Balloon-borne Cosmic Microwave Background experiments

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Abstract. Stratospheric balloon experiments play a unique role in current Cosmic Microwave Background (CMB) studies. CMB research has entered a precision phase, harvesting the detailed properties of its anisotropy, polarization and spectrum, at incredible precision levels. These measurements, however, require careful monitoring and subtraction of local backgrounds, produced by the earth atmosphere and the interstellar medium. High frequencies (larger than 180 GHz) are crucial for the measurements of interstellar dust contamination, but are degraded by atmospheric emission and its fluctuations, even in the best (cold and dry) sites on earth. For this reason, new balloon-borne missions, exploiting long-duration and ultra-long duration stratospheric flights, are being developed in several laboratories worldwide. These experiments have the double purpose of qualifying instrumentation and validating methods to be used on satellite missions, and produce CMB science at a relatively fast pace, synergically to ground-based CMB observatories.

1 Introduction

The Cosmic Microwave Background (CMB) is a faint background of thermal mm-wave photons, filling the entire Universe. These photons where generated a few milliseconds after the big bang, when matter and antimatter annihilated. They were thermalized by repeated Thomson scatterings in the primeval ionized fireball, during the first 380000 years. Later, neutral hydrogen atoms could form, and the universe became neutral (last scattering). At that point CMB photons formed a dazzling 3000K blackbody: the universe was everywhere like in the atmosphere of a red supergiant star. Since then, CMB photons did not interact with matter anymore, and were diluted, and redshifted, due to the expansion of the universe. Today they form a 2.725K blackbody. Having traveled in the Universe for most of its history, CMB photons carry important information on all phases of its evolution, through three main observables: the spectrum, the anisotropy, the polarization.

The power spectra of intrinsic (primary) CMB anisotropy is perfectly well fit by an Inflationary, Λ-CDM universe (see e.g. [1–9]).

The CMB is slightly polarized, due to anisotropic Thomson scattering at recombination. The component due to density fluctuations (irrotational E-modes) has been measured and is consistent with expectations (see e.g. [10–15]). The component due to tensor fluctuations (the gravitational waves generated by the hypothetical inflation phase in the very early universe), called inflationary B-modes due to their rotational nature, is still to be measured, and there are many on going and planned

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missions focusing on this challenging measurement, from the ground, from stratospheric balloons, and from space (see e.g. [16]).

During their long travel, crossing half of the observable cosmos, CMB photons interact with the large scale structure of the universe. These secondary interactions provide additional precision observables of the CMB. Gravitational lensing of CMB photons provide a way to study the development of dark matter structures in the earliest phases of the structure formation process, exploiting the resulting distortion of the CMB anisotropy map (see e.g. [17]). This same effect produces B-modes of the CMB polarization field at small angular scales (see e.g. [18] and references therein). In addition, ionized structures in the universe (clusters of galaxies, filaments) produce inverse Compton scattering in CMB photons (the Sunyaev-Zeldovich effect, [19, 20]), which can be isolated exploiting its well defined and characteristic spectral distortion.

The specific brightness of a 2.725K blackbody peaks at a frequency of 159 GHz. In this high frequency microwaves band, the Earth atmosphere is only partially transparent, and only in the best sites (extremely cold and dry locations). As a result, the long-wavelength side of the CMB spectrum can be accessed quite efficiently from the ground, but the short-wavelength side cannot. Moreover, the emission of interstellar dust, a polarized foreground contaminating precision measurements of the CMB, rises steeply with frequency, and must be monitored and subtracted to obtain clean CMB measurements (see e.g. [21]). These facts drove the development of balloon-borne measurements of the CMB, carrying high-frequency CMB telescopes (with custom photometers, spectrometers and polarimeters), above the bulk of atmospheric emission and fluctuations, using stratospheric balloons.

2 Stratospheric Balloons

2.1 Generalities

Stratospheric balloons are near-space carriers able to reach altitudes of \( \sim 40 \) km (corresponding to an environmental pressure of \( \sim 3 \) mbar). Conventional stratospheric balloons are not sealed, and the gas pressure inside the balloon is the same as the surrounding atmospheric pressure. These balloons provide flight durations reaching 2 months (long duration stratospheric balloons, LDB), if the solar illumination is stable. Recently operated super-pressure balloons are sealed, and provide much longer flight durations (ultra long-duration flights, ULDBs). The lifted payload masses range from a few kg to more than two tons, depending on the balloons size, ranging from a few thousands cubic meters volume at float, to more than 1 million cubic meters. The heaviest payloads (2 tons) are larger and heavier than what can be reasonably carried by a satellite, at a mission cost which is roughly 100 times less than for a satellite mission. Once launched, operated and terminated, a stratospheric balloon payload is recovered and can be flown again, for improved measurements, after a relatively short amount of time since the first flight. This allows a staged development of the instrumentation, which is not possible in the case of satellite missions. Stratospheric balloons are thus important as precursors of satellite missions. They allow the community to test and qualify innovative space instrumentation, and improve it before using it in space. Last but not least, stratospheric missions are a very good way to educate and prepare students and young researchers. They can participate directly in all phases of the development: from the idea, to optimization, planning, construction, test, calibration, flight, data analysis of the mission.

2.2 Flight Options

We focus on LDBs and ULDBs, since CMB surveys require in general long integrations and the repetition of the measurements in different days, to test their robustness against systematic effects (sun
illumination, ground spillover, etc.). LDB flights are carried out very successfully by NASA-CSBF in the summer season in Antarctica (see [22] and references therein), where a stable vortex allows the payload to circumnavigate the south pole. This is a consolidated facility, flying every summer season a few stratospheric payloads for several weeks flights, thanks to NSF and NASA-CSBF.

The Italian Space Agency has supported a pioneering program to fly LDBs from the Arctic airport of Longyearbyen (Svalbard, 78°N) [23–25]. This allowed to fly two heavy payloads (SORA in 2009 and OLIMPO in 2018) and several lighter payloads (PEGASO, DUSTER), even during the Arctic night season, with a stratospheric environment potentially very appealing for CMB survey experiments [26]. In figure 1 we show the launch of a stratospheric balloon from Svalbard, during the Arctic winter.

![Launch of a stratospheric balloon from Svalbard during the Arctic winter.](image)

Successful ULDB flights have been carried out (https://blogs.nasa.gov/superpressureballoon/) keeping a 700 kg payload in the stratosphere for ~ 46 days, and look very promising for future CMB missions.

### 3 CMB missions on stratospheric balloons

The CMB community exploits the stratospheric environment to carry out sensitive observations at high frequency, high resolution, and at the largest angular scales. This is allowed by the strongly reduced atmospheric emission and noise, compared to the best CMB observation sites on Earth (Atacama desert, Antarctica, ..).

In figure 2 we plot the brightness, and the brightness fluctuations due to quantum fluctuations of the photon background, at different altitudes in the mm-wave band. The advantage of the operation of mm-wave instruments for the CMB from the stratosphere, without even considering atmospheric turbulence, is evident. In terms of achievable photon-noise-limited sensitivity, the improvement at 140 and 220 GHz is more than one order of magnitude, implying a reduction of more than two orders of magnitude of the integration time required for a given measurement. The presence of turbulence in atmospheric emission enhances the balloon environment with respect to ground even more. The high opacity of the Earth atmosphere makes balloon-borne measurements the only sub-orbital option for CMB and interstellar dust measurements at frequencies above 320 GHz.

After a pioneering period at the end of the seventies, a series of very successful balloon-borne CMB missions (see e.g. [1–4]) has been crucial for starting the so-called precision cosmology era. The LDB flight opportunities have been used by the BOOMERanG experiment [1], the TopHAT experiment [27], and more recently by a second generation of array-based CMB polarimeters: EBEX [28–31] and SPIDER [32–34]. Important missions to survey the CMB and polarized dust at high frequencies have been proposed [35].
Figure 2. Left: atmospheric brightness in the mm range. Right: quantum fluctuations of the brightness. Both are shown for different altitudes. The dashed lines in the right panel represent the brightness fluctuations of room temperature optical systems, for low and high extreme values of their emissivity (2 % and 0.1 %).

The OLIMPO experiment [36], a large (2.6m aperture) CMB telescope aimed at spectral measurements of the Sunyaev-Zeldovich effect in the range 120 to 480 GHz, has been launched from Longyearbyen on July 7th, 2018 (see figure 3). This experiment has several innovative features, including the use - for the first time in the stratosphere - of arrays of Kinetic Inductance Detectors [37, 38] and a differential Fourier transform spectrometer [39–41]. See http://olimpo.roma1.infn.it.

Figure 3. Launch (left) and ground path (right) of the OLIMPO mission.

The Short Wavelength Instrument for the Polarization Explorer (SWIPE) is a coarse-resolution balloon-borne CMB polarimeter, part of the Large Scale Polarization Explorer (LSPE) [42] mission, to be flown during the Arctic night. The instrument uses multi-moded TES bolometers [43, 44], sensitive to a total of 8800 radiation modes in the 150, 220, 240 GHz bands, and a cryogenic rotating HWP to modulate CMB polarization [45] and mitigate systematic effects. Its flight is planned for the 2020/2021 season. See http://lspe.roma1.infn.it.
4 Conclusions

Stratospheric balloons offer great opportunities for CMB research. They provide high-frequency measurements, which cannot be obtained from the ground, and are mandatory to remove the contaminating polarized signal from interstellar dust. They allow to validate in near-space the performance of key components for the final CMB polarization mission. They also provide an opportunity for measurements of spectral distortions of the CMB, either isotropic or anisotropic (SZ effect). Their development and availability to the scientific community should be continuously supported.

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