PLANNING FUTURE SPACE MEASUREMENTS OF THE CMB

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1. Small scale anisotropies of the Cosmic Microwave Background (CMB)

A central problem in cosmology is the building and testing of a full and detailed theory for the formation of (large-scale) structures in the Universe. It is widely believed that the observed structures today grew by gravitational instability out of very small density perturbations. Such perturbations should have left imprints as small temperature anisotropies in the cosmic microwave background (CMB) radiation.

The COBE satellite has opened up a new era by reporting the first detection of such temperature anisotropies. However, COBE was limited by poor sensitivity, and restricted to angular scales greater than 7° , much more extended than the precursors of any of the structures observed in the Universe today. As a result, these measurements are compatible with a wide range of cosmological theories. On the other hand, high precision measurements at the degree scale will be extremely discriminating, allowing strong constraints on large scale structure formation theories, the ionization history, the cosmological parameters (such as the Hubble and cosmological constants, or the type and amount of dark matter), and very early Universe particle theories. These goals could be met by producing nearly full-sky maps of the background anisotropies with a sensitivity of $\frac{\Delta T}{T} \sim 10^{-6}$ on scales from 10 arc minutes to tens of degrees.

More precisely, the **statistics of the background anisotropies**, if Gaussian, would favor inflationary models, whereas non-Gaussian fluctuations would rather favor models in which irregularities are generated by topological defects such as strings, monopoles and textures. The**shape of**

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the primordial fluctuation spectrum, according to most theories of the origin of the fluctuations in the Universe corresponds to potential fluctuations $\delta\phi$ which should be independent of the scale of the irregularities (λ). Even a few percent deviation from this prediction would have extremely important consequences for the inflationary models. These models also predict a specific **ratio of tensor**[*]**vs. scalar mode anisotropies** depending notably on the scale of the fluctuations. The best way to learn about the **reionization history of the universe** would be through the small-scale anisotropies which may be partly erased if the inter-galactic medium was re-ionized at high redshift. These small scale anisotropies depend also **on the baryon density, the nature of the dark matter and the geometry of the Universe** (and of course on the initial spectrum of irregularities). Observations of the structure of the CMB on scales down to $10'$ will resolve structures comparable in scale to clusters of galaxies ($\sim 10h^{-1}$Mpc[†]) and so allow a much more direct link between observations of **galaxy clustering, galaxy peculiar velocities and temperature anisotropies.** Additionally, the detection of at least 1000 rich clusters[‡] by the **Sunyaev-Zeldovich effect**[§], in combination with X-ray observations would constrain the evolution of rich clusters of galaxies and provide another handle on H_0. Finally, the Doppler effect on the same clusters might provide a unique measurement of **their peculiar velocity dispersion.**

Measuring the cosmological background anisotropies with an accuracy better than a part in a million on scales down to ten arc minutes is a very ambitious goal. Although difficult, it is achievable in the coming decade with a dedicated satellite experiment using the best detectors available today. Several concepts of missions are currently studied and two of them are presented below. The accuracy of the measurements of the cosmological anisotropies will rely on the ability to separate these fluctuations from those coming from the galactic background and from unresolved extra galactic sources. The different contributions to the microwave anisotropies can be non-Gaussian, and the separation of the components is a non-linear process. This calls for numerical simulations of the sub-millimeter and microwave sky.

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[*] generated by gravitational waves.

[†] h is Hubble's constant in units of 100 km s^{-1}Mpc^{-1}.

[‡] assuming a photon noise limited space experiment.

[§] caused by the frequency change of microwave background photons scattered by hot electrons in the gaseous atmospheres of rich clusters of galaxies

2. Sky simulations

By using both theoretical modeling and data extrapolations, the RUMBA group¶ aims at creating maps as realistic as possible of the relevant physical phenomena which may contribute to the detected signals The useful wavelengths for such studies are in the range from 200 μm to 2 cm where sources of flux anisotropies which may contribute in addition to the Primary $\frac{\Delta T}{T}$ of the 2.726 K background at comparable levels are :

- Effects of clusters, through the Sunyaev-Zeldovich effect, and the Doppler shift due to their peculiar velocities.
- Secondary effects like topological defects created during an early Universe Symmetry–breaking phase transition (*e.g.* Cosmic Strings, Textures, Global monopoles, etc...), or Rees-Sciama effect, Vishniac effect, etc...
- Sub-millimeter emission from the galaxies (including starburst galaxies, radio galaxies and AGN's)
- Emission from the Milky Way due mainly to three components, the interstellar dust (even at high galactic latitude : galactic cirrus), the bremsstrahlung and synchrotron emissions.

At this stage, our modeling of the various physical phenomena has been done as follows:

- For the primary $\frac{\Delta T}{T}$ and the effects from clusters, we have created realizations corresponding to specific theoretical models (*e.g.* standard CDM). This was also done for the possible secondary fluctuations from cosmic strings.
- For the galactic emission we use extrapolations of far-infrared data (e.g. IRAS maps and catalogs) by a single temperature model and of radio data at 408 MHz.
- For the unresolved component of the emission of galaxies, we are currently modeling the fluctuations by Monte-Carlo simulations.

All these processes are stored as elementary maps (presently 12.5° × 12.5°, with 500^2 pixels, each of size 1.5 arc minutes). The performances and properties of the instrument itself are included in order to model the expected signals and noises. The structure of our tool is designed to deal easily with further modifications of the experimental configuration. At this stage we assume simplified configurations with top-hat spectral filters, Gaussian lobes and a $1/f$ detector noise with a low frequency cutoff. Thus the final outputs of our simulations are a set of simulated signals as expected to be received

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from the satellite. They can then be used as test beds for the assessment of the feasibility of various signal-separation techniques. Furthermore, we use this tool in an iterative fashion to optimize the instrumental characteristics of the planned experiments.

Of course, our current modeling is far from perfect. For the high–z sources of fluctuations, we have to rely on theoretical models. In some cases, years of effort have led to the development of reliable tools, such as for the primary $\Delta T/T$ fluctuations in Gaussian models. In other case, it is technically hard to make definite predictions, even though the model is perfectly well specified (e.g. for strings, or the SZ effect which depends on the gas behavior in very dense environments). We also have only weak constraints on the high–z distribution of galaxies. For lower–z sources of fluctuations, like those coming from the dust in galaxies, we cannot do much more at this time than to extrapolate the dust emission from the IRAS and COBE measurements. But there might very well be another cold dust population, spatially uncorrelated with the hot one...In any case, the database structure adopted should permit us to incorporate all the latest developments in relevant theoretical modeling and/or new observations, as they appear.

3. Mission Concepts

The European Space Agency is studying a mission (COBRAS-SAMBA) which is aimed at the measurements described above. This mission will be up for selection in the spring of 1996 to become the third medium-size mission of the Horizon 2000 plan. This concept results from the work of the ESA Science Team[||].

The payload will be passively cooled; preliminary thermal models indicate that the focal plane assembly will reach an average temperature of ~100 K, while the telescope optical surfaces will stabilize at ~120 K. These temperatures, in addition to the absence of the atmospheric noise and heat load due to the chosen orbit, insure that the conditions for a low and stable background are met.

An off-axis 1.5 meter gregorian telescope provides the necessary angular resolution and collecting area to meet the objectives of the mission. The separation of the different components of the foreground emissions requires a broad frequency coverage. The proposed mission will incorporate eight frequency bands provided by four arrays of bolometers at high frequency

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[||] The COBRAS/SAMBA Science Team which carried the study was : M. Bersanelli, C. Cesarsky, L. Danese, G. Efstathiou, M. Griffin, J.-M. Lamarre, M. Mandolesi, H.U. Norgaard-Nielsen, O. Pace, E. Pagana, J.-L. Puget, J. Tauber and S. Volonté. Requests for copies of the relevant report can be obtained from S. Volonté, ESA HQ, 8-10 rue Mario Nikis, PARIS CEDEX 15, FRANCE.

and four arrays of passively cooled tuned radio detectors at low frequency. The 50 bolometers require cooling to ~0.1 K, which will be achieved with an active system similar to the one foreseen for the ESA cornerstone mission FIRST. It combines active coolers reaching 4 K with a dilution refrigeration system working at zero gravity, both being developed and space-qualified in Europe. The refrigeration system will include two pressurized tanks of ^{3}He and ^{4}He, giving an operational lifetime of at least two years.

On the low frequency side, HEMT (High Electron Mobility Transistors) amplifiers give the required sensitivity to detect temperature anisotropies of the cosmological background at all angular scales larger than $0\overset{\circ}{.}5$. The frequency and angular coverage will provide good overlap with the COBE-DMR maps.

The frequency band at which the foreground emission is the lowest (~130 GHz) will be covered by both the tuned radio receivers and the bolometers. The fact that the tuned radio detectors are passively cooled insures that the low frequency channels can be operated for a duration limited only by spacecraft consumables.

COBRAS-SAMBA will be in a small size orbit around the L5 Lagrangian point of the Earth-Moon system, at a distance of about 400 000 km from both the Earth and the Moon. The choice of a far-Earth orbit is a distinctive feature of this mission and allows to reduce below significance level the potential contamination from Earth radiation and straylight, which is critical at the goal sensitivities. Compared to a low-Earth orbit, the requirement on side-lobe rejection drops from 10^{-13} to 10^{-9}. The L5 orbit is also very favorable from the point of view of passive cooling and thermal stability as the satellite will always point within ±40° of the anti-solar direction.

The requirement of coverage of a large fraction of the sky is obtained by offsetting the optical axis of the telescope by 30° with respect to the spin axis of the satellite. In the basic configuration, the spin axis is the major axis of symmetry of the spacecraft, and is directed along the line joining the satellite and the Sun. In this nominal position, the optical axis scans a circle of diameter 60° , centered on a point in the ecliptic plane in the anti-Sun direction. In one year, the observed circle sweeps the whole ecliptic. To increase the sky coverage, the spacecraft rotation axis will be moved away from the ecliptic plane by up to ±40° .

Center Frequency	31.5	53	90	125	140	222	400	714
Detector Technology	HEMT arrays				Bolometer arrays			
Detector Temperature	~100 K				0.1-0.15 K			
Number of Detectors	13	13	13	13	8	11	16	16
Angular Resolution	30	30	30	30	10.5	7.5	4.5	3
Optical Transmission	1	1	1	1	0.3	0.3	0.3	0.3
Bandwidth ($\frac{\Delta\nu}{\nu}$)	0.15	0.15	0.15	0.15	0.4	0.5	0.7	0.6
$\frac{\Delta T}{T}$ Sensitivity (1σ, 10^{-6} units, 2 years)								
90% sky coverage	1.7	2.7	4.1	7.2	0.9	1.0	8.2	10^4
2% sky coverage	0.6	0.9	1.4	2.4	0.3	0.3	2.7	5000

Table I: Payload Characteristics. Frequencies are in GHz, Angular Resolutions in arc minute.

The coverage of the sky is not uniform in terms of integration time per pixel. However, the motion of the spin axis can be chosen in such a way as to give deeper integrations in chosen parts of the sky. The regions of lowest galactic emission are of particular interest for the anisotropy measurement, and many of them will be observable during the mission. Table I shows the estimated average sensitivities per pixel at the end of the two year baseline mission, for each frequency channel, assuming an observing strategy as sketched above. The pixel size for each channel is also given in Table I.

A less ambitious version is studied by the French Space Agency (CNES) in collaboration with laboratories in UK, Italy and USA. It relies only on bolometers cooled to 100 mK with the same technique as in COBRAS-SAMBA mission and plans to include only 5 wavelengths channels. It is based on a 80-cm telescope placed in a polar sun-synchronous orbit.