Exploring Cosmic History and Origin

A proposal for a next generation space mission for near-ultimate measurements of the Cosmic Microwave Background (CMB) polarization and discovery of global CMB spectral distortions

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3. Executive summary

In response to the 'Announcement of Opportunity (AO) for future Astronomy mission' (February 3, 2018) by the Indian Space Research Organisation (ISRO), we propose a multifaceted frontier science and astronomy mission to map the sky temperature, linear polarization (~60-1000 GHz) and spectrum (~30-3000 GHz) of the background radiation with unprecedented sensitivity, accuracy and angular resolution. The primary signal is the Cosmic Microwave Background (CMB), which is a nearly isotropic, black-body radiation possessing a temperature of 2.725 K today. The CMB was discovered serendipitously in 1965 and it accounts for almost the entire radiation content of the universe. The CMB photons arriving at us today from different directions in the sky have travelled unimpeded across the observable universe (43 billion light years) and show tiny variations in temperature (of tens of micro-K) referred to as CMB anisotropies, and a net linear polarization pattern at the level of micro-K to tens of nano-K. The CMB anisotropies and polarization are faithfully encoded imprints of the mildly perturbed early universe, making them excellent probes of the primordial universe, cosmic history and the distribution of matter on the largest observable scales.

Sky maps in the CMB frequency range (100-230 GHz) contain very rich and vital cosmological as well as astrophysical information waiting to be extracted from exquisite observations of the CMB polarization that can be carried out only from space. Most of the cosmological information in the CMB temperature fluctuations has been harvested by the Planck mission (ESA, 2009), the third generation of the spectacularly successful CMB space missions following COBE DMR (NASA, 1989) and WMAP (NASA, 2001). This has led us to converge on a standard model of cosmology and determine the parameters involved to a high precision. However, over 90% of the information in the CMB polarization and the entire cosmological information content in the black-body spectrum (virtually unmeasured since COBE-FIRAS) remain essentially untapped. CMB-BHARAT, a 4th generation mission targeting this final frontier of CMB science, implementing further advanced cutting-edge technology now available at high TRL for space, promises a balanced profile of returns that range from potentially pathbreaking scientific discoveries, to high value science and priceless astrophysical data legacy.

A potentially groundbreaking scientific discovery would be to detect the signatures of primordial gravitational waves, which, according to the prevalent paradigm of inflation, are expected to have originated in the early universe, leaving imprints as polarization in the CMB. Accurate measurements of the CMB polarization would therefore reveal ultra-high energy physics, if inflation operates at the energy scale of 10^{16} GeV (about a trillion times than that attained in the Large Hadron Collider!) corresponding to Grand Unified Theories, and would be the first direct evidence of *quantum gravity*. Guaranteed high science returns from measurements of the subtle weak gravitational lensing (WL) signal in the CMB polarization would provide a high signal-to-noise map of the integrated matter distribution in the Universe thought to be dominated by dark matter of unknown nature, whose presence is detected only through its gravitational effects. The resultant high resolution matter power spectrum would enable a determination of the total mass of neutrinos, permitting us to fundamentally establish the neutrino mass hierarchy from astrophysical observations. The additional high frequency channels (above 500 GHz) would be sensitive to the Cosmic Infrared Background (CIB) arising from dust emission due to star formation, besides providing a more robust method to decontaminate the CMB signal of the polarized foreground emissions.

The spectrometer, besides providing high level calibration for the differential polarization signal, will also provide measurements of the deviations from CMB black-body spectrum and will discover the predicted global thermal Sunyaev-Zeldovich signal that traces the distribution of hot gas in the cosmic web. It also carries the potential to discover the signatures of dark matter decay in the early Universe, imprints of non-standard inflationary dynamics, new particles such as the axions and other exotic phenomena that affect the cosmic thermal history.

The mission also promises high value secondary science in providing a more complete catalog of clusters detected at high redshifts through the thermal Sunyaev-Zeldovich effect, the velocity field of these clusters through the kinetic Sunyaev-Zeldovich effect, both of which can be used to probe the nature of dark energy, an enigma that challenges modern physics. It will also yield a more refined map of the Galactic magnetic field and a rich data set for other scientific investigations in many branches of astrophysics, from the solar system to the distant universe.

The mission design for imaging in polarization consists of a ~1.2-1.5 m primary SiC mirror in crossed-Dragone configuration with secondary and tertiary mirrors (of ~0.7-0.9 m in size) reflecting onto a flat ~0.5 m diameter focal plane. The baseline focal plane is populated with about 2400 detectors divided into 22 frequency bands over 60-900 GHz (sec. 6). The CMB dominated bands in the 100-230 GHz range, served by 950 detectors, can achieve a combined polarization sensitivity of 2 μK.arcmin. The design also includes a more ambitious but preliminary focal plane, that packs more than 3 times the number of baseline detectors, which can achieve an enhanced 1 μK.arcmin sensitivity in the combined CMB bands. The spectral capability is achieved by a fitting in a spectrometer that will enable an absolute measurement of the sky intensity at these frequencies with an accuracy of one part in ten-million. The science goals that are accessible according to the forecasts are discussed in sec. 5. Another novel feature would be that the science operation accommodates a two-year long observatory mode operation, after the four year survey that accomplishes the primary science goals. The observatory mode will open vast possibilities to a broader community to propose and seek exciting science with targeted observations and also allow very deep observations to shore up conclusions from selected regions of the sky.

The mission presents a unique opportunity for ISRO to not only showcase its expertise in frontier space capability, but also cross new technological horizons in these directions. The ~2 ton (wet mass) spacecraft will be required to be placed in an orbit around the second Lagrange point (L2) of the Sun-Earth system. Consequently, the mission seeks close to maximal launch capability of GSLV-III to reach L2 orbit with reasonable onboard propulsion. It will co-orbit the Sun with the Earth, following the Earth on a nearly circular orbit. The observations will be carried out in the anti-solar direction, pointing away from contaminating radiation from the Sun, the Earth and the Moon. The mission also demands capability for control and fairly heavy datalink (~8 MBps) for operations at L2. Further, this would possibly be ISRO’s first cryogenic science payload with high requirements of thermal stability. Operations at L2 provide the necessary stable thermal environment as established in previous missions such as Planck & Herschel (ESA), and WMAP (NASA). Building on the experience of the successful Planck mission at L2, the backplane solar panels, service module and hot electronics at > 300 K would be separated using the passive radial V-groove radiator technology from the cold optics and the cryogenic science payload. The mirrors will be passively cooled to 40-100K. A sophisticated cooling chain consisting of a combination of pulse tube coolers, Joule-Thomson coolers and sub-Kelvin cooler based either on ^{3}He-^{4}He dilution or adiabatic demagnetization will ensure that the focal plane and the detectors are maintained stably at 0.1 K.

Observations from space offer the critical advantage of an unobstructed and uniform view over the entire frequency range of interest. On Earth, atmospheric transmission severely limits observation to three frequency windows centred around 90, 150 and 240 GHz, with acceptable transmission and stability of observations only from locations with low precipitable water vapour, such as the South Pole, Atacama in Chile and possibly high deserts of Himalayas in Leh (Hanle) and Tibet. Atmospheric emission increases the load on the detectors, reducing the sensitivity and thus the mapping speed from the ground by a few hundred times as compared to space. Fluctuations of atmospheric emission and transmission further generates systematic errors in the observations. Frequencies above 300 GHz, critical for CIB science and foreground mitigation, are not accessible from the ground over large sections of the sky. Over the past two decades, CMB observations from space have provided the cleanest and richest source of data for understanding our Universe. Globally, the pursuit of the science goals outlined for the next generation CMB space mission is well recognized as a key to understanding our Universe. This presents an opportunity for global inter-agency cooperation to bring together the requisite expertise, resources and manpower to undertake a full fledged next generation CMB space mission to exploit the full potential of the available CMB information in the sky and realize the prized fundamental science goals as well as obtain rich legacy astrophysical data. As detailed in the budget (sec. 12), there is a unique window of opportunity to achieve the goal of an Indian CMB space mission in joint international collaboration. This will enable exchange of high-end technology that will enrich well-planned technology development programmes in the Indian laboratories and institutions. **The CMB-BHARAT mission presents an unique opportunity for India to take the lead on prized quests in fundamental science in a field that has proved to be a spectacular success, while simultaneously gaining valuable expertise in cutting-edge technology for space capability through global cooperation.**