

WOMBAT & FORECAST: Making Realistic Maps of the Microwave Sky

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Abstract. The Wavelength-Oriented Microwave Background Analysis Team (WOMBAT) is constructing microwave maps which will be more realistic than previous simulations. Our foreground models represent a considerable improvement: where spatial templates are available for a given foreground, we predict the flux and spectral index of that component at each place on the sky and estimate uncertainties. We will produce maps containing simulated CMB anisotropy combined with expected foregrounds. The simulated maps will be provided to the community as the WOMBAT Challenge, so such maps can be analyzed to extract cosmological parameters by scientists who are unaware of their input values. This will test the efficacy of foreground subtraction, power spectrum analysis, and parameter estimation techniques and help identify the areas most in need of progress. These maps are also part of the FORECAST project, which allows web-based access to the known foreground maps for the planning of CMB missions.

1. Introduction

Cosmic Microwave Background (CMB) anisotropy observations during the next decade will yield data of unprecedented quality and quantity. Determination of cosmological parameters to the precision that has been forecast (Jungman et al. 1996, Bond, Efstathiou & Tegmark 1997, Zaldarriaga, Spergel & Seljak 1997, Eisenstein, Hu & Tegmark 1998) will require significant advances in analysis techniques to handle the large volume of data, subtract foregrounds, and account for systematics. We must ensure that these techniques do not introduce biases into the estimation of cosmological parameters.

The Wavelength-Oriented Microwave Background Analysis Team (WOMBAT, <http://astro.berkeley.edu/wombat>, see also Gawiser et al 1998) will pro-

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duce state-of-the-art foreground simulations, using all available information about frequency and spatial dependence. Phase information (detailed spatial morphology) offers the possibility of improving upon techniques that only use the angular power spectrum of the foregrounds to account for their distribution. Most techniques assume the frequency spectra of the components is constant across the sky, but we will provide information on the spatial variation of each component's spectral index whenever possible. This reflects our actual sky; with the high precision expected from future CMB maps we must test our techniques on as realistic a map as possible. A second advantage is the construction of a common, comprehensive database for all known CMB foregrounds, *including uncertainties*.

These models provide the starting point for the WOMBAT Challenge, in which we will generate maps for various cosmological models and offer them to the community for analysis without revealing the input parameters. The WOMBAT Challenge promises to shed light on several open questions in CMB data analysis: What are the best foreground subtraction techniques? Will they allow instruments such as MAP and Planck to achieve the precision in C_ℓ reconstruction which has been advertised, or will errors increase significantly due to foreground uncertainties? Perhaps most importantly, do some CMB analysis methods produce biased estimates of the cosmological parameters?

2. Microwave Foregrounds

There are four major expected sources of Galactic emission at microwave frequencies: thermal emission from dust, electric or magnetic dipole emission from spinning dust grains (Draine & Lazarian 1998a,b), free-free emission from ionized hydrogen, and synchrotron radiation from electrons accelerated by the Galactic magnetic field. Good spatial templates exist for thermal dust emission (Schlegel, Finkbeiner & Davis 1998, hereafter SFD) and synchrotron emission (Haslam et al. 1982), although the 0.5 resolution of the Haslam maps means that smaller-scale structure must be simulated. Extrapolation to microwave frequencies is possible using maps which account for spatial variation of the spectra (Finkbeiner, Schlegel & Davis 1999, Platania et al. 1998).

A spatial template for free-free emission based on observations of $H\alpha$ (Smoot 1998, Marcelin et al. 1998) can be created in the near future by combining WHAM observations (Haffner, Reynolds & Tufte 1998) with the southern celestial hemisphere $H\alpha$ Sky Survey (McCullough 1998). While it is known that there is an anomalous component of Galactic emission at 15-40 GHz (Kogut et al. 1996, Leitch et al. 1997, de Oliveira-Costa et al. 1997) partially correlated with dust morphology, it is not yet clear whether this is spinning dust grain emission or free-free emission somehow uncorrelated with $H\alpha$ observations. In fact, spinning dust emission *per se* has yet to be observed, so uncertainties in its amplitude are tremendous. A template for this "anomalous" component will have large uncertainties.

Three nearly separate categories of galaxies will also generate foreground emission: radio-bright galaxies, low-redshift IR-bright galaxies, and high-redshift IR-bright galaxies. The anisotropy from these foregrounds is predicted by Toffolatti et al. (1998) using models of galaxy evolution to produce source counts, and

updated models calibrated to recent SCUBA observations are available (Blain, Ivison, Smail & Kneib 1998, Scott & White 1998). For the high-redshift SCUBA galaxies, no spatial template is available, so a simulation with realistic clustering will be necessary. Scott & White (1998) and Toffolatti et al. (1998) have used very different estimates of clustering, so this issue will need to be looked at more carefully. Limits on anisotropy generated by high-redshift galaxies and as-yet-undiscovered types of point sources are given by Gawiser, Jaffe & Silk (1998) using recent observations over a wide range of frequencies. Their upper limit of $\Delta T/T = 10^{-5}$ for a $10'$ beam at 100 GHz is a sobering result. The 5319 brightest low-redshift IR galaxies detected at $60\mu\text{m}$ are in the IRAS 1.2 Jy catalog (Fisher et al. 1995) and can be extrapolated to 100 GHz with a systematic uncertainty of a factor of a few (Gawiser & Smoot 1997). Sokasian, Gawiser & Smoot (1998) have compiled a catalog of 2200 bright radio sources, some of which have been observed at 90 GHz and fewer still above 200 GHz. They have developed a method to extrapolate spectra with a factor of two uncertainty at 90 GHz.

Secondary CMB anisotropy is generated as CMB photons are scattered after the original last-scattering surface. The most important of these effects occurs as the shape of the blackbody spectrum is altered through inverse Compton scattering by the thermal Sunyaev-Zel'dovich (1972 – SZ) effect. Simulations have been made of the impact of SZ in large-scale structure (Persi et al. 1995), clusters (Aghanim et al. 1997) and groups (Bond & Myers 1996). The brightest 200 X-ray clusters known from the XBACS catalog can be used to incorporate the locations of the strongest SZ sources (Refregier, Spergel & Herbig 1998).

In Figure 1, we show an example of some of the foreground maps we will use: the CMB itself (a realization of standard CDM constrained to the COBE/DMR results, courtesy of E. Scannapieco), the SFD dust map, the Haslam synchrotron map, and the IR and radio source catalog amassed by Gawiser et al. Outside of the galactic plane, the morphology of each component is quite distinct.

3. Reducing Foreground Contamination

Various methods have been proposed for reducing foreground contamination. For point sources, it is possible to mask pixels which represent positive 5σ fluctuations since these are highly unlikely for Gaussian-distributed CMB anisotropy and can be assumed to be caused by point sources. This technique can be improved somewhat by filtering (Tegmark & de Oliveira-Costa 1998 – see Tenorio et al. 1998 for a different technique using wavelets). Sokasian, Gawiser & Smoot (1998) demonstrate that using prior information from good catalogs may allow the masking of pixels which contain sources brighter than 1σ . For the 90 GHz MAP channel, this could reduce the residual radio source contamination by a factor of two. Galactic foregrounds with well-understood spectra can be projected out of multi-frequency observations on a pixel-by-pixel basis (Dodelson & Kosowsky 1995, Brandt et al. 1994).

The methods for foreground subtraction which have the greatest level of sophistication and have been tested most thoroughly ignore the known locations on the sky of some foreground components. Multi-frequency Wiener filtering uses assumptions about the spatial power spectra and frequency spectra of

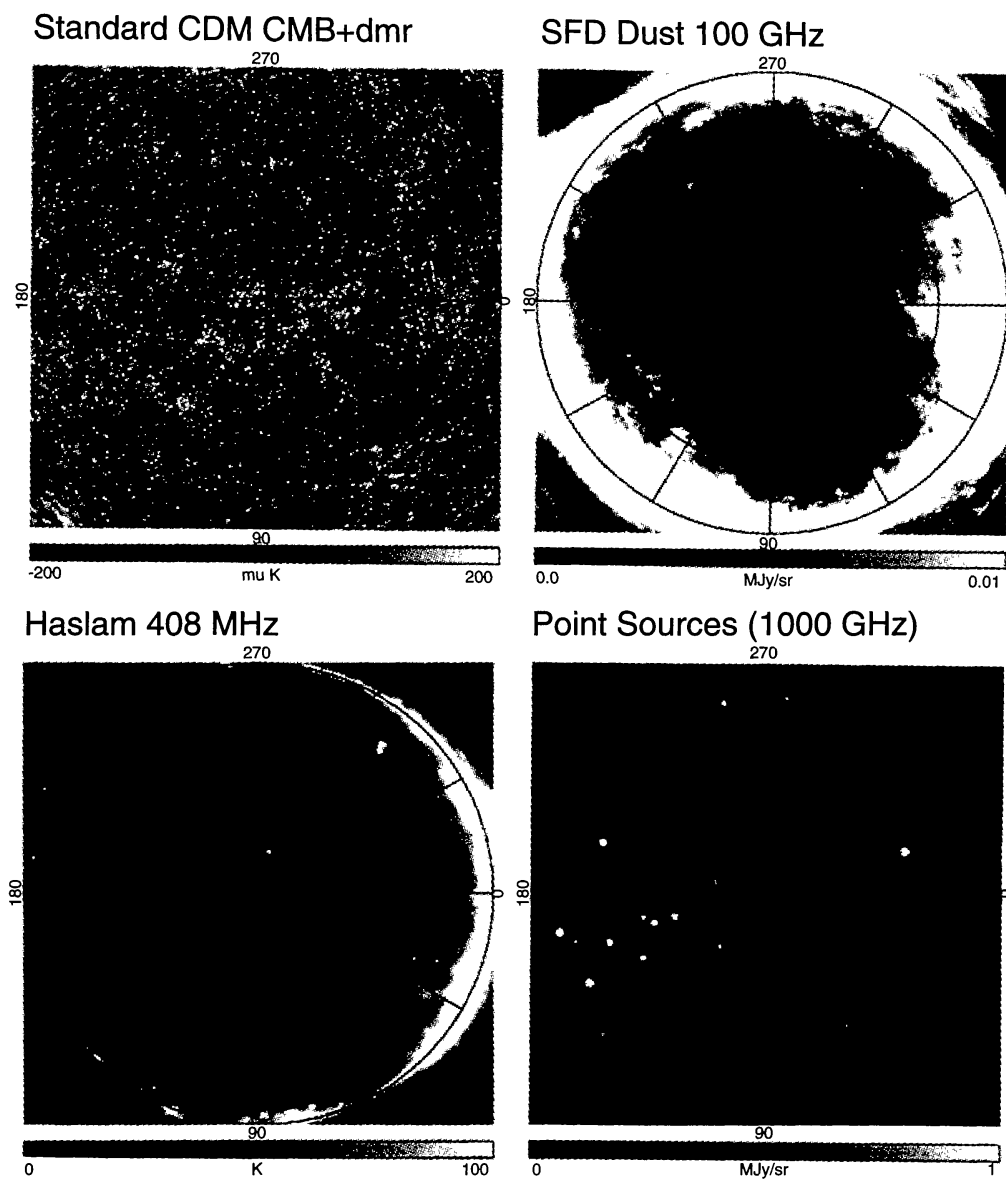


Figure 1. Foreground maps of the Northern Galactic Hemisphere, as labeled. The first author (AHJ) apologizes for the poor resolution and color scale.

the components to perform a separation in spherical harmonic or Fourier space (Tegmark & Efstathiou 1996, Bouchet et al. 1995,1997,1998, Knox 1998). However, it does not include any phase information. The MaxEnt Method (Hobson et al. 1998a) can add phase information on diffuse Galactic foregrounds in small patches of sky but treats extragalactic point sources as an additional source of instrument noise, with good results for simulated Planck data (Hobson et al. 1998b) and worrisome systematic difficulties for simulated MAP data (Jones, Hobson & Lasenby 1998). Both methods have difficulty if pixels are masked due to strong point source contamination or the spectral indices of the foregrounds are not well known (Tegmark 1998).

Since residual contamination can increase uncertainties and bias parameter estimation, it is important to reduce it as much as possible. Current analysis methods usually rely on cross-correlating the CMB maps with foreground templates at other frequencies (see de Oliveira-Costa et al. 1998, Jaffe, Finkbeiner & Bond 1999). It is clearly superior to have localized information on extrapolation of these templates to the observed frequencies; otherwise this cross-correlation only identifies the emission-weighted average spectral index of the foreground.

When a known foreground template is subtracted from a CMB map, it is inevitable that the amplitude used will be slightly different from the true value. This leads to off-diagonal structure in the “noise” covariance matrix of the remaining CMB map, as opposed to the contributions of expected CMB anisotropies which gives diagonal contributions to the covariance matrix of the $a_{\ell m}$. Thus incomplete foreground subtraction, like $1/f$ noise, can introduce correlations into the covariance matrix of the $a_{\ell m}$. These complicate the likelihood analysis necessary for parameter estimation (Knox 1998), but phase information should reduce inaccuracies in foreground subtraction.

4. The WOMBAT Challenge

Our purpose in conducting a “hounds and hares” exercise is to simulate the process of analyzing microwave maps as accurately as possible. We will make our knowledge of the various foreground components available, and each best-fit foreground map will be accompanied by its uncertainties and possible systematic errors. Each simulation of a foreground will incorporate a realization of those uncertainties. Very little is known about the locations of high-redshift IR-bright galaxies and SZ-bright clusters, so WOMBAT will provide simulations of these components. The rough characteristics of these high-redshift sources, but not their locations, will be revealed. This simulates the real observing process in a way not achieved by previous work.

One of the biggest challenges in real-world observations is being prepared for surprises, both instrumental and astrophysical (see Scott 1998 for an eloquent discussion); we will include a few in our maps.

We will release our maps for the community to subtract the foregrounds and extract cosmological information. The WOMBAT Challenge is scheduled to begin on March 1, 1999 and will offer participating groups four months to an-

alyze the maps and report their results.¹ We will produce simulations analogous to high-resolution balloon observations (*e.g.*, MAXIMA and BOOMERANG – see Hanany et al. 1998 and de Bernardis & Masi 1998) and the MAP satellite (10^6 pixels at $13'$ resolution for a full-sky map)². We plan to use the HEALPIX package of pixelization and analysis routines³. We provided a calibration map of CMB anisotropy with a disclosed angular power spectrum in January 1999 so that participants could test the download procedure and become familiar with HEALPIX. Groups who participate will be asked to provide us with a summary of their analysis techniques. They may choose to remain anonymous in our comparison of the results but are encouraged to publish their own conclusions. In Figure 2, we show a very simple example of what we will produce. It extrapolates the maps and catalogs of Figure 1 to frequencies of 10–300 GHz. At low frequencies, the maps (away from the galactic plane) are dominated by synchrotron emission, at 90 GHz by the CMB itself, and at 300 GHz by dust (and by extragalactic point sources which are not easily visible at this resolution). Visually, some sort of separation of the components seems simple, but doing it at the high precision necessary (and claimed) for CMB parameter determination to “unprecedented accuracy” remains a challenge.

5. FORECAST

The other thrust of the microwave mapmaking effort is to aid in the planning of future CMB anisotropy missions. We will enable quick and easy access to the foreground maps, combined with our best-guess extrapolations to experimental frequencies. Because uncertain extrapolation is involved, we will also provide *errors* on the results. Given specific information about the observing strategy, observers will be able to quickly call up predictions for their experiment’s contamination by foreground emission.

As an example, Figure 3 shows a screenshot of the web-based FORECAST software with the (then-) planned observing strategy for the MAXIMA experiment in summer 1998. Note that it is in one of the regions of lowest dust contrast in the sky!

6. Conclusions

Undoubtedly the most important scientific contribution that WOMBAT will make is the production of realistic full-sky maps of all major microwave foreground components with estimated uncertainties. These maps are needed for foreground subtraction and estimation of residual foreground contamination in present and future CMB anisotropy observations. With FORECAST, instrumental teams will be able to conduct realistic simulations without needing to

¹see <http://astro.berkeley.edu/wombat> for timeline, details for participants, and updates

²<http://map.gsfc.nasa.gov>

³<http://www.tac.dk/~healpix>

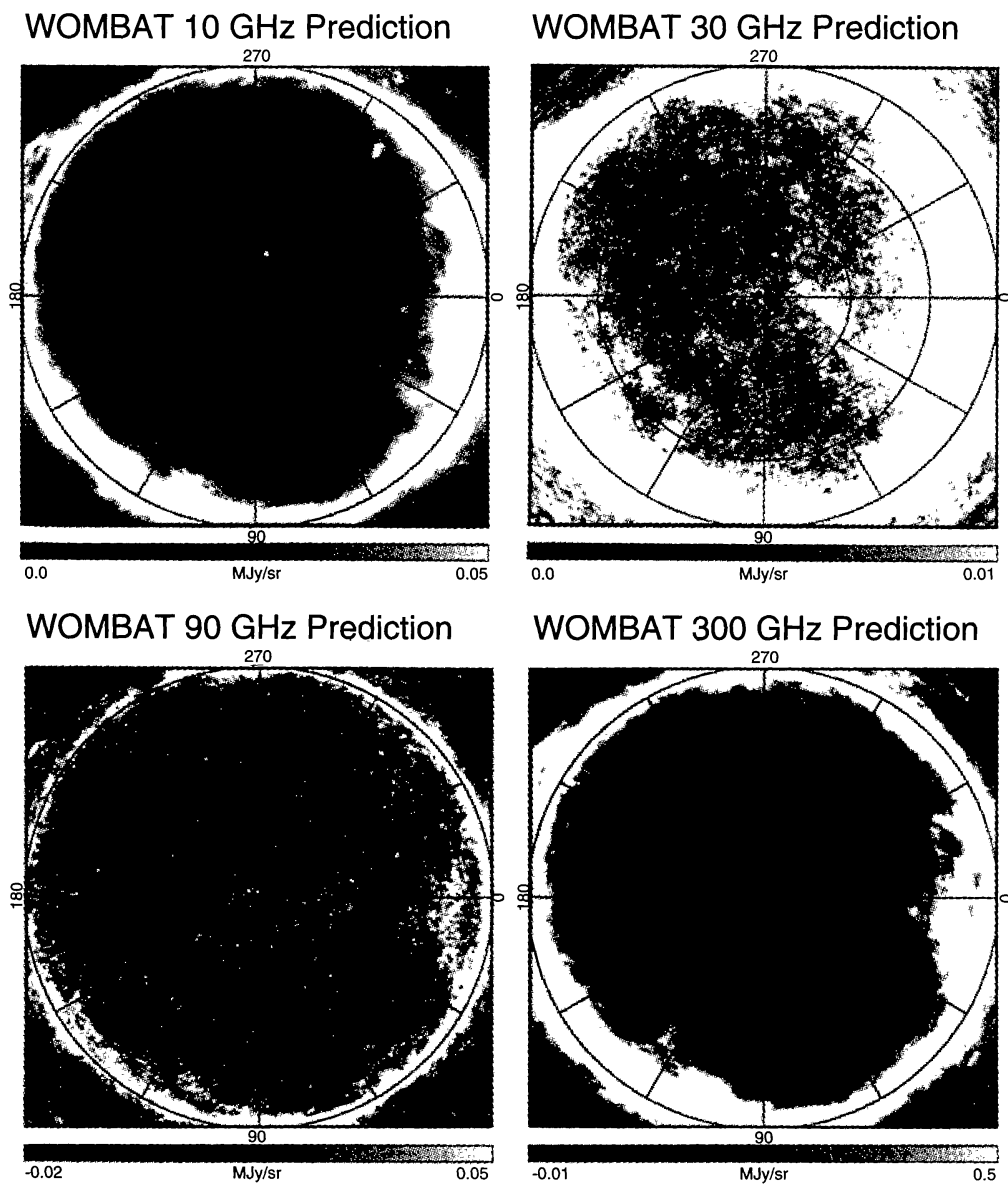


Figure 2. WOMBAT maps of the Northern Galactic hemisphere, extrapolating the maps of Figure 1 to the frequencies labeled. The first author (AHJ) apologizes for the poor resolution and color scale.

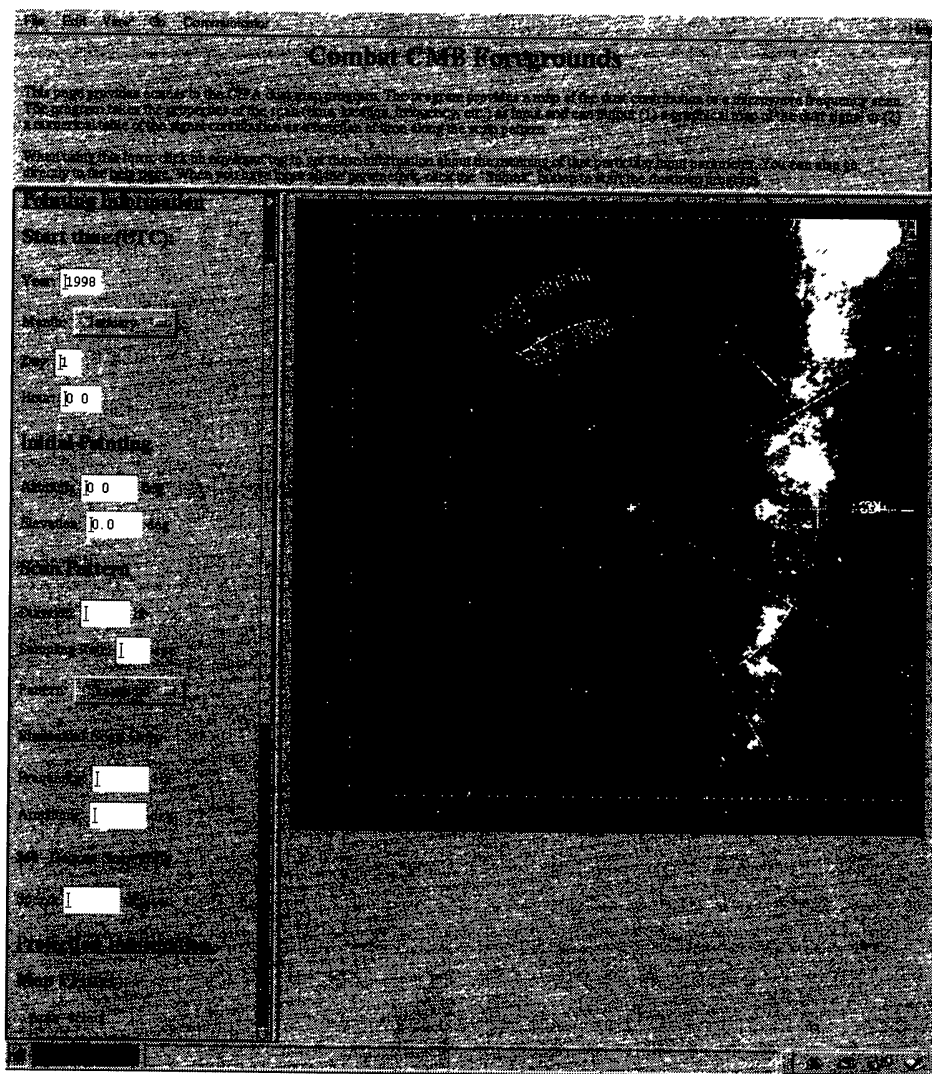


Figure 3. FORECAST Screenshot, showing the SFD map with the MAXIMA 1998 proposed scan pattern superposed on it. <http://cfpa.berkeley.edu/group/cmbanalysis/forecast>

assume overly idealized models for the foregrounds. By combining various realizations of these foreground maps within the stated uncertainties with a simulation of the intrinsic CMB anisotropies, we will produce the best simulations so far of the microwave sky.

We can test the resilience of CMB analysis methods to surprises such as unexpected foreground amplitude or spectral behavior, correlated instrument noise, and CMB fluctuations from non-gaussian or non-inflationary models. Cosmologists need to know if such surprises can lead to the misinterpretation of cosmological parameters.

Perhaps the greatest advance we offer is the ability to evaluate the importance of studying the detailed locations of foreground sources. It may turn out that techniques which use phase information are needed in order to reduce foreground contamination to a level which does not seriously bias the estimation of cosmological parameters. Combining various techniques may lead to improved foreground subtraction methods, and we hope that a wide variety will be tested by the participants in the WOMBAT Challenge.

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