times is not a realistic option, this signal must be removed by a combination of processing, e.g., filtering, exploitation of multi-frequency or multi-detector observations with analysis methods such as those discussed in Refs. (59) or (60), and polarisation modulation with a rotating half-wave-plate. Current observations demonstrate that polarisation modulation can reduce this signal by 2–3 orders of magnitude in amplitude. Even then, residuals are still at a challenging 3 orders of magnitude above the target sensitivity on 2° angular scales. The situation is even worse at larger scales and/or at higher frequencies.

A space mission completely avoids the complexity of atmospheric absorption, emission, and fluctuations. More details about the atmosphere can be found in Appendix A.

4.1.2 Astrophysical foregrounds

CMB observations must address the problem of astrophysical foreground emission. At frequencies below about 100 GHz CMB observations are contaminated by a complex mixture of low-frequency astrophysical sources of electromagnetic radiation that include Galactic synchrotron, free-free, and anomalous dust emission (presumably spinning dust, or possibly magnetic dust, or both), as well as numerous extragalactic radio sources, while at frequencies above about 100 GHz thermal dust emission is the dominant foreground. At frequencies above approximately 200 GHz, in addition to thermal dust emission, anisotropies of the cosmic infrared background (CIB), and to a lesser extent zodiacal-light emission dominate the fluctuations of the observed sky brightness over most of the sky. Molecular lines, notably those of carbon monoxide at multiples of 115 GHz, clearly seen in *Planck* data (61), must also be taken into account (as well as those of isotopologues at nearby frequencies, ^{13}CO and C^{17}O near multiples of 110 GHz, C^{18}O near multiples of 112 GHz). Several lines of CO emission, at about 220, 225 and 230 GHz, are located in one of the main atmospheric windows.

Of all of those foregrounds, synchrotron is the one that is known to be the most polarised (in theory, up to 75%). At high frequency, only thermal dust is known to be very clearly polarised ($\gtrsim$10%). Other sources of emission can be somewhat polarised (at a level $\lesssim$1%).

While for temperature fluctuations there are regions where CMB signals strongly dominate over astrophysical foregrounds, this is not the case for polarisation (see figure 1). To remove foreground contamination, it is necessary to observe the sky at several frequencies and exploit the fact that the emission law of the CMB is substantially different from that of most foreground emission processes (62). Exploiting these colour differences is best done by combining observations in a set of well chosen different frequency bands. *COBE*-DMR observed the sky in three different frequency bands, *WMAP* in five, and *Planck* in nine. To exploit the largest possible fraction of the sky at a sensitivity level at least an order of magnitude better than *Planck*, even more frequency bands will be required.

Although the details will be known only with observations at the appropriate level of sensitivity, i.e., with future CMB data themselves, a simple accounting argument suggests that no less than ten channels are required, and preferably more. The two main known polarised Galactic emission sources in the frequency range of interest are synchrotron and thermal dust. To model the synchrotron (parameterised in each sky pixel by intensity, spectral index, and possible curvature of spectral index), at least three low-frequency channels are required, four to provide some redundancy, or even more if one has to model synchrotron emission with more than one simple emission law per pixel. The same is true for thermal dust at high frequency, for which at least three parameters per pixel are needed to adjust a model with a single modified blackbody emission law. Four channels at least are needed to make this measurement, with an extra channel for a consistency check. This means that a total of eight channels are needed to model the foreground emission if only synchrotron and dust must be taken into account. On top of this, thermal dust emits with more than one population of grains so it is possible that a single modified blackbody is not sufficient for a model that is accurate at the $\lesssim$1% level. Finally, the CMB itself must be observed in at least two frequency bands that are sufficiently distant in frequency for a useful cross-check, which is essential to detect possible residual foreground emission, and preferably more bands to understand the origin of any discrepancy (*Planck* effectively used comparisons between the CMB seen in three channels, at 100, 143, and 217 GHz, to investigate foreground residuals and systematic errors). The conclusions is that ten channels is the absolute minimum to monitor foreground emission in polarisation.

There is no way for this number of frequency channels, which must be well spread over the useful frequency range, to be accommodated in only four atmospheric windows. While synchrotron can in principle be observed from the ground at a few frequencies $\nu \lesssim 30$ GHz, thermal dust emission, which dominates at frequencies where the observing conditions from the ground are poor, must be mapped from space (or, as an intermediate solution, from stratospheric balloons, which, however, have significant residual atmospheric noise, less flexibility for choosing the observing strategy, and much reduced observing time compared with a space mission).

4.1.3 Systematic effects

Very precisely controlling systematic effects due to non-idealities in the instrument, which are a potential major source of error for future sensitive CMB observations, is mandatory for achieving the science goals of future CMB polarisation observations. Instrumental imperfections include complex response of the instrument to external radiation or stimuli. Such non-idealities impact the shape of the response in time, in space (beams), or in frequency (bandpass); in practice these can be different from the design specifications and can be mismatched between detectors. There can also be gain fluctuations, susceptibility to events that are not related to the observations (such as cosmic ray hits), magnetic susceptibility, variations of the observing environment that impact the detector response, etc. To minimise such effects, space offers unmatched observing conditions, in an extremely stable environment. This allows for:

- minimising sidelobe pickup of emission from the Earth, Sun, and Moon;
- minimising thermal fluctuations of parts of the instrument that are optically coupled to the detectors;
- avoiding fluctuations of the response of the instrument, which is essential for enabling the calibration of instrumental imperfections at the level of accuracy required to correct for their impact on the CMB science.

4.1.4 Why space – summary

Sub-orbital CMB observations have been key pathfinders in CMB science, from the initial detection of the CMB more than fifty years ago to now. However, it also is true that all the major steps forward have been achieved by space missions. *COBE*-DMR, *WMAP*, and *Planck* have all been transformational for cosmology: *COBE* confirmed the blackbody spectrum of the CMB, ruling-out alternatives to the hot Big-Bang scenario, and detected the first temperature anisotropies that were required to explain the origin of structures; *WMAP* set the stage for precision cosmology; and *Planck*, in turn extracted essentially all cosmological