Anomalous Microwave Emission

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Abstract. Improved knowledge of diffuse Galactic emission is important to maximize the scientific return from scheduled CMB anisotropy missions. Cross-correlation of microwave maps with maps of the far-IR dust continuum show a ubiquitous microwave emission component whose spatial distribution is traced by far-IR dust emission. The spectral index of this emission, $\beta_{\text{radio}} = -2.2^{+0.5}_{-0.7}$, is suggestive of free-free emission but does not preclude other candidates. Comparison of H$\alpha$ and microwave results show that both data sets have positive correlations with the far-IR dust emission. Microwave data, however, are consistently brighter than can be explained solely from free-free emission traced by H$\alpha$. This “anomalous” microwave emission can be explained as electric dipole radiation from small spinning dust grains. The anomalous component at 53 GHz is 2.5 times as bright as the free-free emission traced by H$\alpha$, providing an approximate normalization for models with significant spinning dust emission.

1. Introduction

Observations of anisotropy in the cosmic microwave background are complicated by the presence of foreground Galactic emission along all lines of sight. At high latitudes ($|b| > 20^\circ$), diffuse Galactic emission is dominated by optically thin synchrotron, dust, and free-free emission. In principle, these components may be distinguished by their different spatial morphology and frequency dependence. In practice, there is no emission component for which both the frequency dependence and spatial distribution are well determined. Synchrotron radiation dominates radio-frequency surveys, but the spectral index steepens with frequency and has poorly-determined spatial variation (Banday & Wolfendale 1991, Bennett et al. 1992). Dust emission dominates far-infrared surveys, but its spectral behavior at longer wavelengths depends on the shape, composition, and size distribution of the dust grains, which are poorly known (Désert, Boulanger, & Puget 1990). Free-free emission from electron-ion interactions has well-determined spectral behavior but lacks an obvious template map: free-free emission never dominates the high-latitude radio sky, while other tracers of the warm ionized interstellar medium (WIM) such as H$\alpha$ emission, pulsar dispersion measure, or N II emission are either incomplete, undersampled, or noise-dominated (Reynolds 1992; Fixsen, Bennett, & Mather 1999).
Figure 1. Spectrum of correlated intensity fluctuations between microwave and far-infrared emission ($|b| > 20^\circ$). No error bars are available for the OVRO point. To factor out variations in dust intensity $\Delta I_{100}$ over different patches of sky, the figure plots the frequency dependence of the correlation coefficient $\alpha$ instead.

The problem is particularly acute for free-free emission: lacking an accurate template for the spatial distribution, estimation of free-free emission in microwave data requires a pixel-by-pixel frequency decomposition which significantly reduces the signal to noise ratio of the desired cosmological signal. Recently, Kogut et al. (1996a,b) proposed using infrared emission from diffuse cirrus as a tracer of the ionized gas responsible for free-free emission,

$$\Delta T_{ff} = \alpha \Delta I_{100}$$

where $\Delta T_{ff}$ is the fluctuation in microwave antenna temperature from free-free emission, $\Delta I_{100}$ is the fluctuation in dust continuum intensity at wavelength 100 $\mu$m, and the coefficient $\alpha$ converts from units MJy/sr to $\mu$K antenna temperature. Cross-correlation of the COBE Differential Microwave Radiometer (DMR) maps at 31.5, 53, and 90 GHz with the Diffuse Infrared Background Experiment (DIRBE) far-infrared maps at 100, 140, and 240 $\mu$m shows statistically significant emission in each microwave map whose spatial distribution on angular scales above $7^\circ$ is traced by the far-infrared dust emission. The frequency dependence of this emission, rising sharply at long wavelengths, is inconsistent with the expected microwave dust emission (Fig. 1). A 2-component fit of the
correlated COBE data to a model with dust plus radio emission

\[ \Delta T_A = \Delta T_{\text{dust}} \left( \frac{\nu}{\nu_0} \right)^{\beta_{\text{dust}}} + \Delta T_{\text{radio}} \left( \frac{\nu}{\nu_0} \right)^{\beta_{\text{radio}}} \]  

(2)

with dust emissivity \( 1.5 < \beta_{\text{dust}} < 2 \) yields spectral index \( \beta_{\text{radio}} = -2.1^{+0.6}_{-0.8} \) for the unknown component, strongly suggestive of free-free emission (\( \beta_{\text{ff}} = -2.15 \)). At high latitudes, spatial fluctuations in the diffuse synchrotron emission are uncorrelated with dust emission, leaving free-free emission (thermal bremsstrahlung) from the WIM as seemingly the only plausible alternative.

The amplitude of the correlated component agrees well with independent estimates of free-free emission derived solely from its frequency dependence. We estimate the amplitude of the total free-free emission (including any uncorrelated component) by analyzing a linear combination of the DMR maps designed to be sensitive to free-free emission, cancel emission with a CMB spectrum, and minimize instrument noise:

\[ T_{\text{ff}} = 0.37 \times \frac{1}{2} (T'_{31A} \pm T'_{31B}) + 0.02 \times \frac{1}{2} (T'_{53A} \pm T'_{53B}) - 0.47 \times \frac{1}{2} (T'_{90A} \pm T'_{90B}), \] 

(3)

where \( T' \) is the antenna temperature in each DMR channel after subtracting synchrotron and dust emission (Kogut et al. 1996b). We smooth the maps with a 7° FWHM Gaussian to further reduce the effects of noise, remove a fitted monopole and dipole, and compare the variance of the (A+B)/2 sum map to the (A-B)/2 difference map. We obtain an estimate for the fluctuations in free-free antenna temperature at 53 GHz from all sources, \( \Delta T_{\text{ff}} = 5.2 \pm 4.2 \mu\text{K} \). This value compares well with the correlated component at the same 10° effective smoothing, \( \Delta T_{\text{radio}} = 6.8 \pm 1.6 \mu\text{K} \) from Eq. 2.

2. Evidence for Anomalous Emission

Two questions of interest for cosmological observations are the extent to which infrared dust reliably traces high-latitude radio emission, and whether the correlation depends significantly on angular scale. The detection of correlation between dust and ionized gas at high latitudes is consistent with the correlation observed between dust and free-free emission along the Galactic plane (Broadbent, Haslam, & Osborne 1989), and supports a picture in which free-free emission from the WIM is traced by continuum emission from warm (19 K) dust, with scaling \( \alpha = 4.4 \pm 0.7 \left( \frac{\nu}{\nu_{100}} \right)^{-2.15} \mu\text{K MJy}^{-1} \text{sr} \) between microwave emission \( \Delta T_{\text{ff}} \) and dust emission \( \Delta I_{100} \) at 100 μm wavelength.

A number of recent microwave observations show that the observed correlation between radio and far-IR emission is ubiquitous and not strongly dependent on angular scale. Figure 2 shows the spectral index of the “radio” component of the correlated emission (Eq. 2), derived from all current microwave detections (DMR: Kogut et al. 1996b; 19 GHz: de Oliveira-Costa et al. 1998; Saskatoon: de Oliveira-Costa et al. 1997; MAX5: Lim et al. 1996; OVRO: Leitch et al. 1997). The 95% confidence interval \( -3.6 < \beta_{\text{radio}} < -1.3 \) is consistent with free-free emission over a frequency range 14 – 100 GHz.
When other tracers of the diffuse ionized gas are considered, the picture becomes significantly more complicated. Hα emission is a widely used tracer of the diffuse gas in the WIM. The intensity of optically thin Hα emission is given by

\[ I(R) = 0.44 \text{EM} \left( \frac{T_e}{8000 \text{ K}} \right)^{-0.5} \left[ 1 - 0.34 \ln \left( \frac{T_e}{8000 \text{ K}} \right) \right] \]  

(4)

where EM = \( \int n_e^2 dl \) is the emission measure in cm\(^{-6}\) pc and the intensity units are Rayleighs (1 R = 10\(^6\) photons / 4\(\pi\) sr = 2.42 \times 10\(^{-7}\) ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) at Hα). Electron-ion collisions in the same gas give rise to microwave free-free emission, with antenna temperature

\[ T_A = 0.83 Z^2 \text{EM} \frac{[1 + 0.23 \ln(T_e/8000 \text{ K}) - 0.15 \ln(Z) - 0.15 \ln(\nu/53 \text{ GHz})]}{(\nu/53 \text{ GHz})^2 (T_e/8000 \text{ K})^{1/2}} \]  

(5)

in μK units, where Z is the net charge of the ion (Oster 1961; Bennett et al. 1992). The WIM is characterized by electron density \( n_e \sim 0.1 \text{ cm}^{-3} \) and temperature \( T_e \sim 8000 \text{ K} \) (Reynolds 1990). Hα emission should thus trace free-free emission as

\[ \Delta T_{\text{ff}} = a \Delta I_{\text{Hα}}, \]  

(6)

with coefficient \( a \approx 1.9 \left( \frac{\nu}{53 \text{ GHz}} \right)^{-2.15} \mu\text{K/R} \) (Bennett et al. 1992).

If we assume that the observed correlation between microwave and far-IR maps results from free-free emission, then a similar correlation should exist.
between H\(\alpha\) and dust emission. Several authors have found marginal correlations between H\(\alpha\) maps and the IRAS or DIRBE 100 \(\mu\text{m}\) maps (McCullough 1997, Kogut 1997). Figure 3 shows the correlation coefficient \(\alpha\) between the far-IR dust continuum and H\(\alpha\) or microwave data, where we have converted H\(\alpha\) values from Rayleighs to \(\mu\text{K}\) using Eq. 6. Both sets of data are positively correlated with the far-IR dust emission, but the microwave results appear systematically higher than the H\(\alpha\) values.

There are no full-sky maps of H\(\alpha\) emission to compare to the full-sky COBE data. Several small H\(\alpha\) maps exist (Reynolds 1980, Gaustad et al. 1996, Simonetti et al. 1996, McCullough 1997), but only one field (the north celestial pole) has been mapped both in H\(\alpha\) and microwaves. There, the small variation in H\(\alpha\) intensity appears inadequate to explain the presumed free-free emission by a factor 3–10, albeit with substantial uncertainties (Simonetti et al. 1996, Leitch et al. 1997, de Oliveira et al. 1997). Leitch et al. (1997) argue that energetics preclude solutions that reduce H\(\alpha\) emission by raising the gas temperature and suggest that alternate explanations are required for the “anomalous” microwave emission.

We can quantify this discrepancy using simple statistics. If the microwave and H\(\alpha\) results trace the same diffuse gas, the values in Figure 3 should be drawn from a single parent population. Table 1 shows the \(\chi^2\) derived from fitting a
Table 1: Mean Correlation Coefficients at 53 GHz

| Model          | Fitted Correlation | $\chi^2$/DOF |
|----------------|--------------------|---------------|
| All Data       | 2.6 ± 0.4          | 13.4 / 7      |
| Microwave Only | 4.4 ± 0.7          | 3.4 / 4       |
| Hα Only        | 1.3 ± 0.4          | 1.4 / 2       |

weighted mean to the full data set and two independent sub-sets composed of the Hα and microwave data, respectively. The full data set has $\chi^2$ of 13.4 for 7 degrees of freedom, improbable for normally-distributed data. If we separate the data into microwave or Hα results, each set is internally consistent: by adding a single degree of freedom (breaking the data into 2 subsets) we reduce the total $\chi^2$ from 13.4 to 4.8, suggesting that the data do, in fact, belong to two separate populations.

3. Spinning Dust

Many experiments show microwave emission correlated with far-IR dust emission, with spectral index suggestive of free-free emission but lacking the strong Hα signal expected on physical grounds. If this is not free-free emission, what could it be? Recent work suggests that the “anomalous” microwave emission could originate from the electric dipole radiation of very small ($N < 10^3$ atoms) spinning dust grains (Ferrara & Dettmar 1994; Draine & Lazarian 1998a,b). A key feature of the spinning dust model is the microwave emission spectrum, which peaks between 10 and 50 GHz depending on the size distribution of the dust grains. Figure 4 shows a typical spectrum, with grain size ($N < 150$ atoms) chosen to agree with the OVRO detection at 14.5 GHz.

Identification of “anomalous” microwave emission as the signature of spinning dust has several advantages. It provides a natural explanation for the observed correlation between emission components at microwave and far-IR wavelengths: both components results from the same physical dust distribution and should be highly correlated at all angular scales. It explains the lack of a strong Hα signal without invoking energetically questionable gas temperature. Finally, since the emission spectrum falls sharply at wavelengths below 10 GHz, it allows detectable “anomalous” signals in the window 30–100 GHz without violating limits from radio surveys at 1420 and 408 MHZ (Reich & Reich 1988, Haslam et al. 1981).

The identification of “anomalous” microwave emission with spinning dust, while suggestive, is not without problems. The spectral index $\beta_{\text{spin}}$ (in antenna temperature) of the calculated dust emission over the frequency range 19–53 GHz where the most sensitive detections occur is between -3.3 and -4, depending on the assumed size distribution of the dust grains (Draine & Lazarian 1998b). Such a steep spectral index lies 1.6 to 2.6 standard deviations from the best fitted index $\beta_{\text{radio}} = -2.2^{+0.5}_{-0.7}$ (Eq. 2). Furthermore, while long-wavelength limits are weak, there is as yet no confirmation of the predicted downturn at frequencies below 20 GHz.
4. Discussion

A large body of observational evidence demonstrates that at least one component of microwave emission is traced by far-IR dust emission. This correlation is ubiquitous on the sky and independent of angular scale. As such, the corresponding signal in microwave anisotropy maps can be removed by correlating independently each microwave frequency channel with a template dust map. The amplitude at microwave frequencies is small enough that residual uncertainties, after subtraction, should not be a major source of error for cosmological applications.\footnote{If the correlated emission is in fact dominated by spinning dust, the partial alignment of the grain spin axis with Galactic magnetic fields may be a source of confusion for measurements of the CMB polarization.}

The source of the correlated emission is still an open question with interesting astrophysical implications. The spectral index, within broad limits, is consistent at the 95% confidence level with either free-free emission or emission from spinning dust grains. From physical arguments, it seems likely that both emission mechanisms may contribute a detectable signal at microwave frequencies. Both microwave and Hα emission are positively correlated with far-IR dust emission. Assuming two separate emission mechanisms, microwave data contain contributions from both free-free and spinning dust, while Hα results trace only the free-free component. We may thus use the data in Table \ref{table:emission} to obtain separate free-free and dust normalizations at 53 GHz. Averaged over the full sky, emission from spinning dust is $2.5 \pm 1.1$ times as bright as free-free emission.
Substantial progress remains to be made in the identification of microwave foregrounds. A key discriminant between free-free and spinning dust models is the spectrum below 20 GHz where emission from spinning dust falls rapidly. A measurement of the correlated emission at a frequency below 10 GHz would provide a definitive test of the two models.

Astrophysical modelling of microwave emission as a probe of physical conditions in the interstellar medium requires a clean separation of individual emission components. Current efforts along these lines are hampered by the lack of high signal-to-noise ratio maps at microwave, Hα, and far-IR frequencies in common regions of the sky. Hα maps from the Wisconsin H-Alpha Mapper (Tuft, Reynolds, & Haffner 1998), in combination with microwave data from the next generation balloon and satellite experiments, should allow a full set of microwave–Hα–dust correlations to separate emission from different phases of the ISM.

Finally, sensitive microwave maps with substantial sky coverage will test for significant variation in the correlated emission from point to point on the sky. While there is no evidence for spatial variation in the correlation, existing full-sky data sets (the COBE and 19 GHz maps) are too noisy to test for variation in the correlation coefficient on angular scales below 60°. Two of the three detections from small patches of sky (OVRO and MAX5) show appreciably larger correlations than the full-sky COBE results, but with substantial uncertainties. How anomalous are these anomalous results? The MAP and Planck satellite data should demonstrate whether full-sky average correlation is physically meaningful, or whether a more complicated model is required.

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