The WOMBAT Challenge: A “Hounds and Hares” Exercise for Cosmology

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ABSTRACT

The Wavelength-Oriented Microwave Background Analysis Team (WOMBAT) is constructing microwave skymaps 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 the uncertainties in these quantities. We will produce maps containing simulated Cosmic Microwave Background anisotropies combined with all major expected foreground components. The simulated maps will be provided to the cosmology community as the WOMBAT Challenge, a “hounds and hares” exercise where such maps can be analyzed to extract cosmological parameters by scientists who are unaware of their input values. This exercise will test the efficacy of current foreground subtraction, power spectrum analysis, and parameter estimation techniques and will help identify the areas most in need of progress.

1. Introduction

Cosmic Microwave Background (CMB) anisotropy observations during the next decade will yield data of unprecedented quality and quantity. Determination of cosmological

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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 foreground contamination, and account for instrumental systematics. To guarantee accuracy we must ensure that these analysis techniques do not introduce unknown biases into the estimation of cosmological parameters.

The Wavelength-Oriented Microwave Background Analysis Team (WOMBAT, http://astro.berkeley.edu/wombat) will produce state-of-the-art simulations of microwave foregrounds, using all available information about the frequency dependence, power spectrum, and spatial distribution of each component. Using the phase information (detailed spatial morphology as opposed to just the power spectrum) of each foreground component offers the possibility of improving upon foreground subtraction techniques that only use the predicted angular power spectrum of the foregrounds to account for their spatial distribution. Most foreground separation techniques rely on assuming that 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. The most obvious advantage of this approach is that it reflects our actual sky. With the high precision expected from future CMB maps we must test our foreground subtraction techniques on as realistic a sky map as possible. A second advantage is the construction of a common, comprehensive database for all known CMB foregrounds. The database will include known uncertainties in the estimation of the foregrounds. Such a database should prove valuable for all groups involved in measuring the CMB and extracting cosmological information from it. Section 2 describes our plans to generate foreground models which include phase information, and Section 3 gives a brief survey of existing subtraction techniques and their limitations.

These microwave foreground models provide the perfect starting point for the WOMBAT Challenge, a “hounds and hares” exercise in which we will generate skymaps for various cosmological models and offer them to the cosmology community for analysis without revealing the input parameters. This challenge is similar to the “Mystery CMB Sky Map challenge” posted by our sister collaboration, COMBAT, except that our emphasis is on dealing with realistic foregrounds rather than the ability to analyze large data sets. Section 4 describes our plans to conduct this foreground removal challenge. 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

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6Cosmic Microwave Background Analysis Tools, http://cfpa.berkeley.edu/group/cmbanalysis
Planck to achieve the precision in $C_\ell$ reconstruction which has been advertised, or will the error bars increase significantly due to uncertainties in foreground models? Perhaps most importantly, do some CMB analysis methods produce biased estimates of the radiation power spectrum and/or cosmological parameters?

2. Microwave Foregrounds

Phase information is now available for Galactic dust and synchrotron and for the brightest radio galaxies, infrared galaxies, and X-ray clusters on the sky. By incorporating known information on the spatial distribution of the foreground components and spatial variation in their spectral index, we will greatly improve upon previous highly-idealized foreground models.

There are four major expected sources of Galactic foreground emission at microwave frequencies: thermal emission from dust, electric or magnetic dipole emission from spinning dust grains (Draine & Lazarian 1998a, 1998b), 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) 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 1998; Platania et al. 1998). The COMBAT collaboration has recently posted a software package called FORECAST\(^7\) that displays the expected dust foreground for a given frequency, location, and observing strategy. Our best-fit foreground maps will be added to this user-friendly site in the near future, and this should be a useful resource for planning and simulating CMB anisotropy observations.

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) which is 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 grain emission has yet to be observed, so the

\(^7\)Foreground and CMB Anisotropy Scan Simulation Tools, [http://cfpa.berkeley.edu/group/cmbanalysis/forecast](http://cfpa.berkeley.edu/group/cmbanalysis/forecast)
uncertainties in its amplitude are tremendous. A template for the “anomalous” emission component will undoubtedly have large uncertainties.

Three nearly separate categories of galaxies will also generate microwave foreground emission; they are radio-bright galaxies, low-redshift infrared-bright galaxies, and high-redshift infrared-bright galaxies. The level of anisotropy produced by 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 also available (Blain, Ivison, Smail, & Kneib 1998, Scott & White 1998). For the high-redshift galaxies detected by SCUBA, no spatial template is available, so a simulation of these galaxies with realistic clustering will be necessary. Scott & White (1998) and Toffolatti et al. (1998) have used very different estimates of clustering to produce divergent results for its impact, so this issue will need to be looked at more carefully. Upper and lower limits on the 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 microwave frequencies. Their upper limit of $\Delta T/T = 10^{-5}$ for a $10'$ beam at 100 GHz is a sobering result; while the real sky would need to conspire against us to produce this much anisotropy it cannot be ruled out at present, and we will need to look for it with direct observations and design analysis techniques that might manage to subtract it. The 5319 brightest low-redshift IR galaxies detected at 60$\mu$m are contained 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). This method needs to be improved to account for the spectral difference between Ultraluminous Infrared Galaxies and normal spirals. Sokasian, Gawiser, & Smoot (1998) have compiled a catalog of 2200 bright radio sources, 758 of which have been observed at 90 GHz and 309 of which have been observed at frequencies above 200 GHz. They have developed a method to extrapolate radio source spectra which has a factor of two systematic uncertainty at 90 GHz. Radio source variability represents a major challenge for most foreground subtraction techniques, and the information present in this catalog allows one to estimate the mean and variance of the source fluxes as a function of frequency.

The secondary CMB anisotropies that occur when the photons of the Cosmic Microwave Background radiation are scattered after the original last-scattering surface can be viewed as a type of foreground contamination. The shape of the blackbody spectrum can be altered through inverse Compton scattering by the thermal Sunyaev-Zel’dovich (SZ) effect (Sunyaev & Zel’dovich 1972). The effective temperature of the blackbody can be shifted locally by a doppler shift from the peculiar velocity of the scattering medium (the kinetic SZ and Ostriker-Vishniac effects) as well as by passage through nonlinear structure (the Rees-Sciama effect). Secondary anisotropies can be treated as a type of
foreground contamination. Simulations have been made of the impact of the SZ effects in large-scale structure (Persi et al. 1995), clusters (Aghanim et al. 1997), groups (Bond & Myers 1996), and reionized patches (Aghanim et al. 1996, Knox, Scoccimarro, & Dodelson 1998, Gruzinov & Hu 1998, Peebles & Juskiewicz 1998). The brightest 200 X-ray clusters are known from the XBACS catalog and can be used to incorporate the locations of the strongest SZ sources (Refregier, Spergel, & Herbig 1998). The SZ effect itself is independent of redshift, so it can yield information on clusters at much higher redshift than does X-ray emission. However, nearly all clusters are unresolved for 10′ resolution so higher-redshift clusters occupy less of the beam and therefore their SZ effect is in fact dimmer. In the 4.5′ channels of Planck this will no longer be true, and SZ detection and subtraction becomes more challenging and potentially more fruitful as a probe of cluster abundance at high redshift.

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 $5\sigma$ fluctuations since such fluctuations are highly unlikely for Gaussian-distributed CMB anisotropy and can be assumed to be caused by point sources. This pixel masking 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 source catalogs may allow the masking of pixels which contain sources brighter than the $1\sigma$ level of CMB fluctuations and instrument noise. For the 90 GHz MAP channel, this could reduce the residual radio point source contamination by a factor of two, which might significantly reduce systematic errors in cosmological parameter estimation. Galactic foregrounds with well-understood frequency spectra can be projected out of multi-frequency observations on a pixel-by-pixel basis (Dodelson & Kosowsky 1995, Brandt et al. 1994). Prior information in the form of spatial templates can be included in this projection, but uncertainty in the spectral index is a cause for concern.

Perhaps surprisingly, the methods for foreground subtraction which have the greatest level of mathematical sophistication and have been tested most thoroughly ignore the known locations on the sky of some foreground components. The multi-frequency Wiener filtering approach uses assumptions about the spatial power spectra and frequency spectra of the foreground 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 at present. The Fourier-space Maximum Entropy
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). Maximum Entropy has not yet been adapted to handle full-sky datasets. Both methods have difficulty if pixels are masked due to strong point source contamination or the spectral indices of the foreground components are not well known (Tegmark 1998).

Since residual foreground 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 1998). It is clearly superior to have region-by-region (or pixel-by-pixel) information on how to extrapolate these templates to the observed frequencies; otherwise this cross-correlation only identifies the emission-weighted average spectral index of the foreground from the template frequency to the observed frequency.

Because each foreground has a non-Gaussian spatial distribution, the covariance matrix of its $a_{\ell m}$ coefficients is not diagonal, although this has often been assumed. When a known foreground template is subtracted from a CMB map, it is inevitable that the correlation coefficient used for this subtraction will be slightly different than the true value. This expected under- or over-subtraction of each foreground leads to off-diagonal structure in the "noise" covariance matrix of the remaining CMB map, as opposed to the contributions of expected CMB anisotropies and uncorrelated instrument noise, both of which give diagonal contributions to the covariance matrix of the $a_{\ell m}$. Thus incomplete foreground subtraction, like $1/f$ noise, can introduce non-diagonal correlations into the covariance matrix of the $a_{\ell m}$. These correlations complicate the likelihood analysis necessary for parameter estimation (Knox 1998). Having phase information on the brightness and spectral index of foreground emission should reduce inaccuracies in foreground subtraction, and this motivates us to produce the best estimates we can of these quantities along with estimates of their uncertainties.

4. The WOMBAT Challenge

Our purpose in conducting a “hounds and hares” exercise is to simulate the process of analyzing microwave skymaps as accurately as possible. In real-world observations the underlying cosmological parameters and the exact amplitudes and spectral indices of the foregrounds are unknown, so Nature is the hare and cosmologists are the hounds. We
will make our knowledge of the various foreground components available to the public, and each best-fit foreground map will be accompanied by a map of its uncertainties and a discussion of possible systematic errors. Each simulation of that foreground will be different from the best-fit map based upon a realization of those uncertainties. Very little is known about the spatial locations of high-redshift infrared-bright galaxies and high-redshift SZ-bright clusters, so WOMBAT will provide simulations of these components. The rough characteristics of these high-redshift foreground sources, but not their locations, will be revealed. This simulates the real observing process in a way not achieved by previous foregrounds simulations.

We will release our simulated 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 analyze the skymaps and report their results. 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 to the MAP satellite. This will indicate how close the community is to being able to handle datasets as large as that of MAP (10^6 pixels at 13’ resolution for a full-sky map). Given current computing power, complex algorithms appear necessary for analyzing full-sky MAP datasets (Oh, Spergel, & Hinshaw 1998), although simpler approximations may be possible (e.g. Wandelt, Hivon, & Górski 1998). We plan to use the publicly available HEALPIX package of pixelization and analysis routines. We will provide a calibration map of CMB anisotropy with a disclosed angular power spectrum in January 1999 so that participants can test the download procedure and become familiar with HEALPIX. Groups who analyze the Challenge maps 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 based on their participation.

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). An exercise such as the WOMBAT Challenge is an excellent way to simulate these surprises, and we will include a few in our skymaps. The results of the WOMBAT Challenge will provide estimates of the effectiveness of current techniques of foreground subtraction, power spectrum analysis, and parameter estimation.

8 see http://astro.berkeley.edu/wombat for timeline, details for participants, and updates
9 http://map.gsfc.nasa.gov
10 http://www.tac.dk/˜healpix
5. 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. They will allow instrumental teams to conduct realistic simulations of the observing and data analysis process without needing to 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. Using these simulations in a “hounds and hares” exercise should test how well the various foreground subtraction and parameter estimation techniques work at present. It is easy to question the existing tests of analysis methods which assume idealized foregrounds in analyzing similarly idealized simulations.

Data analysis techniques will undoubtedly improve with time, and we hope to reduce the current uncertainty in their efficacy such that follow-up simulations by the instrumental teams themselves can generate confidence in the results of real observations. 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. In the future, we envision producing time-ordered data, simulating interferometer observations, and adding polarization to our microwave sky simulations.

Perhaps the greatest advance we offer is the ability to evaluate the importance of studying the detailed locations of foreground sources. If techniques which ignore this phase information are still successful on our realistic sky maps, that is a significant vote of confidence. Alternatively, 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 of techniques will be tested by the participants in the WOMBAT Challenge.

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