Part X

New Observational Approaches

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Beyond FIRST and Planck

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Abstract. Prospects for future satellite missions, operating in the FIR-mm wavelength region, to study the polarisation of the cosmic background radiation (CBR) and to carry out imaging and spectroscopy of high-redshift galaxies, are discussed. Full characterisation of the CBR polarisation offers the possibility of determining the energy scale of inflation and constraining the form of the inflaton potential. Current technology in FIR imaging and spectroscopy falls well short of matching capabilities in the optical/UV and the mm regions. Filling this gap is important to allow detailed examination of the physics and evolution of high-redshift galaxies, and will be possible with future FIR observatories which are now being studied.

1. Introduction

Advances in observational capabilities in the FIR and submm range are now making it possible to investigate the early universe through measurements at these wavelengths. After the successes of IRAS and ISO, planned satellites include SIRTF, Astro-F, FIRST, and Planck surveyor. The third-generation CBR satellite mission, Planck, will make the definitive measurement of the angular power spectrum of temperature anisotropies, and will also reveal some of the information expected to be encoded in the polarised components of the anisotropies. Deep surveys by ASTRO-F, SIRTF and FIRST will detect many thousands of high redshift galaxies out to redshifts of around five. In order to take advantage of the full potential of the FIR-mm region, a new generation of satellite missions will be needed. After Planck, an experiment devoted to sensitive measurement of the CBR polarisation could be a unique probe of the history and physics of the very early universe; and a long-baseline FIR space interferometer would allow access to the epoch of galaxy formation and early evolution with observational capabilities comparable to those that are currently brought to bear on the local universe.

2. Cosmic background polarisation anisotropy measurements

The recent spectacular results of BOOMERanG and MAXIMA (de Bernardis et al. 2000; Lange et al. 2000; Hanany et al. 2000) have supported inflation and cold dark matter models as the favoured theory describing the early universe and accounting for the origin of large-scale structure. These results emphasise the power of CBR anisotropy measurements as a powerful probe of the early evolution of the universe and of fundamental physics at high energy. They also provide strong support for the MAP and Planck missions by showing experimentally that they are on the right track, and they give us a foretaste of what MAP and Planck will do.

For the curl-free (E-mode) polarised component of the CBR anisotropies, imprinted by scalar fluctuations, MAP is expected to produce a clear detection, and Planck to produce a high S/N measurement of the power spectrum (e.g. Tegmark et al. 2000). The polarisation measurements will allow more accurate estimation of the cosmological parameters than the temperature anisotropies alone, and will probe the ionisation history of the universe through its effects on polarisation on large angular scales. But that will not necessarily be the final story. Detection of the curl component (B-mode, due to tensor fluctuations) of the CBR polarisation, which is something that is probably beyond the capabilities of Planck, would constitute observation of anisotropy structure imprinted on CBR by primordial gravitational waves. The importance of CBR measurements for fundamental physics at high energy has been reviewed by Kamionkowski & Kosowski (1999), and the prospects for measuring the B-mode polarisation power spectrum are discussed by Kinney (1998). The strength of the B-mode component depends on the energy scale of inflation and so on the form of the inflaton potential. Inflation models can be characterised by the r-n plane, where r is the ratio of the tensor to scalar quadrupole amplitudes and n is the spectral index of the scalar fluctuation spectrum (which is just less than one for most models). Planck with polarisation can place strong constraints on the parameter space for large values of r. But if r is small, corresponding to inflation at low energy, then it would take a more sensitive experiment to constrain it. If the energy scale of inflation is very low, then the B-mode component may not be detected at all - but an upper limit would place a strong constraint on the energy scale.

2.1. Requirements for ultimate CBR polarisation experiment

Measurement of the B-mode polarisation component poses a formidable experimental challenge - a typical model (e.g., Kinney 1998) involves a maximum amplitude which is more than four orders of magnitude smaller than that of the temperature anisotropies (which have only recently been crudely characterised).

The optimum wavelength range for CBR anisotropy measurement is a few mm, where the CBR spectrum is near its peak and the foreground contamination is lowest (e.g., Tegmark et al. 2000). A reasonable spectral bandwidth is about 25%, giving a good compromise between sensitivity and ability to control the beam. Ideally, the detectors are polarisation-sensitive and the photon noise from the CBR itself dominates. Under these conditions, the required detector NEP of a few $\times 10^{-18}$ W/$\sqrt{\text{Hz}}$ is not challenging to achieve with current technology. Therefore, the only way to achieve the very high sensitivity levels required for accurate polarisation measurements is to use a large array of detectors.

The current state-of-the-art for CBR detector technology is represented by the Planck HFI feed/bolometer system (Church et al. 1996; Griffin 2000). This uses a triple-horn arrangement. The first horn defines the illumination of the telescope in a way that is unaffected by any additional components between the feed and the telescope; the second horn expands the beam to allow quasi-optical filtering; and the final horn re-condenses the beam onto an NTD germanium bolometer. This configuration works well but is complex and bulky, and not really suitable for large arrays. A more desirable detector feed configuration, which requires some development, could use a single horn with the output waveguide coupled to a superconducting bolometer via a transmission line circuit incorporating appropriate microwave circuit elements to define the spectral passband. Some elements of this design have already been demonstrated (e.g., Yassin et al. 2000). Such a configuration could have a number of important advantages for large arrays: smaller size, easier mass production, higher overall efficiency, and comparable sensitivity or speed at a higher operating temperature through the use of superconducting detectors.

An instrument optimised for CBR polarisation measurement will incorporate as many as possible of the following features: (i) angular resolution comparable to that of Planck; (ii) multiple detectors to provide the highest possible mapping speed; (iii) superconducting detectors, which can have better sensitivity per detector (or the same sensitivity at a higher operating temperature); (iv) polarisation-sensitive detectors; (v) pairs of detectors observing with the same beam on the sky in orthogonal polarisations (so they should view the telescope through the same beam-defining antenna); (vi) filtering effected by microwave circuits instead of quasi-optically; (vii) multi-frequency observations for effective foreground characterisation

It remains to be seen whether CBR polarisation can be adequately characterised from the ground or whether this project will require a fourth-generation CBR space mission. Ground-based experiments are relatively cheap and can have high per-pixel sensitivity, but inevitably have limited sky and wavelength coverage, and are prone to atmospheric and systematic effects. Space-borne experiments are expensive, but can have much greater sky and wavelength coverage, and better control of systematics.

The compromise between per-pixel sensitivity and sky coverage has been investigated by Jaffe et al. (1999). Their Fig. 2 shows that, for an experiment optimised for B-mode detection, the best final sensitivity is achieved by concentrating the integration time on a fairly small region of sky (about 10 sq. deg. in their example). Likewise, the ability of the planned QUARTS/CMBPol ground-based experiment to make a detection of the tensor component could be comparable to that of Planck HFI (S. Church, private communication). However, such comparisons must be regarded as highly speculative at present, when polarisation in the CBR has yet to be detected, let alone mapped at a sensitivity level several orders of magnitude better than current limits, and potential problems of polarised foreground subtraction and suppression of systematic effects are largely unexplored.

Many earth-based CBR polarisation experiments are now operational or planned (see Staggs et al. 1999 for a recent review). We can expect incremental progress in the coming years from these and similar endeavours. Ground and balloon experiments will pave the way for Planck measurements, as is already happening for the temperature anisotropy measurements. The ultimate CBR experiment may well need a fourth generation space experiment to minimise systematics and achieve a good combination of wavelength coverage, sky coverage, and sensitivity. The justification for this would be the huge information content of the polarisation signal on the very early history of the universe and the light it can shed on fundamental physics.

3. Far infrared and submillimetre study of high-redshift galaxies

CBR anisotropy measurements will reveal a great deal about the history of the universe up to the era decoupling of matter and radiation. On fine angular scales, measurements of spectral and spatial distortions due to intervening ionised gas, using the CBR as a well-understood backlight, will also allow the early evolution of large scale structure to be explored (e.g., Peterson et al. 1999). However, after the decoupling of matter and radiation, the behaviour of the universe became increasingly dominated by non-linear processes, and it is unlikely that theoretical modelling of galaxy formation and evolution, no matter how sophisticated it becomes, will ever be a substitute for direct observation of that epoch.

The extragalactic background radiation (e.g., Gispert, Lagache, & Puget 2000), contains roughly as much energy in the FIR as in the well-studied IR-UV region, due to the conversion of gravitational energy and stellar radiation into FIR radiation from interstellar dust and gas. For high-redshift galaxies, the FIR thermal peak is redshifted into the submm band: its observation is thus facilitated by the strong negative K-correction that results in a very weak dependence of observed flux density on redshift. An advantage of this is that the submm band is potentially very powerful for probing the high-redshift universe; a disadvantage is that submm photometric detections alone provide only very poor constraints on redshift, and require spectroscopic follow-up if the location or nature of the emitting source is to be clarified.

In comparison to the optical/NIR region, observational capabilities at FIR and submm wavelengths are very primitive at present. To see this, one only needs to compare the image of the Hubble deep field as observed by the HST itself and as observed by SCUBA on the JCMT, the world's premier submm camera (Hughes et al. 1998). An optical instrument operating under equivalent conditions to SCUBA would fit inside a 1-mm size box. It would contain a state-of-the-art detector array with around 100 pixels, and would view the sky through a 1-cm telescope at a temperature of 6000 K. Improved sensitivity and angular resolution in the FIR, equivalent to what is now achieved at shorter wavelengths, would clearly allow us to investigate the high-redshift universe in much more detail. This requires the combination of cold telescopes, to reduce the thermal background, and long-baseline interferometry to provide the necessary angular resolution.

SIRTF, ASTRO-F and FIRST will make great advances in surveying galaxies out to redshifts of five or so; but, being limited either by aperture size or thermal background, they will lack the sensitivity and angular resolution needed to study their detailed physics and chemistry in the same way that we can currently do for nearby galaxies. On the ground, ALMA will provide high angular resolution and sensitivity in the mm-submm region, but due to atmospheric and technical limitations it will not probe the short submm/FIR region which contains the bulk of the energy emitted by high-redshift dusty galaxies.

Progress towards these long-term aims will be made incrementally, with significant advances at each stage. Following FIRST, the next step will be to have a reasonably large cold aperture, as proposed for the Japanese HIIL2 mission (Nakagawa et al. 1998). The scientific and technical case for a 10-m class cold-aperture FIR telescope is detailed by Rieke et al. (1999). A cold 10-m telescope would close the sensitivity gap between optical/IR (NGST) and millimetre (ALMA) regions, and allow the individual galaxies contributing to the FIR background to be detected; but it would still have angular resolution two orders of magnitude short of what is required for detailed imaging. Achieving comparable sensitivity with much better angular resolution requires an interferometer with a far longer baseline - up to 1 km. As pointed out by Leisawitz et al. (2000), the photon rate at FIR wavelengths is such that a large collecting area is not essential, so only a few dishes are needed. The SPECS concept (Leisawitz et al. 2000; Shao et al. 2000) involves a number of 3-m class cold antennas with adjustable spacing for good u-v plane coverage and tethers for economical formation flying. Equipped with next-generation detector arrays (e.g., Shoelkopf et al. 2000), such a facility would be able to carry out sensitive imaging and spectroscopy of high-redshift galaxies.

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