The low frequency tail of the CMB spectrum, down along the radio range (∼1 GHz), may carry weak spectral distortions which are fingerprints of processes occurred during different epochs of the thermal history of the Universe, from z ∼ 3 × 10⁶ to reionization. TRIS and ARCADE2 are the most recent experiments dedicated to the exploration of this chapter of CMB cosmology. The level of instrumental accuracy they reached in the determination of the absolute sky temperature is such that the removal of galactic and extra-galactic contamination is the true bottleneck towards the recovery of the cosmological signal. This will be certainly the case also for future experiments in the radio domain. Here we present an update of a study originally done to recognize the contribution of unresolved extra-galactic radio sources to the sky brightness measured by TRIS. Despite the specific context which originated our analysis, this is a study of general interest, improved by the inclusion of all the source counts available up-to-date from 150 MHz to 8.4 GHz.

1 Scientific case

The frequency spectrum of the Cosmic Microwave Background (CMB) recovered by the FIRAS instrument on board the COBE satellite is an almost perfect planckian spectrum at the thermodynamic temperature of 2.728 ± 0.004 K, even if a more recent analysis and an update of this result can be found in a recent work by Fixsen. No signatures of spectral distortions have been found on the monopole scale. Nevertheless, there are important arguments suggesting that deviations from a blackbody curve originated in the pre-recombination Universe, may be present in the CMB spectrum. In particular, we know that if an energy injection in the photon-baryon fluid occurred in the redshift range ∼ 10⁵ < z < ∼ 3 × 10⁶, corresponding to a temperature of the photon-baryon fluid ∼ 0.1keV < T < ∼ 1keV, than the system relaxes towards a kinetic equilibrium, the photons having Bose-Einstein spectrum with a chemical potential µ ≠ 0. Several mechanisms have been proposed as possible sources of perturbation, among them decay of relic massive particles, dissipation of primordial magnetic fields, annihilation of relic particles and dissipation of acoustic oscillations in the fluid. Was the spectrum a Bose-Einstein one, we would observe a dip in the plot Temperature vs Frequency of the CMB at frequencies <∼1 GHz, given the present estimate of H₀ (Hubble parameter) and Ωₙ (baryon density). The amplitude of this distortion, ∆T/T ≈ µ(Ωₙh²)^−2/3 (h being H₀ in units of 100 (km/s)/Mpc), is strongly model dependent. Extrapolating to lower frequencies the FIRAS upper limit on µ, we expect a temperature dip smaller than few tens of mK.

Another effect able to produce a monopole scale spectral distortion is free-free emission during reionization. This effect produces a signal ∆T/T ∝ Y_{ff}λ², which is essentially the
optical depth to bremsstrahlung, $\lambda$ being the wavelength and $Y_{ff}$ a distortion parameter as defined by Bartlett and Stebbins. Despite new tighter limits on $Y_{ff}$ obtained by Gervasi et al., we are still far from the possibility of testing reionization scenarios like those investigated by Weller et al.

Both effects are more relevant at decimetric wavelengths, where (1) calibrations are more difficult due to the size of antennas, (2) the brightness of the Galaxy overcomes the CMB and (3) the signal of Unresolved Extragalactic Radio Sources (UERS), the subject of this study, may introduce a temperature offset if not properly evaluated and subtracted.

Two recent experiments searched for low frequency CMB spectral distortions: TRIS and ARCADE2. In the framework of TRIS, a new estimate of the brightness temperature of UERS has been proposed by Gervasi et al. Here we present an update of those results, exploiting all the most recent radio source counts from 150 MHz to 8.4 GHz and adding a new frequency to those used in the previous study.

## 2 Unresolved Extragalactic Radio Sources contamination

### 2.1 Aims and Methods of this study

As stated in the previous section, the purpose of this work is to develop the earlier work by Gervasi et al. enlarging the data-set described in table 1 of this reference. Here we included all the deepest radio source counts done in the last few years, especially those obtained at VLA and GMRT. In particular, we enriched our analysis taking into account new results at 150 MHz, 610 MHz and 1400 MHz. We completed the 8400 MHz counts by adding the results by Henkel and Partridge. We added also a new frequency in our analysis, namely the 325 MHz channel (Oort et al., Owen et al.).

Typical experiments looking for spectral distortions in the CMB spectrum have beams $>7^\circ$ (e.g. FIRAS), so that, on average, pointing in different directions, the radiometer will detect the same blend of AGNs, quasars and normal galaxies, with only a poissonian fluctuation in their number. Therefore, UERS are seen as an isotropic diffuse radiation. We calculate its temperature in two steps. First, we fit the differential source counts normalized to the euclidean counts, that is $Q(S) = S^{2.5}dN/dS$, $S$ being the flux. Then we use the definition of brightness temperature,

$$T_{b,UERS} = \frac{\lambda^2}{2k_B} \int_{S_{min}}^{S_{max}} Q(S)S^{-3/2}dS$$

($k_B$ Boltzmann constant), to calculate the integrated contribution of sources between two limiting values of flux. Here a problem is evident: given the fact that a survey will be complete at a flux limit $S_{min}$, how can we take into account the contribution of sources fainter than that? If we stop our integration within the data range, we get a lower limit of the temperature of UERS, introducing a bias in our analysis. A solution is to extrapolate our integral at fainter fluxes. In absence of a physical cut-off, to circumvent this problem we simply look for a functional form of $Q(S)$ such that $T_{b,UERS}$ remains finite when $S_{min} \to 0$, avoiding a kind of Olbers’paradox.

### 2.2 Radio Source counts

As originally proposed by Gervasi et al., we assume

$$Q(S) = Q_1(S) + Q_2(S) = \frac{1}{A_1S^{\epsilon_1} + B_1S^{\beta_1}} + \frac{1}{A_2S^{\epsilon_2} + B_2S^{\beta_2}}$$

(2)
where \( A_i, B_i, \varepsilon_i \) and \( \beta_i \) \( (i = 1, 2) \) are parameters to be fitted. This analytical description, inspired by source evolutionary models proposed by Danese, Franceschini and collaborators (see Danese et al.\(^\text{[20]}\) and Franceschini et al.\(^\text{[21]}\)), has the property of being integrable at faint fluxes, even if it is not good as \( \log(S) \) polynomials to describe features within the experimental range. One of the basic assumptions underlying our approach is that the four parameters of \( Q_i(S) \) giving the slopes \( (\varepsilon_i \text{ and } \beta_i) \) are frequency independent. Moreover, following again a suggestion of the model by Franceschini et al., and analyzing the data at 600, 1400 and 5000 MHz (frequencies where both faint and strong fluxes are well sampled), we fix \( \varepsilon_1 = \varepsilon_2 \), simplifying further the description of source counts. Now, the \( Q_1 \) and \( Q_2 \) terms, following the notation of Gervasi et al.\(^\text{[13]}\), are dominant respectively in the strong and faint flux regimes, so that two ratios can be calculated at the three frequencies with the widest flux coverage: 
\[
 r_A = \frac{A_2}{A_1} \quad \text{and} \quad r_B = \frac{B_2}{B_1}, 
\]

at 600, 1400 and 5000 MHz. These ratios, \( r_A \) in particular, can be used to reconstruct the faint flux tails of counts at those frequencies where data are not deep enough. Since they show a weak frequency dependence (see tab. 1 for \( A_2/A_1 \)), our choice has been to use the \( r_A \) and \( r_B \) calculated at the frequency closest to the one we want to reconstruct.

| 600 MHz | 1400 MHz | 5000 MHz |
|-------|--------|--------|
| \( A_2/A_1 \) | 0.17 ± 0.02 | 0.23 ± 0.01 | 0.31 ± 0.03 |

### 3 Results

The main result we have obtained is a new estimate of the brightness temperature of the blend of UERS in the range 150 MHz - 8400 MHz. The calculated temperature values are well described by a single power law (eq. 3) with spectral index -2.75 (see fig.1). Our estimates are well in agreement with those found by other authors\(^\text{[22]}\), and the main result is

\[
 T_{b,\text{UERS}}(\nu) = (0.91 \pm 0.02) \left( \frac{\nu}{610 \text{ MHz}} \right)^{-(2.75 \pm 0.02)} \text{K} \quad (3) \]

for the contribution of unresolved sources to the overall temperature of the radio sky.

This formula allows us to calculate the UERS temperature in correspondence of TRIS frequency channels, namely 600, 820 and 2500 MHz: we find, respectively, 950 ± 20 mK, 408 ± 9 mK and 20.6 ± 0.7 mK.

### 4 Conclusions

This update of our previous work allowed us a better reconstruction of differential source counts, especially at faint fluxes. In fact, unlike the first study, we could determine the ratio \( A_2/A_1 \) finding a hint for weak frequency dependence. Improved source count fits lead directly to a more accurate estimate of the brightness temperature: this is very well described by a single power-law frequency spectrum. Then, using eq. 3, we could evaluate the UERS contribution at TRIS frequencies with uncertainties almost a factor 10 smaller than those commonly assumed before new estimates by Gervasi et al.\(^\text{[13]}\). By virtue of that, the subtraction of this foreground is no longer a limiting factor in low frequency CMB experiments, the overall error budget being now dominated by the reconstruction of the absolute temperature scale and by the disentangling of galactic and cosmological signals. Finally, we conclude that the estimate given by eq.3.


Figure 1: Left panel: Temperature vs Frequency plot; calculated temperatures and power law fit (solid line); 1σ error bars. Right panel: the same as in left panel, but with temperature rescaled by a factor $\propto \nu^{2.75}$ to appreciate the scatter of points around the single power law fit.

exclusively based on source counts, doesn’t agree with the extragalactic radio excess detected as a diffuse signal by the ARCADE2 collaboration[23]. The discrepancy is around a factor 5 at 600 MHz, and still the origin of the radio excess remains mysterious. If its origin is truly extragalactic, there must be a number of sources able to produce an intense integrated signal, but individually so weak to escape from detection with radio interferometers. The case is intriguing and again tells us how non trivial is searching for CMB spectral distortions, and how unpredictable are the outcomes.

References

1. D.J.Fixsen, et al., ApJ 473, 576 (1996)
2. D.J.Fixsen, ApJ 707, 916 (2009)
3. R.A.Sunyaev & Ya.B. Zeldovich, Ap&SS 7, 20 (1970)
4. W.Hu & J.Silk, PRL 70, 2661 (1993)
5. P.McDonald, R.J.Scherrer & T.P. Walker, PRD 63, 023001 (2000)
6. K.Jedamzik, V.Katalinić & A.V.Olinto, PRL 85, 700 (2000)
7. J.D.Barrow & P.Coles, MNRAS 248, 52 (1991)
8. J.G.Bartlett & A.Stebbins, ApJ 371, 8 (1991)
9. M.Gervasi, et al., ApJ 688, 24 (2008)
10. J.Weller, R.A.Battye & A.Albrecht, PRD 60, 103520 (1999)
11. M.Zannoni, et al., ApJ 688, 12 (2008)
12. J.Singal, et al., ApJ accepted, arXiv:0901.0546
13. M.Gervasi, et al., ApJ 682, 223 (2008)
14. C.H.Ishwara-Chandra, et al., MNRAS accepted, arXiv:1002.0691
15. T.Garn, et al., MNRAS 387, 1037 (2008)
16. E. Ibar, et al., MNRAS 397, 281 (2009)
17. B.Henkel & R.B. Partridge, ApJ 635, 950 (2005)
18. M.J.A., Oort , W.J.G. Steemers & R.A Windhorst, A&A 73(Suppl), 103 (1988)
19. F.N. Owen, et al., Astron.J. 137, 4846 (2009)
20. L.Danese, G. De Zotti, A.Franceschini, & L. Toffolatti, ApJ 318, L15 (1987)
21. A.Franceschini, L. Toffolatti, L. Danese & G. De Zotti, ApJ 344, 35 (1989)
22. G. De Zotti et al, A&A Rev. 18, 1 (2010)
23. D.J. Fixsen, et al., arXiv:0901.0555