Snowmass2021 - Letter of Interest

CMB-S4: The time-variable millimeter-wave sky

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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This Letter is adapted from the CMB-S4 Science Case, Reference Design, and Project Plan[1]
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Abstract:

We encourage the Snowmass process to consider a comprehensive program to support multi-messenger astrophysical studies as cosmic probes of fundamental physics. CMB-S4 will provide a unique platform to conduct a wide-field time-domain survey in the millimeter band, covering over half of the sky to few-mJy depths at least once every two days. In this waveband, the time-variable sky is largely unexplored, with the exception of a shallow survey by *Planck*, surveys of the Galactic Plane (such as with the JCMT), targeted measurements of a few individual sources, and a single survey by SPTpol[17]; this is largely the result of limited observing time and fields of view for mm-band instruments (e.g., ALMA), which tend to focus on high-resolution observations of known objects. Despite this, a wide variety of sources are either known or believed to have particularly interesting time-variability in bands observed by CMB-S4. Expected sources include tidal disruption events, nearby supernovae, X-ray binaries, and classical novae. Particularly good candidates are γ-ray bursts and active galaxies, such as the time-variable blazar that was identified as a possible source of high energy neutrinos. The combination of high sensitivity and wide area for CMB-S4 will open a new window for time domain astronomy and multi-messenger astrophysics.

Summary

CMB-S4 will play an active role in multi-messenger astronomy, in concert with both high-energy neutrino and gravitational wave searches. Although there have been relatively few studies of the variable sky at mm-wavelengths, accreting black holes are known to be highly variable. A CMB survey can provide a long baseline with high time sampling in both intensity and linear polarization. This will create a mm-wave archive for multi-messenger astronomy, in particular for future blazars that are discovered to be sources of high-energy neutrinos (such as the blazar TXS 0506+056, thought to be associated with the IceCube event IC170922A). With a large catalog of time-variable blazars, it will be possible to derive detailed variability statistics over several years with nearly daily monitoring for both the detected objects and the sources that are observed to *not* be neutrino sources. Additionally, the natural wide-area nature of the survey will make it straightforward to search for gravitational wave sources that happen to be poorly localized. Although the first binary neutron star merger, GW170817, was not detected at millimeter wavelengths, this was likely due to the low density of the merger environment[2]. There is reason to expect, based on observations of short gamma-ray bursts, that at least some mergers can occur in denser environments, which will make them fainter in the optical, *but* enhance their mm emission[3].

Targeted follow-up observations of gamma-ray bursts, core-collapse supernovae, tidal disruption events, classical novae, X-ray binaries, and stellar flares have found that there are many transient events with measured fluxes that would make them detectable by CMB-S4. A systematic survey of the mm-wave sky with a cadence of a day or two over a large fraction of the sky would be an excellent complement to other transient surveys, filling a gap between radio and optical searches. Gamma-ray burst afterglows can be detected within a few hours of the burst in many cases, and there is a possibility of capturing mm-wave afterglows that have no corresponding gamma-ray trigger either from the geometry of relativistic beaming and/or from sources being at very high redshift. CMB-S4 will also measure the thermal emission from planets, dwarf planets, and asteroids.

Multi-messenger astrophysics

The IceCube neutrino source TXS 0506+056 appeared to be associated with a blazar[8] that is mm-bright. With CMB-S4, this source would have had nearly daily flux measurements over many years, as well as many other similar sources that could be used to characterize the statistics of variability.

The first binary neutron star merger, GW170817, was not visible at mm-wavelengths[2], most likely due to the low density of the environment for that particular event. It is expected that at least some future events should be in denser environments that will enhance the mm-wave flux[3]. If there is no other detectable emission, CMB-S4 would provide arcminute localization as part of regular survey operations. In addition, the mm-wave light curve can be compared with emission at other wavelengths to better understand gravitational-wave events.

We do not know what fraction of future GW sources will turn out to be optically-obscured, but visible in the millimeter—so it seems wise to have an instrument that is regularly scanning the sky in this waveband. Provided that the GW source is in the southern hemisphere, then it *will* be in the CMB-S4 deep and wide survey field, and observed every few days as a matter of normal survey operations. *The same reasoning applies to all other future examples of transient source for which astronomers would like rapid follow-up observations.*

Gamma-ray bursts

Gamma-ray bursts (GRBs) are one of the primary time-domain science targets for CMB-S4. The spectrum of GRB afterglows has a broad emission peak from approximately 100 GHz to 1 THz[16], with emission lasting on the order of one week. The existence of so-called orphan afterglows from bursts without detected prompt γ-ray emission—either because of the γ-ray instrument field of view, misalignment of the jet with Earth, or absorption of the primary γ-ray emission —is a generic prediction of GRB models, but none have ever been detected, despite a number of possible candidates[6,10]. At the frequencies where orphan GRBs are bright enough to be detectable (including the millimeter band), either few or no blind surveys have been conducted.

CMB-S4's observing strategy and sensitivity are expected to change this picture dramatically, delivering a factor of 2000 improvement on the only previous time-domain millimeter blind survey[17], which had a candidate detection, and gives an expected 1700 afterglow detections from a population model of on- and off-axis bursts (PSYCHE,[7]) over a 7-year CMB-S4 survey. Other theoretical predictions find that at all times during the survey there should be an ongoing detectable GRB afterglow[12]. Detecting such objects would:

- constrain the existence of a large population of γ-dark GRB-like objects, which are potential sources of the TeV–PeV diffuse neutrino background observed by IceCube;
- improve modeling of off-axis emission, and connect with gravitational-wave sources;
- confirm measurements of the beaming angle of GRBs from jet breaks and thus the total energy budget for GRBs in the Universe;
- potentially detect afterglows from GRBs made by population-III stars at high-z, during and prior to reionization.

Although pop-III uncertainties are large, CMB-S4 has sufficient sensitivities for interesting constraints[11]. Detecting even one of these would provide valuable insight on the early Universe, while a non-detection would constrain models of the first generation of star formation.

Fast transients

Fast radio bursts (FRBs) are a striking astrophysical phenomenon of unknown origin. They have been seen serendipitously in radio-frequency observations with Arecibo, the Canadian Hydrogen Intensity Mapping Experiment (CHIME), Green Bank, and Parkes radio telescopes[4,9,13], with around 100 detected to date. This implies a full-sky rate of FRBs of roughly 5000 per day, if they are isotropically distributed. They are very bright (0.3 to 30 Jy at frequencies of a few GHz) and very fast (durations from less than 1 ms to 5 ms). Most have no useful polarization information, although a few (such as FRB150807[14]) have been observed to have linear polarization at various levels.

FRBs are consistent with having random sky locations (with the exception of two repeating sources[5,15]). They also have dispersion measures ranging from 375 to $1600\,\mathrm{pc\,cm^{-3}}$, supporting the idea that FRBs are at cosmological distances of order 1 Gpc. Their frequency spectrum is unknown but limited evidence in the 1–2 GHz range suggests consistency with a flat spectrum in flux density. If these intriguing sources do have a flat spectrum, some will be potentially detectable in microwave-background experiments, with flux densities greater than a few mJy at microwave frequencies.

The detection of FRBs at microwave wavelengths would establish their frequency spectrum, while upper limits on their rate would significantly constrain the flux distribution. Either outcome would contribute substantially to understanding these mysterious extragalactic events.

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