Astro2020 Science White Paper

Tracking the time-variable Millimeter-wave sky with CMB experiments

Thematic Areas: ☑ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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Abstract: Cosmic microwave background experiments are making wide-area, sensitive, high-cadence maps of the sky at millimeter-wavelengths. The sensitivity of these maps (several mJy in a daily map) is now at the point where it is expected that a wide variety of moving (solar system objects), time-variable (stars, active galactic nuclei), or transient sources (novae, tidal disruption events, gamma-ray bursts, nearby supernovae, gravitational wave events) can be detected. Future experiments, like CMB-S4, will be making such maps of ∼half of the sky with roughly daily cadence.

1 Introduction

Wide-area millimeter-wave sky surveys have historically been the domain of cosmic microwave background (CMB) experiments. However, while the sky signal at large scales is dominated by the CMB, smaller angular scales encode a range of astrophysical signals from diverse origins. To date, the *WMAP* and *Planck* satellites have compiled all-sky catalogs of hundreds to thousands of bright mm-wave sources (Bennett et al., 2013; Planck Collaboration et al., 2016), with linear polarization detected in some cases. Other experiments (e.g., the South Pole Telescope and the Atacama Cosmology Telescope) have detected large numbers of fainter mm-wave sources, but over a small fraction of the sky and largely avoiding our Galaxy (Mocanu et al., 2013; Marsden et al., 2014). At slighty shorter wavelengths, the SCUBA-2 camera on JCMT has patchy coverage of only $\sim$1000 deg^2, biased towards the Galactic plane.[1] Future CMB experiments will be significantly more sensitive to the intensity and polarization of such sources over a large fraction of the sky, providing a view of the mm-wave sky that will be highly complementary to radio and optical surveys. These wide surveys will include a large fraction of the Galactic plane.

Maps of the CMB are constructed by coadding repeated observations of the same patch of sky, a process that opens up the time domain for discovery. To date, there has been only one systematic time domain survey at mm wavelengths; this was conducted by the SPTPOL experiment (Whitehorn et al., 2016). This survey covered $\sim$100 deg^2 at high Galactic latitude over two years, with sensitivity to transients on timescales from days to months; one candidate event was discovered. With an experiment like CMB-S4 (Abazajian et al., 2016) such a survey could be done roughly daily at higher sensitivity for several years over more than half the sky (i.e., more than 200 times more area), including a majority of the Galactic plane. Expected sources of time-variable emission that could be detectable include moving objects in the solar system, variable sources in our Galaxy, nearby extragalactic transients, and sources at cosmological distances.

Particular extragalactic targets for a mm-wave survey are discussed below and include afterglows of otherwise-unobserved gamma-ray bursts, which peak in the millimeter band, and active galactic nuclei (AGN), thousands of which will be monitored daily by a future CMB survey. In addition, the near-absence of blind time-domain surveys in and around the 100 GHz band opens a great deal of discovery space. The recently observed and poorly-understood source AT2018cow, for instance, was so bright in the mm-band (Ho et al., 2019) that it could have been detected at high signal-to-noise in less than a day by a blind CMB survey of the type discussed here. Whether such sources are common, or whether there are other similar surprises waiting in this band, is something that such a survey would answer definitively.

2 Wide-Area Millimeter-wave Surveys

Wide area surveys have been carried out across the electromagnetic spectrum, from radio wavelengths to gamma-rays, and the sensitivity of a number of such surveys that have/will observe a large fraction of the sky are shown in Figure 1.[2] While optical surveys are extremely sensitive and have provided large catalogs, there are some sources that are not easily detected at such wave-

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[1] `https://www.eaobservatory.org/jcmt/science/archive/`

[2] Points shown are LSST, Pan-STARRS, SDSS, GALEX, 2MASS, WISE, *AKARI*, *IRAS*, *Planck*, AT20G, PMN, SUMSS, NVSS, VLASS, and EMU

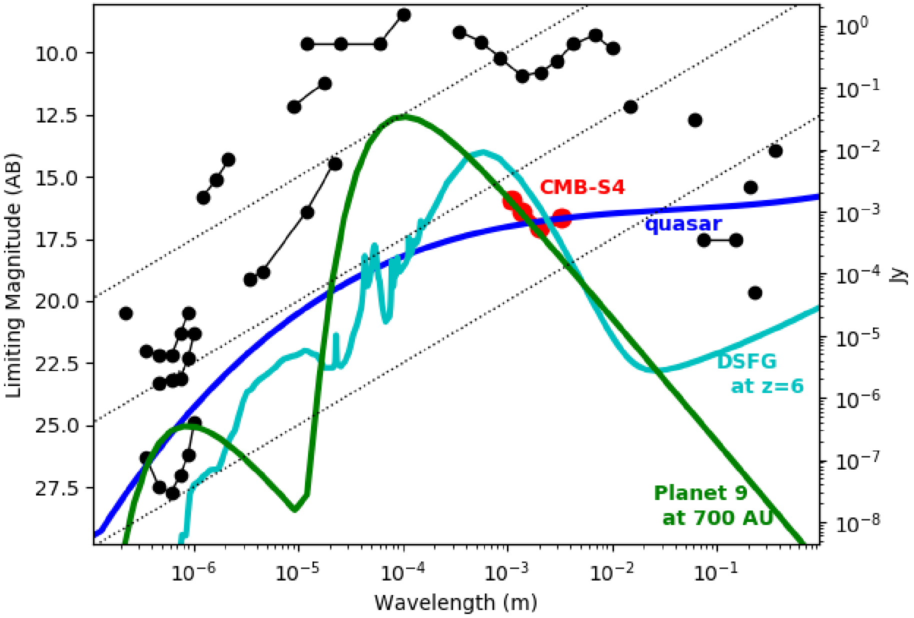

Figure 1: Black points show detection limits (AB magnitudes, 5σ) for a wide variety of surveys (past, current, or near-future) that cover a substantial fraction of the sky, ranging from ultraviolet to radio (X-ray and γ-ray surveys not shown); red points are forecast CMB-S4 detection limits. Indicated are full survey depths; for maps with roughly daily cadence (as expected for CMB-S4), per-visit maps will be roughly 3 magnitudes higher. Dotted lines show lines of constant νf_ν. Sample spectral energy distributions are shown in dark blue for a quasar with a spectrum like 3C 373 (but scaled to be dimmer), in light blue for a dusty star-forming galaxy at $z = 6$ with a rest spectrum similar to Arp 220 (a common steady source that can be seen with a mm-wave survey), and in green for a Neptune-sized possible planet in the outer solar system at a distance of 700 AU.

lengths. Radio-loud quasars (for example, with the observed SED of 3C 273), high-redshift dusty star-forming galaxies (e.g., the SED of nearby star-forming galaxy Arp 220, redshifted to $z = 6$), or possible new planets in the outer solar system (e.g., a Neptune-sized object at 700 AU) are sources that could be found in a CMB survey like CMB-S4 or that to be conducted by the Simons Observatory (Ade et al., 2019), which are too faint to see with current optical surveys. Owing to dust obscuration, many high-redshift dusty star-forming galaxies will even be beyond the detection limits of LSST. The angular resolution of CMB surveys is relatively modest (arcminute scales), but follow-up of these sources will be straightforward with ALMA or will naturally come from future radio surveys such as SKA. This will allow precise localization and—with ALMA observations—redshift information (e.g., Vieira et al. 2013) for careful comparisons with measurements at other wavelengths. In addition to discovering new objects, future CMB surveys can provide a wide-area catalog for filling in panchromatic SED measurements.

3 Time-Domain Science at Millimeter wavelengths

Ground-based experiments build up a sensitive map of the CMB with a large number of observations of the same patch of sky. The reference cadence for the CMB-S4 experiment results in $\sim 60\%$ of the sky (including a large fraction of the Milky Way) being observed every two days to an approximately uniform depth per observation of 5–10 mJy rms at mm wavelengths. The instantaneous field of view will be tens of square degrees, leading to a non-zero probability of transient sources being observed within a few ms of the beginning of the event, and many sources being observed within a few hours.

Current and future experiments have the sensitivity to detect a wide variety of moving, time-variable or transient sources. Sources that have been measured in follow-up at mm wavelengths to have fluxes detectable for CMB surveys or have strong theoretical support include the following classes:

- **gamma-ray bursts**
  Observations of GRBs at mm wavelengths (de Ugarte Postigo et al., 2012) can be extremely useful for characterizing these events, as evidenced by the recent detection of a possible reverse shock with ALMA (Laskar et al., 2018). CMB surveys will only be sensitive to relatively bright sources, but with a wide survey area and regular cadence it will be possible to detect many bursts (Metzger et al., 2015), some at early times. The GRB afterglow emission reaches its peak brightness in the millimeter band, making a CMB survey an ideal tool for detection of so-called *orphan afterglows*, GRBs without visible gamma-ray emission. CMB-S4 would be expected to see hundreds to thousands of these so-far-unobserved objects in the course of a 5-year survey (Ghirlanda et al., 2014).

- **supernovae**
  Some nearby core collapse supernovae have been detected to be mm-bright (Soderberg et al., 2012; Horesh et al., 2013; Weiler et al., 2007), giving insights into the surrounding medium, while there can also be surprising mm-luminous objects such as AT2018cow (Ho et al., 2019)

- **tidal disruption events**.
  The object Swift J164449.3+573451 was highly luminous in the mm-band (Berger et al., 2012; Zauderer et al., 2011), and would have been easily detected by a CMB survey (Metzger et al., 2015).

- **variable active galactic nuclei**
  AGN vary on a wide range of timescales. At the fainter fluxes detectable by current and future CMB experiments, long-term AGN monitoring will be possible, while blazars will be strongly detected in near-daily intensity and polarization maps (Chen et al., 2013; Giommi et al., 2012; MAGIC Collaboration et al., 2018). The large number of detectable AGN would allow the assembly of detailed, unbiased statistical information about AGN behavior at these wavelengths, which is currently not well-constrained. The light curves can also be combined with other probes, such as gamma-rays (Hovatta et al., 2015), or high-energy neutrinos (IceCube Collaboration et al., 2018). In particular, one of the mysteries with the IceCube neutrino source TXS 0506+056 (assumed to be associated with IC170922A) is the bright orphan neutrino flare observed in Dec. 2014 in the almost-complete absence of

gamma-ray emission from the source. The lack of all-sky, or near all-sky, monitoring at longer wavelengths than gamma rays at this time has left this mystery unresolvable and a challenge to models. One possibility is that a dense environment near the central region obscured the high-energy emission while simultaneously providing a pion-production target, boosting neutrino emission. As with dusty sources, millimeter observations would help flag such cases.

- **classical novae**
  Observations of classical novae and other cataclysmic variables have shown that they can be mm-bright, providing a new probe of the surrounding medium and details of mass loss mechanisms (Ivison et al., 1993; Chomiuk et al., 2014).

- **stellar flares**
  Some young stellar objects are variable at radio and mm wavelengths, sometimes with large flare events (Bower et al., 2003; Salter et al., 2008; Mairs et al., 2019). CMB surveys can supply long baselines to characterize statistics for both flaring stars and similar stars that do not flare.

- **solar system objects**
  Thermal emission from asteroids, dwarf planets, and planets can be detected at mm wavelengths. This part of the spectrum is relatively free of strong lines and emissivity effects are not strong. CMB measurements will be complementary to both infrared surveys (Mainzer et al., 2012)—with CMB surveys detecting only the larger objects (over several km in diameter), but at a different wavelength and with extended time coverage for studies of asteroid rotation—and also to optical surveys, being less sensitive to albedo effects and able to detect possible planets in the far reaches of the outer solar system, where the reflected light can be small (Cowan et al., 2016; Baxter et al., 2018).

- **gravitational wave events**
  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's environment (Alexander et al. 2017). 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 enhance their mm emission (Berger 2014). In particular, for certain binary orientations we may expect the emission from the jet to peak first in the mm-band (Fong et al. 2015). CMB observatories may contribute to these detections in two ways: through follow up of LIGO/Virgo triggers (which will generally have large localizations regions of ~ 100 deg^2) and secondly through blind detections in the course of the survey operations.

- **neutrino events**
  As with gravitational wave events, neutrino events are poorly resolved (though to only ~ 1 deg^2) such that follow-up in most bands is challenging, leaving all-sky, or near-all-sky, surveys with wide instantaneous fields of view as a prime resource. Millimeter observations are particularly interesting, given that proton acceleration in dense environments is associated with much higher neutrino emission as the result of a high rate of $pp \rightarrow \pi^+ \rightarrow \nu$ interactions. This favorable neutrino environment is (as described in the gravitational wave section)

Distance	Luminosity Limit (νL_ν)	Sources
60 pc	10^{26} erg/s	Flares from stars
6 kpc	10^{30} erg/s	Novae, X-ray binaries
60 Mpc	10^{38} erg/s	Core collapse supernovae
1 Gpc	3×10^{40} erg/s	Gamma-ray bursts, Tidal disruption events, Blazars

Table 1: CMB-S4 RMS noise levels in a 2-day map, turned into source luminosity at different distances. Examples of sources that have been observed to be detectable by a CMB survey are listed. Maps at this cadence can be made continuously for several years.

also associated with enhanced millimeter emission and decreased emission in other bands (Berger 2014).

Fast radio bursts (FRBs) are another potential source to be detected in CMB surveys (though the spectrum is currently unknown) as—given the wide field of view of next generation cameras—there should be several FRBs per day coincident with CMB observations. With detector readout faster than 100 Hz, the instantaneous rms noise for a time-unresolved source would be several Jy-ms, comparable to bursts measured at radio frequencies (Petroff et al., 2016).[3] The extremely large number of beams ($> 10,000$) per camera for next-generation CMB instruments will also provide critical rejection of instrumental backgrounds to FRB searches.

4 Conclusions

The wide-area nature of CMB surveys, with round-the-clock observations resulting in thousands of square degrees surveyed per day at modest (arcminute-scale) angular resolution, makes them highly complementary to transient searches at other wavelengths. While they will not be a replacement for targeted high-resolution observations at mm wavelengths (the sensitivity of even the full depth of future surveys can be reached with barely a snapshot of ALMA time, with sub-arcsecond resolution), the limited (tens of arcseconds) field of view of an instrument like ALMA makes it a poor match for wide surveys. New sources could be discovered in CMB surveys, and CMB data can serve as a sky archive for follow-up of sources detected in other bands and with other messengers, providing long baselines covering the times before, during, and after events, possibly extending for years in either direction. In these roles CMB surveys can be an important part of the transient astronomy ecosystem.

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[3] http://frbcat.org/

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