffuse emission and the blend of unresolved extragalactic sources.

$T_{\text{gal}}$ and $T_{\text{egs}}$ have power law frequency spectra. The spectral index $\gamma$ of $T_{\text{gal}}$ can be obtained analyzing the TRIS drift scans made at two frequencies by the T-T plot method [33, 34]. The value of $T_{\text{egs}}$ can be obtained from data in literature [16] and references therein. Having $\gamma$ and $T_{\text{egs}}(\nu)$ we can then extract $T_{\text{CMB}}(\nu)$ modelling the data collected at three frequencies, in different directions and disentangling it from the galactic signal.

TRIS observations went to a halt in May 2001, when we were forced to move our equipment to a different site, because the Campo Imperatore observing site was closed. We are now carrying on data analysis. Only the reduction of the 0.6 GHz has been concluded, while the analysis of the 0.82 and 2.5 GHz data is still going on. Results so far obtained are given in Table 2 and 3. At the moment we can only give the temperature of $T_{\text{CMB}}$ at 0.6 GHz: being based on data at one frequency the accuracy is still limited (27%). We expect, when the complete set of observations will be fully analyzed, to bring to 10% the accuracy on $T_{\text{CMB}}$ below 1 GHz.
Table 3: Measured values of the temperatures of CMB and foregrounds at r.a. = 09h57m, dec. = 42°26' - preliminary results

| ν (GHz) | 0.61     | 0.82     | 2.50     |
|---------|----------|----------|----------|
| $T_{sky}(K)$ | 8.53±0.09 | under analysis | under analysis |
| $T_{atm}(K)$  | 1.06±0.02 | 1.18±0.02 | 1.37±0.03 |
| $T_{gnd}(K)$  | 0.07±0.05 | 0.07±0.05 | 0.07±0.05 |
| $T_{egs}(K)$  | 0.81±0.14 | 0.34±0.07 | 0.016±0.003 |
| $T_{gal}(K)$  | 4.74±0.81 | 2.06±0.37 | 0.087±0.024 |
| $T_{CMB}(K)$  | 2.98±0.80 | under analysis | under analysis |

5 Conclusions

The frequency region close to 1 GHz of the CMB frequency spectrum is potentially very interesting. Here in fact we can expect distortions whose measurement can provide an important cosmological parameter, the barion density $\Omega_b$. Because the data in literature are insufficient to decide about the existence of this distortion, we set up TRIS an experiment with the aim of measuring the CMB spectrum between 0.6 and 2.5 GHz. Observations have been completed but data reduction is still going on. We expect to reach an accuracy of $\approx 10\%$ sufficient to improve the present upper limits on the amplitude and frequency of, or hopefully detect, the expected deep in the distribution of $T_{CMB}$ versus $\nu$.

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