The Diffuse Microwave Emission Survey (DIMES) has been selected for a mission concept study for NASA’s New Mission Concepts for Astrophysics program. DIMES will measure the frequency spectrum of the cosmic microwave background and diffuse Galactic foregrounds at centimeter wavelengths to 0.1% precision (0.1 mK), and will map the angular distribution to 20 μK per 6° field of view. It consists of a set of narrow-band cryogenic radiometers, each of which compares the signal from the sky to a full-aperture blackbody calibration target. All frequency channels compare the sky to the same blackbody target, with common offset and calibration, so that deviations from a blackbody spectral shape may be determined with maximum precision. Measurements of the CMB spectrum complement CMB anisotropy experiments and provide information on the early universe unobtainable in any other way; even a null detection will place important constraints on the matter content, structure, and evolution of the universe. Centimeter-wavelength measurements of the diffuse Galactic emission fill in a crucial wavelength range and test models of the heat sources, energy balance, and composition of the interstellar medium.
1 Introduction

The origin and evolution of the observed structures in the present-day universe is a fundamental unsolved problem of cosmology. The paradigm for structure formation consists of the gravitational infall and collapse of small “seed” perturbations in the density of the early universe. The central result of the Cosmic Background Explorer (COBE) was the support of this basic picture through the detection of CMB anisotropy without a corresponding distortion from a blackbody spectrum. Within this broad outline, however, a number of more detailed questions remain unanswered. What mechanism created the metric perturbations which serve as the seeds for structure formation? What is the nature of “dark matter”, inferred through its gravitational effects? When and how did the first collapsed objects form?

To answer these questions, we must turn to relics from the early universe. The CMB spectrum records the energetics of the universe from redshift \( z \approx 10^7 \) (about one year after the Big Bang) to the present epoch. Distortions in the CMB spectrum away from a Planck spectrum are an unavoidable consequence of structure in the early universe. Precise measurements of the CMB spectrum at centimeter wavelengths probe different physical processes than the COBE results at millimeter and sub-mm wavelengths and provide quantitative information on the energetics of the evolving universe, including:

- The photo-ionization of the intergalactic medium by the first generation of collapsed objects
- The abundance, lifetimes, and decay modes of non-baryonic particles, including massive neutrinos, supersymmetric partners of known particles, or other dark matter candidates
- The decay of short-wavelength metric perturbations and primordial turbulence

Figure 1 summarizes recent precise measurements of the CMB spectrum. The COBE Far Infrared Absolute Spectrophotometer (FIRAS) provides a precise determination of the CMB spectrum near its peak at millimeter and sub-mm wavelengths, limiting deviations from a

![Figure 1: Precise measurements of the CMB thermodynamic temperature. The dotted line represents a 2.73 K blackbody, while the dashed line shows the DIMES frequency band. The CMB spectrum is poorly constrained at centimeter or longer wavelengths.](image-url)
blackbody to be less than $5 \times 10^{-5}$ of the peak intensity\(^1\). Although the precise COBE measurements carry implications for possible distortions at longer wavelengths, the absence of distortions near the peak CMB intensity does not imply correspondingly small distortions at longer wavelengths. Distortions as large as 5% could exist at wavelengths of several centimeters or longer without violating existing observations\(^2\).

Where should further effort, if any, be directed? Several factors point to spectrum measurements at centimeter wavelengths (frequencies 2–100 GHz) to precision 0.1 mK as both technologically feasible and cosmologically interesting. Measurements in this band probe different physical processes than the COBE measurements a decade higher in frequency, yet lie at wavelengths short enough to reduce Galactic emission to manageable levels. A multi-channel experiment with 0.1 mK precision per channel would improve existing cm-band results by a factor of 300, limit energetic events to $\Delta E/E < 10^{-5}$ at redshift $10^4 < z < 10^7$, and provide a decisive test of reionization from the first collapsed objects.

## 2 Spectral Distortions

The simplest distortion results from free-free cooling of a warm plasma (electron temperature $T_e \sim 10^4$ K) at recent epochs ($z<1000$), corresponding to photoionization of the intergalactic medium by the first generation of stars and galaxies. The distortion to the present-day CMB spectrum is given by\(^3\)

$$\Delta T_{ff} = T_\gamma Y_{ff} \frac{x}{x^2}$$

where $T_\gamma$ is the undistorted photon temperature, $x$ is the dimensionless frequency $h\nu/kT_\gamma$, $Y_{ff}$ is the optical depth to free-free emission

$$Y_{ff} = \int_0^z \frac{k[T_e(z) - T_\gamma(z)]}{T_e(z)} \frac{8\pi e^6 h^2 n_e^2 g}{3m_e(kT_\gamma)^3 \sqrt{6\pi m_e kT_e}} \frac{dt}{dz'}$$.

$n_e$ is the electron density, and $g$ is the Gaunt factor. The distorted CMB spectrum is characterized by a quadratic rise in temperature at long wavelengths as the photon distribution thermalizes to the plasma temperature.

If the gas is sufficiently hot ($T_e > 10^6$ K), Compton scattering ($\gamma + e \rightarrow \gamma' + e'$) of the CMB photons from the hot electrons provides the primary cooling mechanism. Compton scattering transfers energy from the electrons to the photons while keeping the photon number fixed. For recent energy releases ($z<10^5$), the gas is optically thin, resulting in a uniform decrement $\Delta T_{RJ} = T_\gamma (1 - 2y)$ in the Rayleigh-jeans part of the spectrum where there are now too few photons, and an exponential rise in temperature in the Wien region where there are now too many photons. The magnitude of the distortion is related to the total energy transfer\(^4\)

$$\frac{\Delta E}{E} = e^{4y} - 1 \approx 4y$$

where the parameter $y$ is given by the integral

$$y = \int_0^z \frac{k[T_e(z) - T_\gamma(z)]}{m_e c^2} \sigma_T n_e(z) c \frac{dt}{dz'} dz'$$.

of the electron pressure $n_e kT_e$ along the line of sight and $\sigma_T$ denotes the Thomson cross section.
Figure 2: Current 95% confidence upper limits to distorted CMB spectra. The FIRAS data and DIMES 0.1 mK error box are also shown; error bars from existing cm-wavelength measurements are larger than the figure height. An absence of distortions at millimeter and sub-mm wavelengths does not imply correspondingly small distortions at centimeter wavelengths.

Together, free-free and Comptonized spectra can be used to detect the onset of nuclear fusion by the first collapsed objects. Ultraviolet radiation from the first collapsed objects is expected to photoionize the intergalactic medium. Since these objects form by non-linear collapse of rare high-density peaks in the primordial density distribution, the redshift at which they form is a sensitive probe of the statistical distribution of density peaks and the matter content of the universe. Various models of structure formation predict significant ionization at redshifts ranging from $10 < z < 150$, depending on the matter content and power spectrum of density perturbations, with a “typical” value $z_{\text{ion}} \approx 50$.

The FIRAS measurement at sub-mm wavelengths shows no evidence for Compton heating from a hot IGM. Since the Compton parameter $y \propto n_e T_e$ (Eq. 3), the IGM at high redshift must not be very hot ($T_e < 10^5$ K) or reionization must occur relatively recently ($z_{\text{ion}} < 10$). DIMES provides a definitive test of these alternatives. Since the free-free distortion $Y_{\text{ff}} \propto n_e^2 / \sqrt{T_e}$ (Eq. 2), lowering the electron temperature increases the spectral distortion. Figure 3 shows the limit to $z_{\text{ion}}$ that could be established from the combined DIMES and FIRAS spectra, as a function of the DIMES sensitivity. A spectral measurement at centimeter wavelengths with 0.1 mK precision can detect the free-free signature from the ionized IGM, allowing direct detection of the onset of hydrogen burning.

DIMES also provides a sensitive test for early energy releases, such as the decay of exotic heavy particles or metric perturbations from GUT and Planck-era physics. Compton scattering from an early energy release alters the photon energy distribution while conserving photon number. After many scatterings the system will reach statistical (not thermodynamic) equilibrium, described by the Bose-Einstein distribution with dimensionless chemical potential $\mu_0 = 1.4 \Delta E / E$. Free-free emission thermalizes the spectrum to the plasma temperature at long
wavelengths. Including this effect, the chemical potential becomes frequency-dependent,

$$\mu(x) = \mu_0 \exp\left(\frac{-2x_b}{x}\right),$$

where $x_b$ is the transition frequency at which Compton scattering of photons to higher frequencies is balanced by free-free creation of new photons. The resulting spectrum has a sharp drop in brightness temperature at centimeter wavelengths$^7$.

DIMES will provide a substantial increase in sensitivity for non-zero chemical potential (Figure 2). Such a distortion arises naturally in several models. The COBE anisotropy data are well-described$^8$ by a Gaussian primordial density field with power spectrum $P(k) \propto k^n$ per comoving wave number $k$, with power-law index $n = 1.2 \pm 0.3$. Short-wavelength fluctuations which enter the horizon while the universe is radiation-dominated oscillate as acoustic waves of constant amplitude and are damped by photon diffusion, transferring energy from the acoustic waves to the CMB spectrum and creating a non-zero chemical potential$^{9,10}$. The energy transferred, and hence the magnitude of the present distortion to the CMB spectrum, depends on the amplitude of the perturbations as they enter the horizon through the power-law index $n$. Models with "tilted" spectra $n>1$ produce observable distortions.

Exotic particle decay provides another source for non-zero chemical potential. Particle physics provides a number of dark matter candidates, including massive neutrinos, photinos, axions, or other weakly interacting massive particles (WIMPs). In most of these models, the current dark matter consists of the lightest stable member of a family of related particles, produced by pair creation in the early universe. Decay of the heavier, unstable members to a photon or charged particle branch will distort the CMB spectrum provided the particle lifetime is greater than a year. Rare decays of quasi-stable particles (e.g., a small branching ratio for massive neutrino decay $\nu_{\text{heavy}} \rightarrow \nu_{\text{light}} + \gamma$) provide a continuous energy input, also distorting the CMB spectrum. The size and wavelength of the CMB distortion are dependent upon the decay mass difference, branching ratio, and lifetime. Stringent limits on the energy released by exotic

![Figure 3](image-url)  

Figure 3: Upper limits to the redshift $z_{\text{ion}}$ at which the intergalactic medium becomes reionized, as a function of the DIMES spectral precision. The cosmologically interesting region $z_{\text{ion}} < 100$ requires precision 0.1 mK or better.
particle decay provides an important input to high-energy theories including supersymmetry and neutrino physics.

3 Galactic Astrophysics

Measurements of the diffuse sky intensity at centimeter wavelengths also provide valuable information on astrophysical processes within our Galaxy. Figure 4 shows the relative intensity of cosmic and Galactic emission at high galactic latitudes. Diffuse Galactic emission at centimeter wavelengths is dominated by three components: synchrotron radiation from cosmic-ray electrons, electron-ion bremsstrahlung (free-free emission) from the warm ionized interstellar medium (WIM), and thermal radiation from interstellar dust. Despite surveys carried out over many years, relatively little is known about the physical conditions responsible for these diffuse emissions. Precise measurements of the diffuse sky intensity over a large fraction of the sky, calibrated to a common standard, will provide answers to outstanding questions on physical conditions in the interstellar medium (ISM):

- What is the heating mechanism in the ISM? Is the diffuse gas heated by photoionization from the stellar disk, shocks, Galactic fountain flows, or decaying halo dark matter?
- How are cosmic rays accelerated? Is the energy spectrum of local cosmic-ray electrons representative of the Galaxy as a whole?
- What is the shape, constitution, and size distribution of interstellar dust? Is there a distinct “cold” component in the cirrus?

The Galactic radio foregrounds may be separated from the CMB by their frequency dependence and spatial morphology. DIMES will map radio free-free emission from the warm ionized
interstellar medium. The ratio of radio free-free emission to Hα emission will map the temperature of the WIM to 20% precision, probing the heating mechanism in the diffuse ionized gas. DIMES will have sufficient sensitivity to map the high-latitude synchrotron emission, probing the magnetic field and electron energy spectrum throughout the Galaxy. Cross-correlation with the DIRBE far-infrared dust maps will fix the spectral index of the high-latitude cirrus to determine whether the dust has enhanced microwave emissivity.

4 Instrument Description

Figure 5 shows a schematic of the DIMES instrument. It consists of a set of narrow-band cryogenic radiometers (Δν/ν ∼ 10%) with central frequencies chosen to cover the gap between full-sky surveys at radio frequencies (ν < 2 GHz) and the COBE millimeter and sub-mm measurements. Each radiometer measures the difference in power between a beam-defining antenna (FWHM ∼ 6°) and a temperature-controlled internal reference load. An independently controlled blackbody target is located on the aperture plane, so that each antenna alternately views the sky or a known blackbody. The target temperature will be adjusted to null the sky-antenna signal difference in the longest wavelength channel. With temperature held constant, the target will then move to cover the short-wavelength antennas: DIMES will measure small spectral shifts about a precise blackbody, greatly reducing dependence on instrument calibration and stability. The target, antennas, and radiometer front-end amplifiers are maintained near thermal equilibrium with the CMB, greatly reducing thermal gradients and drifts.

DIMES uses multiple levels of differences to reduce the effects of offset, drifts, and instrumental signatures. To reduce gain instability or drifts, each receiver is rapidly switched between a cryogenic antenna and a temperature-controlled internal reference load. To eliminate the instrumental signature, each antenna alternately views the sky or a full-aperture target with emissivity ε > 0.9999. To maximize sensitivity to spectral shape, all frequency channels view the same target in progression, so that deviations from a blackbody spectrum may be determined much more precisely than the absolute blackbody temperature.

Figure 5: Schematic drawing of DIMES instrument.
DIMES will remove the residual instrument signature by comparing the sky to an external full-aperture blackbody target. The precision achieved will likely be dominated by the thermal stability of the target. While the use of a single external target rejects common-mode uncertainties in the absolute target temperature, thermal gradients within the target or variations of target temperature with time will appear as artifacts in the derived spectra and sky maps. We reduce thermal gradients within the external target by using a passive multiply-buffered design in which a blackbody absorber (Eccosorb CR-112, an iron-loaded epoxy) is mounted on a series of thermally conductive plates with conductance $G_1$ separated by thermal insulators of conductance $G_2$. Thermal control is achieved by heating the outermost buffer plate, which is in weak thermal contact with a superfluid helium reservoir. Radial thermal gradients at each stage are reduced by the ratio $G_2/G_1$ between the buffer plates. Typical materials (Fiberglass and copper) achieve a ratio $G_2/G_1<10^{-3}$; a two-stage design should achieve net thermal gradients well below 0.1 mK. No heat is applied directly to the absorber, and a conductive copper layer surrounds the absorber on all sides except the front: the Eccosorb lies at the end of an open thermal circuit, eliminating thermal gradients from heat flow.

DIMES will not be limited by raw sensitivity. HEMT amplifiers cooled to 2.7 K easily achieve $\text{rms}$ noise 1 mK Hz$^{-1/2}$, reaching 0.1 mK sensitivity in 100 seconds of integration. The DIMES spectra are derived from comparison of the sky to the external blackbody target. The largest systematic uncertainties arise from thermal drifts or gradients within the target and emission from warm objects outside the DIMES dewar (e.g., the Earth). Thermometers buried in the microwave absorber monitor thermal gradients and drifts to precision 0.05 mK. Emission from the Earth must be rejected at the -70 dB level to avoid contributing more than 0.1 mK to the total sky signal. DIMES will achieve this rejection using corrugated antennas with 6$^\circ$ beam and good sidelobe response; two sets of shields between the aperture plane and the Earth provide further attenuation of thermal radiation from the Earth. COBE achieved -70 dB attenuation with a 7$^\circ$ beam and a single shield\textsuperscript{11}, so the DIMES requirement should be attainable.

DIMES will eliminate atmospheric emission completely by observing from low Earth orbit. We are currently investigating the possibility of utilizing the Spartan-400 carrier, which will provide free-flyer capability to Shuttle orbits for 700 kg instruments for a nominal mission of 6 to 9 months.

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