Review Article

The Discovery of Anomalous Microwave Emission

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We discuss the first detection of anomalous microwave emission, in the Owens Valley RING5M experiment, and its interpretation in the context of the ground-based cosmic microwave background (CMB) experiments of the early 1990s. The RING5M experiment was one of the first attempts to constrain the anisotropy power on sub-horizon scales, by observing a set of 7'-size fields around the North Celestial Pole (NCP). Fields were selected close to the NCP to allow continuous integration from the Owens Valley site. The experiment detected significant emission at both 14.5 GHz and 30 GHz, consistent with a mixture of CMB and a flat-spectrum foreground component, which we termed *anomalous*, as it could be explained neither by thermal dust emission, nor by standard models for synchrotron or free-free emission. A significant spatial correlation was found between the extracted foreground component and structure in the IRAS 100 μ m maps. While microwave emission from spinning dust may be the most natural explanation for this correlation, spinning dust is unlikely to account for all of the anomalous emission seen in the RING5M data.

1. Introduction

From the perspective of the 21st century cosmology, it can be hard to imagine how primitive the state of our knowledge was a short twenty years ago and how rapidly the landscape was changing at the time. Today, ground-based experiments like the South Pole Telescope (SPT) and the Atacama Cosmology Telescope (ACT) have measured the high- ℓ power spectrum with enough resolution to detect the first nine Doppler peaks (SPT [1, 2], ACT [3]) and enough sensitivity to detect the background of SZ power from unresolved galaxy clusters [4]. The combination of ground, balloon-borne, and space-based missions have already determined fundamental cosmological parameters to uncertainties of a few percent (c.f. DASI [5], ACBAR [6], Boomerang [7], WMAP [8]), and new data from Planck are poised to refine these further. The E-mode polarization of the CMB, whose detection was unthinkable twenty years ago, is now routinely measured by ground-based experiments (first detected by DASI [9, 10], with progressive improvements in resolution and sensitivity by CBI [11], QUaD [12], BICEPI [13], and QUIET [14]), while ever more sensitive limits on the B-mode power spectrum are beginning to place interesting constraints on the tensor-to-scalar ratio r [13]

(with the next generation cameras like SPTpol, BICEP2, the Keck Array, PolarBear, and ACTpol already in operation).

By contrast, the early 1990s had just witnessed the first ever detection of CMB anisotropy on super-horizon scales by the COBE satellite [15]. A small number of Antarctic ground-based experiments were trying to detect any indication of a rise toward the first Doppler peak and where that peak might lie (e.g., ACME [16], Python [17], MAX [18], IAB [19]). It is indicative of the state of the field that model power spectra were routinely displayed in log space, since the only feature anyone hoped to detect at the time was the rise in power at intermediate ℓ .

The Owens Valley RING5M experiment was one of a small complement of experiments designed to probe the CMB anisotropy spectrum at arcminute scales; these scales were assumed to be sub-horizon, but that had yet to be demonstrated. At the time of its inception, only upper limits had been achieved by a small handful of experiments (at 12' by Tucker et al. [20] and at 2' by the OVRO NCP experiment [21]). Collectively these instruments constituted the deepest probes of the microwave spectrum to date, and by contrast with the large-scale experiments, the resolution

FIGURE 1: (Reproduced from [22]) (a) The state of CMB anisotropy detections in 1993. The points are from COBE [15], Python [17], MAX [18] and IAB [19]. Also shown is the upper limit from the OVRO NCP experiment [21]. (b) The state of the field in early 1998. Shown are COBE [36], FIRS [37], Tenerife [38], SP94 [39], Python [40], ARGO [41], MAX [42], Saskatoon [24], CAT [25], and the OVRO RING5M [23]. (The solid line is a CDM model with $H_0 = 30$, $\Omega_0 = 1$ and $\Omega_b = 0.05$, and is also indicative of the state of late 20th century cosmology).

of the RING5M instruments presented one of the first opportunities for probing microwave emission from specific galactic features. It is therefore not surprising, in retrospect, that these observations resulted in the first detection of anomalous microwave emission from the Galaxy, as we discuss in Section 3.

In the following section, we review details of the RING5M experiment design relevant to understanding the data. In Section 3, we present the evidence for anomalous emission in the RING5M data and discuss its interpretation in the context of multifrequency observations of the NCP in Section 4. Finally, in Section 5 we consider the relation of the anomalous emission detected near the NCP to the dust correlated components seen in degree-scale CMB experiments.

2. The RING5M Experiment

Figure 1, reproduced from [22], shows the state of anisotropy detections when the RING5M experiment was constructed. Taken together, results from the early Antarctic experiments were somewhat suggestive of a rise in power at scales approaching $\sim 1^\circ$, while the NCP upper limit (also shown in

Figure 1) demonstrated that the power had dropped significantly at $\sim 2'$ scales. The RING5M experiment was, therefore, designed to operate at $7' - 22'$ scales, where the peak of the power spectrum might lie in an $\Omega < 1$ universe, but which should nonetheless be detectable even in an $\Omega = 1$ cosmology. Like our counterparts in the southern hemisphere, we were driven to observe near the celestial pole; in our case, the North Celestial Pole (NCP) was the only part of the northern hemisphere sky available for round-the-clock observations.

The experiment consisted of two independent telescopes operating at widely separated frequencies. A 30 GHz channel was provided by a dual-feed receiver installed on a 5.5-meter telescope at the Owens Valley Radio Observatory (OVRO), with a beam of approximately $7'$ FWHM. To provide leverage against potential foreground contamination, a second 14.5 GHz receiver was constructed on the OVRO 40-meter telescope, with optics designed to underilluminate the dish, so that matched beams were produced at both frequencies. A Dicke switch provided fast azimuthal switching between two positions on the sky separated by $22'$, while a second, slower level of differencing was achieved by slewing the telescope to alternate the beams on the target field, producing an effective beam pattern indicated in Figure 2. In all, 36 fields were

FIGURE 2: (a) Source-subtracted Ka (30 GHz) and Ku-band (14.5 GHz) data plotted to equal brightness temperature scale. Both represent sky amplitudes, convolved with the double-switched beam pattern of the RING5M observations, indicated at the bottom left of the figure. Approximately half of the RING5M fields show CMB-like signals (equal brightness temperature at both frequencies), while the other half show temperature signals with a steep spectral dependence. (b) The likelihood of the spectral index of the RING5M data, assuming that a single process is responsible for the signals at both frequencies. Clearly pure CMB ($\beta = 0$) is ruled out with high significance.

observed and spaced evenly in a ring around the NCP. The fields were observed only during transit, so that common mode contamination from the ground would be removed by the double switching.

As detailed in [23], over three years of observation, a variety of null tests demonstrated high signal-to-noise detection of structure in the RING5M data at both frequencies, consistent from year-to-year. These data were ultimately used to place a sensitive new constraint on the small-scale ($\ell \sim 600$) CMB anisotropy [23] that remains in excellent agreement with modern measurements (see Figure 1). By 1997, the Saskatoon experiment had released data that started to resolve some of the scatter at low- ℓ into a more convincing picture of a primary Doppler peak [24], and the CAT experiment had also released its preliminary results, which were in good agreement with ours [25].

3. Detection of Anomalous Emission

The analysis of the RING5M data was, however, not as simple as that story might imply. Taken together, the two frequency channels showed signals consistent with CMB (equal brightness temperature at 14.5 and 30 GHz) in roughly half the fields and signals consistent with a steep-spectrum foreground (comparable intensity at 14.5 and 30 GHz) in the other half, as can be seen in Figure 2. Modeling the dual-frequency data as a single Gaussian process with $T(\nu) \propto \nu^\beta$, we found that a pure CMB signal could be ruled out with high confidence, with the likelihood peaking for $\beta \sim -1$.

Modeling the data as the sum of a CMB component and a power-law foreground enabled us to place only a weak constraint of $\beta < -2$ on the foreground spectral index from the RING5M data alone. However, from the absence of

structure in 325 MHz maps of the NCP regions from the Westerbork Northern Sky Survey (WENSS, [26]), we were able to place a lower bound of $\beta > -2.2$ on the spectral index of a single foreground, making synchrotron emission an untenable model for the 14.5 GHz signals, unless the fields happen to be associated with an active region where the normally steep synchrotron spectrum is kept unusually flat by the injection of high-energy electrons, for example, a supernova remnant that has undergone recent repowering (see for example [27]). The lack of any correlation with the WENSS synchrotron maps, however, makes synchrotron of any variety an unlikely explanation.

Moreover, although the spectral index was consistent with free-free emission, the amplitude of the signals was not. Maps of the NCP from the Wisconsin H α Mapper (WHAM, [28]) were almost featureless; when convolved with the double-switched RING5M beam, the H α template for the RING5M fields predicted a free-free *rms* at 14.5 GHz from a warm ($\sim 10^4$ K) component that is nearly two orders of magnitude lower than the amplitude of the signals we detected. To reconcile the radio emission with the absence of structure in the H α maps would require a plasma temperature of at least 10^6 K. These considerations, and the lack of any correlation with the low-frequency synchrotron maps, led us to consider the radio emission “anomalous” (Leitch et al. [29]).

The dual-frequency data were ultimately used to separate this foreground component from the CMB signal to produce the bandpower reported in [23]. As can be seen in Figure 3, when this anomalous component was extracted from the 14.5 GHz and 30 GHz data assuming that $\beta = -2.2$, we found a remarkable correlation between the extracted anomalous component and the emission in the IRAS 100 μm

FIGURE 3: Extracted anomalous component, assuming that $\beta = -2.2$ (solid line) is overplotted with amplitudes from the IRAS $100\ \mu\text{m}$ map (dashed line). Both represent sky amplitudes, convolved with the double-switched beam pattern of the RING5M observations, indicated at the bottom left of the figure.

maps. The correlation is quite significant, as noted in [29]. Factoring in the artificial correlation introduced by the double-switched observing strategy, an analysis of the rank correlation between these two data sets indicates a probability to exceed of 10^{-6} , prompting a closer examination of the morphology of the NCP region, which we review in the next section.

4. Interpretation of the Anomalous Emission

A wide-field IRAS $100\ \mu\text{m}$ image of the NCP is shown in Figure 4, with the locations of the RING5M fields near $\delta = 88^\circ$ indicated for reference. As is clear from the figure, the fields are embedded in the wall of a prominent HI feature known as the North Celestial Pole Loop (after Heiles [30]). Heiles concludes from an examination of HI column densities, that the NCP Loop is unlikely to be a shell, but instead is probably filamentary in nature. (Note that the NCP Loop, near the north *Celestial* pole, is not to be confused with the North Polar Spur, a prominent feature near the north *galactic* pole, which is well understood as a supernova remnant.) The abundance of molecular species in individual clouds in the NCP Loop was extensively studied from 1970–1990 (see [31] for a review), and the magnetic fields and pressure support were investigated by Heiles [30], from Zeeman-splitting measurements of the 21-cm line at locations within and around the NCP Loop.

In the comprehensive study of Meyerdierks et al. [31], who analyze the radio continuum, X-ray, and far infrared properties of the NCP Loop, this structure is understood as the massive shell of an expanding cylindrical cavity in the galactic HI disk. At 408 MHz, the radio continuum shows a deep deficit within the Loop [32], consistent with expulsion of magnetized material from the interior of the shell. The model that best matches the HI velocity data, and at the same time explains the depth of the radio continuum deficit, has the cylinder inclined nearly along the line of sight.

FIGURE 4: IRAS $100\ \mu\text{m}$ map, showing the NCP Loop and the locations of the RING5M fields (near $\delta = 88^\circ$, top center). (Note that this figure is intended to illustrate the large-scale morphology of the NCP Loop—the location of the RING5M fields is indicated for reference only).

Given the morphology of the Loop, it is perhaps not surprising that interpretation of the high-frequency radio emission observed in the RING5M experiment as either synchrotron or free-free suggests an unusual kinematic environment. As noted earlier, the spectral flatness of the anomalous component could be explained most naturally by synchrotron emission if the Loop is associated with a supernova remnant that has undergone recent repowering. As previously pointed out by Heiles [30], however, the nonspherical nature of the shock inferred from the HI column densities suggests a different mechanism. Meyerdierks et al., furthermore, cite the absence of OB stars within the Loop and the deep radio deficit within the Loop that requires expulsion of magnetic material for a long distance along the line of sight, and suggest that infall of a cloud from the galactic halo may be a more natural explanation for the source of the shell [31].

Similarly, the shocked morphology of the Loop also makes high-temperature free-free a potentially viable explanation for the anomalous emission in this region. Meyerdierks et al. [31] also found an enhancement of soft X-ray emission in the interior of the shell, suggesting the presence of a thin hot medium within the cavity; they estimate that the temperature could be as high as $5 \times 10^5\ \text{K}$, with large uncertainties due to the estimated HI absorption.

We have argued for the reasonableness of interpreting the anomalous emission near the NCP as either flat-spectrum synchrotron or high-temperature free-free in the light of the $100\ \mu\text{m}$ morphology, HI velocity structure, radio continuum deficit, and soft X-ray emission, all of which indicate a shocked environment in the vicinity of the NCP. In the next section, however, we discuss an alternative explanation that explains the emission as arising from the dust itself, obviating

the need to invoke any special kinematic environment near the boundary of the Loop.

5. Discussion: Spinning Dust

Either of the explanations proposed earlier would rely on the superposition of emission from a shocked component at the edge of the cavity with emission from the dense neutral medium in the wall of the Loop to explain the extraordinary correlation of the anomalous component with the IRAS maps. In 1998, Draine and Lazarian proposed a more natural explanation for the dust correlation observed in the RING5M data, with the anomalous component arising from dipole emission from very small dust grains [33].

The model could also explain the all-sky dust-correlated component seen at $>7^\circ$ scales in the COBE DMR maps by Kogut et al. [34], and the marginal correlation with DIRBE reported at 1° by the Saskatoon experiment [35]. We note, however, that no new mechanism was required to explain these results, as neither of those authors found anything anomalous about the large-scale dust-correlated components. Both results were adequately explained by free-free emission from a warm-ionized component, with amplitudes consistent with predicted levels.

Kogut et al. cross-correlated the all-sky COBE DMR 2-year sky maps with far infrared COBE DIRBE maps and found evidence for a component of microwave emission that correlates with the large-scale structure in the infrared maps. They interpret this component as a free-free emission from 10^4 K ionized gas and interpret the correlation with the dust maps as due to evaporating cloud surfaces embedded in that ionized medium. Kogut et al. further note that the amplitude of this correlated free-free component is in good agreement with the predicted *rms* variation in the free-free signal at 7° scales, as inferred from fluctuations in the $H\alpha$ emission.

Similarly, de Oliveira-Costa et al. found that a cross-correlation of the 30 and 40 GHz Saskatoon data with the COBE DIRBE maps detects a correlated free-free component at 1° scales. They note that assuming an ℓ^{-3} power spectrum for the diffuse free-free emission, the amplitude of the correlated signal detected in the Saskatoon data is also in good agreement with the amplitude of the correlated signal detected by Kogut et al. on large scales. Accordingly, de Oliveira-Costa et al. argued that free-free contamination was the most likely explanation for the correlated emission at degree angular scales as well.

While the spinning dust model is certainly the simplest explanation for the observed dust correlations, it is likely that the anomalous component detected toward the NCP in the RING5M data represents a mixture of emission from several components. While the spinning dust models can reproduce the amplitude of the anomalous component at 30 GHz, a significant increase in the assumed grain dipole moment would be required to match the amplitude of the signals at 14.5 GHz [33]. At the same time, the coincidence of the RING5M fields with the wall of the NCP Loop is consistent with some or all of the emission arising from either flat-spectrum synchrotron or high-temperature free-free. We note that Draine and Lazarian advanced an argument

rejecting high-temperature free-free emission as a possible source of the anomalous component on energetic grounds [33]. That argument, however, was based on a conflation of two unrelated results: the localized small-scale emission from the wall of the NCP Loop, for which high-temperature free-free poses no energetic problems, and the full-sky dust-correlated component detected by COBE, for which high-temperature free-free was neither required nor suggested as an explanation.

The combination of increasingly sophisticated models and observations with better frequency resolution will ultimately decide whether spinning dust can explain the anomalous emission detected in the RING5M fields. What is clear from the results in this volume, however, is that the evidence for anomalous microwave emission is mounting in a variety of astrophysical contexts and that spinning dust may provide a cogent model for its origin.

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