IL NUOVO CIMENTO Vol. 20 C, N. 5 Settembre-Ottobre 1997

The COBRAS/SAMBA space mission(*)

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(ricevuto il 5 Dicembre 1996; approvato il 27 Febbraio 1997)

Summary. — COBRAS/SAMBA is an ESA mission designed for extensive, accurate mapping of the anisotropies of the Cosmic Background Radiation, with angular sensitivity from sub-degree scales up to and overlapping with the COBE-DMR resolution. This will allow a full identification of the primordial density perturbations which grew to form the large-scale structures observed in the present universe. The COBRAS/SAMBA maps will provide powerful tests for the inflationary model and decisive answers on the origin of cosmic structure. A combination of bolometric and radiometric instrumentation will ensure the sensitivity and wide spectral coverage required for accurate foreground discrimination. A far-Earth orbit has been selected to minimize the unwanted emission from the Earth. The project is currently in the Phase A study within the European Space Agency M3 programme.

PACS 96.40 – Cosmic rays.
PACS 01.30.Cc – Conference proceedings.

(*) Paper presented at the VII Cosmic Physics National Conference, Rimini, October 26-28, 1994.

1. – Introduction

In April 1992 the COBE team announced the detection of intrinsic temperature fluctuations in the CBR at angular scales larger than $\sim 7^\circ$, with brightness amplitude $\Delta T/T \sim 10^{-5}$ (Smoot *et al.*, 1992). These fluctuations have been interpreted as due to the Sachs-Wolfe effect (Sachs and Wolfe, 1967) and yield information on the spectrum of primordial density fluctuations. This result represents a major milestone for cosmology and establishes the inflationary Big Bang model as the theoretical paradigm. The angular resolution of COBE-DMR, however, provides no direct information on scales that correspond to any of the structures observed in the present universe. The COBE-DMR angular resolution corresponds to present day physical size $\lambda \gtrsim 1000\ h^{-1}$ Mpc, or about 100 times larger than the scales typical of clusters of galaxies. The COBRAS/SAMBA mission is designed to image nearly the whole sky with resolution $\sim 10'$–$30'$ and with sensitivity approaching $\Delta T/T \sim 10^{-6}$. These observations will provide decisive answers to several major open questions relevant to the structure formation epoch and will provide powerful tests for the inflationary model.

The COBRAS/SAMBA mission is the result of the merging of two proposals presented in 1993 to the European Space Agency *M3 Call for Mission Ideas*: COBRAS (Cosmic Background Radiation Anisotropy Satellite; Mandolesi *et al.*, 1993) and SAMBA (Satellite for Measurements of Background Anisotropies; Puget *et al.*, 1993). The COBRAS/SAMBA team completed the ESA assessment study in May 1994, and the project has been selected for the Phase A study.

2. – Scientific objectives

The COBRAS/SAMBA mission will produce near all-sky maps of the background anisotropies in 8 frequency bands in the range 30–800 GHz, with peak sensitivity $\Delta T/T \sim 10^{-6}$. Individual hot and cold regions should be identified above the statistical noise level, at all angular scales from $\lesssim 10'$ up to very large scales, thus providing a high-resolution imaging of the last scattering surface. It is the information contained in this wide range of angular scales (or large number of multipoles in a spherical harmonics decomposition) that can probe the various proposed scenarios of structure formation and the shape of the primordial fluctuation spectrum.

The statistics of the $\Delta T/T$ distribution as observed by COBRAS/SAMBA will provide a key test for structure formation mechanisms. The inflationary model predicts Gaussian statistics for the fluctuations of the CBR anisotropies, while alternative models based on the presence of topological defects predict non-Gaussian statistics (*e.g.*, Coulson *et al.* 1994). The angular resolution and sensitivity of COBRAS/SAMBA will allow discrimination between these alternatives.

Extensive measurements with a wide range of angular scales will allow an accurate measure of the spectral index n of the primordial fluctuation spectrum:

$$(\delta\phi)^2 \propto \lambda^{(1-n)}\,,$$

where $\delta\phi$ is the potential fluctuation responsible for the CBR anisotropies, and λ is the scale of the density perturbation. The proposed observations will be able to verify accurately the scale-invariant "Harrison-Zel'dovich" spectrum ($n = 1$) predicted by inflation. The COBE-DMR limit on the spectral index after two years of observations

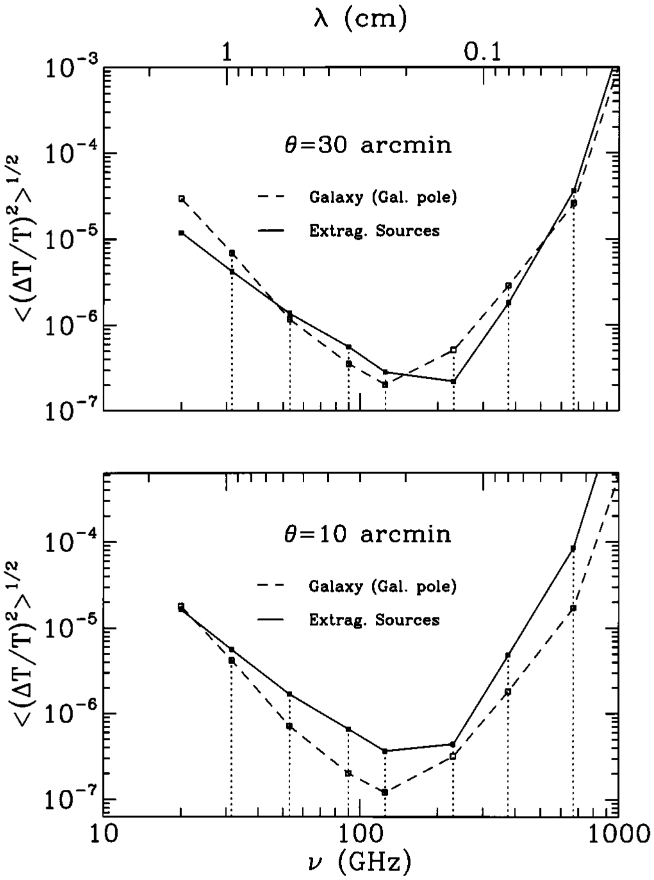

Fig. 1. – Estimated fluctuation levels due to galactic polar emission (dashed lines) and to extragalactic sources (solid lines), from Toffolatti *et al.* (1994). The vertical dotted lines show the COBRAS/SAMBA frequencies.

($n = 1.1^{+0.3}_{-0.4}$, 68% CL; Gorski *et al.*, 1994) can be constrained ∼ 10 times better by the COBRAS/SAMBA results.

Temperature anisotropies on large angular scales can be generated by gravitational waves (tensor modes), in addition to the energy-density perturbation component (scalar modes). Inflationary models predict that the ratio of the tensor and scalar mode anisotropies is related to the spectral index n (*e.g.*, Davis *et al.*, 1992). The COBRAS/SAMBA maps will allow to verify this relationship, since the temperature anisotropies from scalar and tensor modes vary with multipoles in different ways.

Small angular scale anisotropies are sensitive to the ionization history of the universe (*e.g.*, Sugiyama *et al.*, 1993). They can be erased if the intergalactic medium underwent reionization at high redshifts. Temperature anisotropies at sub-degree scales depend on key cosmological parameters, such as the initial spectrum of irregularities, the baryon density of the universe, the nature of dark matter, and the geometry of the universe (see, *e.g.*, Crittenden *et al.*, 1993; Bond *et al.*, 1994; Kamionkowski *et al.*, 1994). The COBRAS/SAMBA maps will provide constraints on these parameters within the context of specific theoretical models.

Finally, the high-resolution, high-frequency channels will measure the Sunyaev-Zel'dovich effect for more than 1000 rich clusters. Combined with X-ray observations these measurements can be used to estimate the Hubble constant H_0.

3. – Foreground radiation

The temperature fluctuations measured by a CBR anisotropy experiment need to be well understood in terms of the various components that add to the CBR signal. Foreground structures are caused by unresolved extragalactic sources, galactic radiation (interstellar dust, free-free and synchrotron radiation), and interplanetary dust (fig. 1). The COBRAS/SAMBA observations will be performed near the minimum foreground emission, and will reach the required control on the various components in two ways. First, the large sky coverage will allow accurate modeling of these foregrounds where they are dominant. Second, the observations will be performed in a spectral range as broad as possible. The frequency channels will span the spectral region of minimum foreground intensity (50–300 GHz), but with enough margin at high and low frequency to monitor "in real time" the effect of the various foreground components (see, *e.g.*, Brandt *et al.*, 1994). By using the COBRAS/SAMBA spectral information and modeling the spectral dependence of galactic and extragalactic emissions it will be possible to remove the foreground contributions with high accuracy. In the high-frequency channels ($\nu \gtrsim 140$ GHz) the main foreground components will be dust emission, while towards the low-frequency range ($\nu \lesssim 70$ GHz) galactic synchrotron and free-free emission become increasingly important (Toffolatti *et al.*, 1995).

In most COBRAS/SAMBA channels the final limitation to the cosmological information is expected to be due to the residual uncertainties in the separation of the foreground components rather than statistical noise. Therefore the overall design of the instrument and payload is highly driven by the need of achieving a spectral coverage as wide as possible. Performing measurements where the dominant foreground components are different will permit a powerful cross check on residual systematic errors in the CBR temperature fluctuation maps.

4. – The payload

The COBRAS/SAMBA model payload (see fig. 2) consists mainly of a shielded, off-axis Gregorian telescope, with a parabolic primary reflector and a secondary mirror, leading to an integrated instrument (Focal Plane Assembly, FPA). The payload is part of a spinning spacecraft, with a spin rate of 1 rpm. The focal plane assembly is divided into low-frequency (LFI) and high-frequency (HFI) instrumentation according to the technology of the detectors, each covering four observing bands (see table I). The highest-frequency LFI channel and the lowest HFI channel overlap near the minimum foreground region.

A clear field of view is necessary for the optics of a high-sensitivity CBR anisotropy experiment to avoid spurious signals from the mirrors or from supports and mechanical mounting. A Gregorian configuration has been chosen, with a primary parabolic mirror of 1.5 m, and an elliptic secondary mirror (0.57 m diameter). Stray satellite radiation and other off-axis emissions are minimized by underilluminating the low-emissivity optics. Blockage is a particularly important factor to avoid the effect of local radiation (*e.g.* from the Earth, the Sun and the Moon). A large, flared shield surrounds the entire telescope

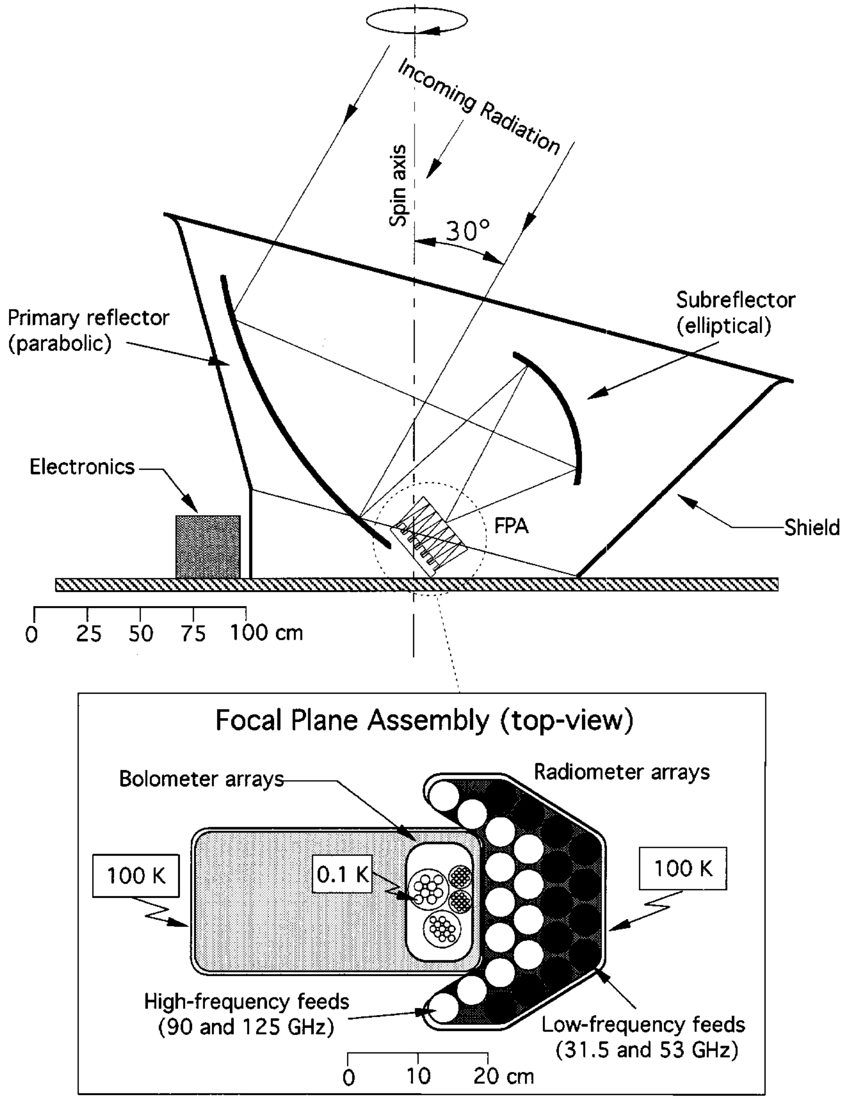

Fig. 2. – System diagram of the COBRAS/SAMBA payload, showing the concept of the shielding and optics design. The inset shows a top view of the Focal Plane Assembly, with the bolometric system (HFI) cooled at 0.1 K, sharing the focal plane with the arrays of passively cooled feed horns (LFI).

and FPA, to screen the detectors from contaminating sources of radiation. The shield also plays an important role as an element of the passive thermal control of the spacecraft.

The necessary wide spectral range requires the use of two different technologies, bolometers and radiometers, incorporated in a single instrument. Both technologies have shown impressive progress in the last ten years or so, and more is expected in the near future.

4·1. *The low-frequency instrument.* – The LFI consists of an array of 26 corrugated, conical horns, each exploited in the two orthogonal polarization modes, feeding a set of

TABLE I. – *Payload characteristics.*

Telescope	1.5 m diameter Gregorian; system emissivity 1% Viewing direction offset 30° from spin axis							
Instrument	LFI				HFI			
Center frequency (GHz)	31.5	53	90	125	140	222	400	714
Wavelength (mm)	9.5	5.7	3.3	2.4	2.1	1.4	0.75	0.42
Bandwidth ($\frac{\Delta\nu}{\nu}$)	0.15	0.15	0.15	0.15	0.4	0.5	0.7	0.6
Detector technology	HEMT receiver arrays				Bolometers arrays			
Detector temperature	$\sim$ 100 K				0.1–0.15 K			
Cooling requirements	Passive				Cryocooler + dilution system			
Number of detectors	13	13	13	13	8	11	16	16
Angular resolution (arcmin)	30	30	30	30	10.5	7.5	4.5	3
Optical trasmission	1	1	1	1	0.3	0.3	0.3	0.3
$\frac{\Delta T}{T}$ Sensitivity ($1\sigma, 10^{-6}$ units, 90% sky coverage, 2 years)	1.7	2.7	4.1	7.2	0.9	1.0	8.2	10^4
$\frac{\Delta T}{T}$ Sensitivity ($1\sigma, 10^{-6}$ units, 2 % sky coverage, 2 years)	0.6	0.9	1.4	2.4	0.3	0.3	2.7	5000

state-of-the-art, high-sensitivity radio receivers. The receivers will be based on MMIC (Monolithic Microwave Integrated Circuits) technology with HEMT (High Electron Mobility Transistor) ultra-low noise amplifiers (see, *e.g.* Pospieszalski, 1993). Since the whole LFI system will be passively cooled, it can be operated for a duration limited only by spacecraft consumables (up to 5 years). The three lowest center frequencies match the COBE-DMR channels.

4·2. *The high-frequency instrument.* – About 50 bolometers will be used in the HFI instrument, which require cooling at ~ 0.1 K. The cooling system combines active coolers reaching 4 K with a dilution refrigeration system working in zero gravity. The refrigeration system will include two pressurized tanks of ^{3}He and ^{4}He for an operational lifetime of 2 years.

5. – Orbit and observation strategy

COBRAS/SAMBA will operate from a far-Earth orbit to avoid unwanted radiation from the Earth, a serious potential contaminant at the high goal sensitivity and angular resolution. Adopting a low-Earth orbit, such as that used by the COBE satellite, the requirement on straylight and sidelobe rejection (for both LFI and HFI) would be a factor of 10^{13}, which is beyond the capabilities of present microwave and sub-mm systems and testing equipment. COBRAS/SAMBA will operate from a small 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. From this location the required rejection is relaxed by four orders of magnitude, which is achievable with careful, standard optical designs. The selected L5 orbit is also very favorable from the point of view of passive cooling and thermal stability (Farquhar and Dunham, 1990). The telescope optical axis is offset by 30° from the spin axis. Thus at each spacecraft spin rotation the telescope pointing direction sweeps a 60° circle in the sky. The spacecraft will be normally operated in the anti-solar direction, with part of the sky observations performed within ±40° from anti-solar.

The main goal of the mission is to observe nearly the whole sky ($\gtrsim 90\%$) with a sensitivity of 10–15 μK within the two year mission lifetime. Deeper observation of a limited ($\sim 2\%$) sky region with low foregrounds would significantly contribute to the cosmological information. Preliminary simulations have shown that these observational objectives can be achieved simultaneously in a natural way, using the spinning and orbit motion of the spacecraft, with a relatively simple scheme.

6. – Conclusions

An accurate, extensive imaging of CBR anisotropies with sub-degree angular resolution would provide decisive answers to several major open questions on structure formation and cosmological scenarios. While ground-based and balloon-borne experiments provide very important results, the observational requirements for a full characterization of the primordial CBR anisotropy can be met only by a carefully planned space mission with a far-Earth orbit (*e.g.*, Danese *et al.*, 1996)

The assessment study has shown that a mission combining bolometric and radiometric technologies is feasible within the European Space Agency Medium Mission scope, thus ensuring a powerful control over foreground structures and other potential systematic effects. The wide spectral range (30–800 GHz), limited only by the unavoidable galactic and extragalactic emissions, the sensitivity to a very broad spectrum of angular scales ($\sim 10'$ to several degrees), and the choice of the L5 Lagrangian orbit are the main features that characterize the COBRAS/SAMBA mission.

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Several people contributed to the work so far accomplished. In particular we acknowledge all the researchers and groups who supported the original COBRAS and SAMBA proposals, and the ESA staff members at Estec and Esoc who have contributed to the Assessment Study.

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