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TENTATIVE DETECTION OF ELECTRIC DIPOLE EMISSION FROM RAPIDLY ROTATING DUST GRAINS

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ABSTRACT

We present the first tentative detection of spinning dust emission from specific astronomical sources. All other detections in the current literature are statistical. The Green Bank 140 foot telescope was used to observe 10 dust clouds at 5, 8, and 10 GHz. In some cases, the observed emission was consistent with the negative spectral slope expected for free-free emission (thermal bremsstrahlung), but in two cases it was not. One H II region (LPH 201.663+1.643) yields a rising spectrum, inconsistent with free-free or synchrotron emission at the $\sim 10\sigma$ level. One dark cloud (L1622) has a similar spectrum with lower significance. Both spectra are consistent with electric dipole emission from rapidly rotating dust grains (“spinning dust”), as predicted by Draine & Lazarian.

Subject headings: cosmic microwave background — diffuse radiation — dust, extinction — ISM: clouds — radiation mechanisms: thermal — radio continuum: ISM

1. INTRODUCTION

In the last decade, the *COBE* satellite and several ground- and balloon-based experiments (QMAP, Saskatoon, MAXIMA, BOOMERANG, TOCO, DASI, CBI, and others) have greatly increased our knowledge of cosmic microwave background (CMB) radiation. Some of these careful observations of the microwave sky have also revealed new and surprising features in the interstellar medium at $14\text{ GHz} < \nu < 53\text{ GHz}$. At frequencies above 100 GHz ($\lambda < 3\text{ mm}$), the emission from Galactic cirrus is consistent with thermal emission. This emission is a broken power law, with the break at $\sim 500\text{ GHz}$, interpreted by Finkbeiner, Davis, & Schlegel (1999) as emission from two dust components. Although this interpretation fits the data from 100 to 3000 GHz, a dramatic deviation arises at lower frequencies. This deviation motivates the work presented here.

The *COBE*/DMR data (7° FWHM) exhibit dust-correlated emission at 90 GHz at approximately the level predicted by a detailed model of the thermal dust spectrum based on DIRBE and FIRAS data (Finkbeiner et al. 1999). In the other DMR channels there is a pronounced excess—more than a factor of 10 at 31.5 GHz (Kogut et al. 1996). The 19 GHz data from Cottingham’s thesis (Cottingham 1987; Boughn et al. 1992) also indicate such an excess (de Oliveira-Costa et al. 1998). This microwave excess appears in the Saskatoon experiment as well, but with less significance (de Oliveira-Costa et al. 1997). Owens Valley Radio Observatory (OVRO) observations in a ring around the north celestial pole at 14 and 31 GHz have demonstrated a correlation of 14 GHz emission with dust at the highest resolution ($7'$) to date, but at a level ~ 1000 times brighter than the expected thermal (vibrational) dust emission

(Leitch et al. 1997). This excess has been called the “mystery component” (de Oliveira-Costa et al. 2001).

The spectral shape of these early measurements is consistent with free-free emission from ionized gas, motivating a comparison with H α maps. Leitch et al. (1997) noted the weakness of H α emission in the OVRO fields and concluded that only $T > 10^6\text{ K}$ gas (e.g., shock-heated gas in a supernova remnant) could produce the observed emission. The observed emission, however, would require an energy injection rate at least 2 orders of magnitude greater than that provided by supernovae (Draine & Lazarian 1998a). Another possibility is magnetic dipole emission³ from ferromagnetic or ferrimagnetic grains, resulting from thermal fluctuations in the magnetization of the grain material. This component is certainly present at some level but is subdominant in the current data (Draine & Lazarian 1999).

The currently favored emission mechanism is electric dipole emission from rapidly rotating dust grains, an idea first proposed by Erickson (1957) and improved upon by Ferrara & Dettmar (1994). Recent work by Draine & Lazarian (1998b) has refined this idea and shown that ion encounters with dust grains are the dominant spin-up mechanism, leading to concrete predictions of emission as a function of the temperature, density, and ionization fraction of the surrounding gas. This emission mechanism has never been unambiguously observed but can be made to agree with the observed microwave data for reasonable model parameters. It was previously impossible to tell if the excess emission results from spinning dust or free-free emission because the predicted spectral slope is similar for $20\text{ GHz} \lesssim \nu \lesssim 40\text{ GHz}$, and earlier observations were insufficient to rule out either mechanism. The Tenerife data (de Oliveira-Costa et al. 1999) at 10 and 15 GHz have good leverage on the spectral shape but provide only a statistical detection by

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³ Note that this mechanism has nothing to do with grain rotation.

cross-correlation. To date, no one has observed spinning dust emission from a specific source.

The spinning dust is expected to have an emission peak at ~ 15 GHz (in temperature units) and to be dominated by free-free below ~ 5 –10 GHz, so by choosing frequencies in this range, one can hope to unambiguously detect this component. We have obtained data for several dust clouds at 5, 8, and 10 GHz, a frequency range over which the spinning dust spectrum differs measurably from that of free-free or synchrotron emission.

2. OBSERVING STRATEGY

This study used the NRAO⁴ 43 m (“140 foot”) telescope at Green Bank shortly before its decommissioning on 1999 July 19. Cassegrain C-band (5 GHz) and X-band (8–10 GHz) receivers were used with a 300 MHz bandwidth and gave a typical system temperature of 30–60 K.

Data were obtained during two runs, 1999 April 22–27 and June 1–6. The nutating subreflector on the 140 foot can switch at up to 2.5 Hz with a 12' throw. Switching is restricted by hardware to a position angle of $292^\circ.5$ (east of north) for the X-band (8–10 GHz) receiver. A second level of switching was accomplished by driving the telescope along the position angle (PA) = $292^\circ.5$ direction at a rate of $3' \text{ s}^{-1}$, completing a 48' scan every 16 s (Figs. 1 and 2). During the scan, the on–off difference was recorded by a digital continuum recorder (DCR) for every chop. The same strip was then observed in the “reverse” direction, a sequence requiring nearly 1 minute for a round trip (including turnaround time). During the turnaround time, a calibration noise source was flashed at 1 Hz. In C band

⁴ The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

FIG. 1.—Scan location for the LPH cloud (black lines) overplotted on SHASSA (Gaustad et al. 2001) H α (gray scale) and SFD98 $E(B-V)$ (contours). Contour levels are 1, 1.5, 2, and 3 mag. H α brightness is measured in rayleighs with the scale on the right. $1 \text{ R} = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

FIG. 2.—Scan location for L1622 (black lines) overplotted on H α (grayscale) and SFD98 $E(B-V)$ (mag) (contours).

(5 GHz), switching is restricted to a direction orthogonal to the scan line, so switching was not performed at 5 GHz.

The beam of the 140 foot telescope at 5 GHz (6' FWHM) is well matched to the Schlegel, Finkbeiner, & Davis (1998, hereafter SFD98) 100 μm map, to which the data are compared in § 3. At 8 and 10 GHz, multiple parallel scans were performed to subsample a 6' Gaussian beam. For a typical system temperature of 40 K and 200 ms integration (2 Hz switch, so four samples per second with 50 ms blanking time) we obtain a theoretical sensitivity of 7.3 mK per difference per polarization. Typically, 1 hr was spent on each target in each band, yielding a theoretical sensitivity of ~ 1 mK per polarization per pointing. Observations were also attempted at 18 GHz, but the system temperature was too high to obtain any useful data. The 14 GHz receiver was not available at the time of our observing run.

A bandwidth of 300 MHz was used throughout the run. RFI affected a negligible number of the measurements, and these are easily found and discarded later in the analysis.

3. ANALYSIS

The DCR records the difference between the on position and off position some 12' away as the telescope scans over a target. The P.A. of the chop is fixed at $292^\circ.5$, so as not to interfere with point source measurements when scanning east-west or north-south. This arrangement is ideal for point sources because the off never crosses the source and the baseline difference is easily established when the on position is away from the source. When observing the diffuse interstellar medium (ISM), there is no local zero-brightness position to compare to along the scan. We therefore scan parallel to the chop direction to reduce the problem to one dimension.

The measured difference for each chop (Fig. 3a) is dominated by sidelobe and atmospheric contamination and drifts with time. All these effects are generally smooth functions of time and are removed with a low-order polynomial fit with appropriate outlier rejection. The data are then

FIG. 3.—For the diffuse H II region LPH 201.663+1.643: (a) observed differences vs. time; (b) differences folded vs. R.A. for forward (black line) and return (gray line) scans; (c) data (dashed line) and SFD98-based (solid line) prediction using the conversion factor for 10 GHz from de Oliveira-Costa et al. (1999) for the forward scan; (d) correlation of data vs. prediction for the forward scan; (e) same as (c) for the return scan; and (f) same as (d) for the return scan. Correlation slopes would be unity at 10 GHz for a correct prediction and would be somewhat less at 8 GHz. The points in (c) and (e) represent a subsampled 6" FWHM Gaussian, so the right ascension range is reduced relative to (b). Only RCP data are shown. LCP data look similar, and there is no evidence for circular polarization.

“folded” by plotting as a function of sky position (Fig. 3b) to reveal the beam-convolved and differenced structure on the sky. Because of sidelobe and atmospheric contamination, an artificial slope is present in these plots; it is also fitted and removed. The data are binned in right ascension and the median of each bin is overplotted. Note that for the source LPH 201.663+1.643 shown in Figure 3, there is a difference between forward and reverse scans. In the forward direction, the on position is slightly less than 12' ahead of the off position because the telescope is moving

east. In the reverse direction, on is slightly more than 12' away as the telescope drives west. This means that forward and reverse scans must be analyzed separately, even though they are overplotted in Figure 3b.

Finally, we consider the correlation slope between predicted and observed emission. Because of the double-switched observing strategy, it is impossible to uniquely recover the observed flux of an object. A suitable template, however, may be convolved with the same observing strategy and compared to observation. The SFD98 100 μ m and

TABLE 1
CORRELATION SLOPES

NAME	ν	RCP		LCP		AVERAGE	N_σ
		Forward	Return	Forward	Return		
L1622.....	5.00	1.29 ± 0.39	3.49 ± 0.84	0.48 ± 0.38	3.05 ± 0.77	1.31 ± 0.25	5.3
L1622.....	8.25	1.25 ± 0.29	0.26 ± 0.37	0.67 ± 0.41	0.52 ± 0.35	0.75 ± 0.17	4.4
L1622.....	8.25	1.14 ± 0.37	1.24 ± 0.44	1.05 ± 0.38	1.11 ± 0.33	1.13 ± 0.19	6.1
L1622.....	9.75	1.65 ± 0.67	0.76 ± 0.77	0.84 ± 0.73	0.78 ± 0.65	1.03 ± 0.35	2.9
LPH.....	5.00	53.16 ± 5.28	57.01 ± 5.68	54.12 ± 5.39	58.05 ± 5.90	55.41 ± 2.77	20.0
LPH.....	8.25	25.45 ± 1.69	25.92 ± 1.91	29.16 ± 1.93	29.50 ± 2.25	27.22 ± 0.96	28.4
LPH.....	9.75	23.96 ± 2.09	23.33 ± 1.70	27.89 ± 2.49	27.17 ± 1.90	25.25 ± 0.99	25.4

NOTE.—Correlation slopes for forward and return scans of RCP and LCP polarizations. These correlation slopes are for T_B vs. a prediction of $50 \mu\text{K}/I_{100}$, where I_{100} is the DIRBE temperature-corrected *IRAS* intensity at $100 \mu\text{m}$ in MJy sr^{-1} . This temperature-corrected map may be obtained by dividing the SFD98 $E(B-V)$ prediction by 0.0184. The prediction used includes a factor of $\frac{1}{2}$ for single-polarization measurements, so RCP and LCP are combined by averaging, not adding. Values in the table may be multiplied by 50 to obtain units of $\mu\text{K}/I_{100}$ in order to compare to, e.g., de Oliveira-Costa et al. 1999. Note that L1622 was observed twice at 8.25 GHz.

temperature maps are used to predict a microwave brightness temperature (Figs. 3c and 3e) using the factor of $50 \mu\text{K}$ at 10 GHz per $I_{100, \mu\text{m}}$ in MJy sr^{-1} (de Oliveira-Costa et al. 1999). The correlation slope is then measured and tabulated; it should be consistent with 1 at 10 GHz for a correct prediction and vary at other frequencies with the shape of the spinning dust spectrum. Separate numbers are tabulated for each combination of polarization and direction (Table 1). The prediction includes a factor of $\frac{1}{2}$ for comparison to the single-polarization data. This is why the left-circular polarization (LCP) and right-circular polarization (RCP) measurements are combined by averaging rather than adding them. The (total Stokes I) T_B per I_{100} in units of $\mu\text{K} (\text{MJy sr}^{-1})^{-1}$ may be obtained from Table 1 by multiplying the correlation slopes by 50. Note that L1622 was observed on two occasions at 8.25 GHz (Fig. 4).

3.1. Calibration

For calibration standards, we use the fits of C. Salter (2001, private communication), who follows Kuehr et al. (1981) in using the form $\log_{10} S = a_0 + a_1 x + a_2 \exp(-x)$, where $x = \log_{10} \nu$, ν is in MHz, and S is in Jy. With $a_0 = 3.523$, $a_1 = -0.779$, and $a_2 = -3.732$ for 3C 138, we obtain $S(5, 8.25, 9.75 \text{ GHz}) = (3.54, 2.50, 2.22) \text{ Jy}$. This agrees with

a simple power-law fit to 87GB (Gregory & Condon 1991) and the Wright et al. (1991) survey to within 2%. Cross-checks were done with 3C 245 and BL Lac, and agreed to 5%. The definitive calibration was determined by 3C 138, however, because it was observed near L1622 and LPH 201.663 + 1.643 in both space and time.

4. RESULTS

Of the targets observed (Table 2), two clouds show significant dust-correlated emission at 5–10 GHz. The non-detection of the other targets is not very surprising because the parameters describing the physical properties of these clouds span a wide range of values, so the relative intensities may vary widely. Both of the detected clouds (L1622 and LPH 201.663 + 1.643) show a steep rise from 8 to 10 GHz, with the 5 GHz brightness apparently contaminated by free-free (Table 3). In order to compare these results to previous correlation measurements, results from several experiments are overplotted on the Draine & Lazarian (1998b) models in Figure 5. All data and model curves are normalized to emission per H atom for ease of comparison. In practice this is done by normalizing to SFD98 $E(B-V)$ values and then applying a conversion factor. The free-free emission curves corresponding to two values of

TABLE 2
TARGET LIST

Name	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	Result	Comment
L1622	05 54 23	+01 46 54	Detected	Dark cloud
LPH 201.663+1.643.....	06 36 40	+10 46 28	Detected	Diffuse H II
L1591	06 09 55	+13 44 34	ND	Dark cloud
IRAS 07225–1617	07 24 47	–16 23 21	Weak	<i>IRAS</i> source
IRAS 15522–2540	15 55 16	–25 49 40	No 10	<i>IRAS</i> source
VSS II-79	16 33 58	–23 43 48	Negative correlation	Near L1709C
IRAS 18146–1200	18 17 29	–11 58 52	Eight only	Near H II
IRAS 19441+2926	19 46 08	+29 33 34	ND	<i>IRAS</i> source
IRAS 23339+4811	23 36 23	+48 28 01	ND	<i>IRAS</i> source
IRAS 23350+4815	23 37 28	+48 32 18	ND	<i>IRAS</i> source

NOTE.—List of targets observed. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. ND = not detected. Most of these have other names in the literature. VSS II-79 has a significant negative correlation with dust emission, perhaps from an H II shell around the dust filament. LPH = Lockman et al. 1996, *IRAS* = Joint *IRAS* Science Working Group 1985, L = Lynds 1962, and VSS = Vrba, Strom, & Strom 1976.

FIG. 4.—Same as Fig. 3 but for L1622. Notice that the correlation slope is approximately unity in this region.

TABLE 3
EMISSION PER H

NAME	$N(\text{H}) \times 10^{21} \text{ cm}^{-2}$	EMISSION ($\times 10^{-19} \text{ Jy sr}^{-1} \text{ H}^{-1}$)		
		$j_{\nu}(5 \text{ GHz})/n_{\text{H}}$	8.25 GHz	9.75 GHz
L1622.....	18	7.8 ± 3.9	6.6 ± 1.3	10.1 ± 3.4
LPH	27	147 ± 17	191 ± 7	247 ± 10

NOTE.— $N(\text{H})$ is estimated by using the SFD98 $E(B-V)$ extinction estimate and a conversion factor of $N(\text{H})/E(B-V) = 8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$.

FIG. 5.—Model dust emissivity per H atom for DC, MC, CNM, WNM, and WIM conditions (as in Draine & Lazarian 1998b, Fig. 9). Solid thin lines are total emissivity, while dashed lines are rotational emission. Gray lines are emission from free-free for given n_H , or rather $\langle n_e n_p \rangle / \langle n_H \rangle$ averaged along the line of sight. The top thick line is the sum of free-free, vibrational dust, and 12 times the WIM spinning dust model, shown for reference. Also shown are measurements from the COBE/DMR (open diamonds) from Finkbeiner et al. (1999), similar to Kogut et al. (1996), Saskatoon (open circles; de Oliveira-Costa et al. 1997), the Cottingham & Boughn 19.2 GHz survey (open square; de Oliveira-Costa et al. 1998), OVRO data (filled squares; Leitch et al. 1997), Tenerife data (filled circles; de Oliveira-Costa et al. 1999), and this paper: LPH 201.663+1.643 (crosses) and L1622 (stars). The OVRO points have been lowered a factor of 3 relative to Draine & Lazarian (1998b, Fig. 9), because the unusual dust temperature near the north celestial pole caused an underestimate of the H column density along those lines of sight. Given the large range of model curves, all measurements are consistent with some superposition of spinning dust, vibrational dust, and free-free emission.

$\langle n_e n_p \rangle / \langle n_H \rangle$ are shown, with the upper curve determined by an emission measure derived from the H α survey⁵ of Gaustad et al. (2001).

Because free-free emission clearly contributes to the measured signal, it is desirable to have an independent limit on the free-free and show that it is consistent with our measurements. This limit may be derived from H α as follows. The emission coefficient j_v for free-free, with electrons assumed to interact with ions of charge $Z_i e$ and particle density n_i , is

$$j_v = 5.44 \times 10^{-16} \frac{g_{\text{ff}} Z_i^2 n_e n_i}{T^{1/2}} e^{-h\nu/kT} \text{ Jy sr}^{-1} \text{ cm}^{-1}, \quad (1)$$

where g_{ff} is the Gaunt factor for free-free. For microwave frequencies, a useful approximation is

$$g_{\text{ff}} = \frac{3^{1/2}}{\pi} \left[\ln \frac{(2kT)^{3/2}}{\pi e^2 v m_e^{1/2}} - \frac{5\gamma}{2} \right], \quad v_p \ll v \ll \frac{kT}{h}, \quad (2)$$

where γ is the Euler constant ($\gamma \approx 0.577$) and v_p is the plasma frequency (Spitzer 1978). Evaluating for $v = 10^{10}$ Hz and $T = 10^4$ K we find $g_{\text{ff}} \approx 4.69$ and $J(10 \text{ GHz}) = 78.8 \text{ Jy sr}^{-1}$ for $\text{EM} = 1 \text{ pc cm}^{-6}$. The emission measure for

these clouds may be estimated from the H α emission shown in Figures 1 and 2. Note that $1 \text{ R} = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and corresponds to $\text{EM} \approx 2 \text{ pc cm}^{-6}$ for H α at $T = 10^4$ K. For LPH 201.663+1.643, the peak of the cloud is about 200 R, or $\text{EM} = 400$. Using a conversion factor of $N(\text{H}) = 8 \times 10^{21}$ for 1 mag $E(B-V)$, we get free-free emission of $3.2 \times 10^4 \text{ Jy sr}^{-1}$ for $N(\text{H}) = 2.4 \times 10^{22}$, or $j_v/n_H = 1.3 \times 10^{-18} \text{ Jy sr}^{-1} \text{ atom}^{-1}$ at 10 GHz. The SFD98 map shows about 6 mag extinction ($\tau \approx 6.5$) for an H α photon traveling completely through this cloud, so this free-free estimate should be taken as a lower limit for photons from within the cloud. If the H α -emitting material is uniformly mixed with dust in a cloud with total optical depth τ , the effective flux observed is

$$J_{v, \text{eff}} = \frac{J_v}{\tau} \int_0^\tau d\tau' e^{-\tau'} = \frac{J_v}{\tau} (1 - e^{-\tau}). \quad (3)$$

In the limit of large τ , the flux is simply reduced by a factor of τ . In Figure 5, the level of predicted free-free has been multiplied by a factor of 7 and appears to be in good agreement with the uniform mixture hypothesis. Of course, this result is very sensitive to the configuration of material on the front side of the cloud, so the agreement may be largely coincidental.

5. FUTURE WORK

5.1. Requirements

In order to demonstrate convincingly that the excess emission detected by this work is electric dipole emission from spinning dust, the following requirements are proposed.

1. Observations for any line of sight must agree with the model over a wide frequency range (5–60 GHz) for reasonable values of the model parameters (gas and dust temperature, density, and ionization fraction). The observations must be inconsistent with free-free alone at high confidence. Simply stated, the spectral shape should exhibit a “roll-off” on both sides of the emission peak.

2. Variation in the spectrum of spinning dust emission should trace variation in the parameters as derived from spectral line information and the SFD98 maps. The nature of this variation should be (at least qualitatively) similar to that anticipated by the Draine & Lazarian (1998b) model.

3. Alternative explanations for the excess (such as magnetic dipole emission) should be ruled out by the spectral shape. Polarimetry is also useful, as the spinning dust emission is relatively unpolarized (Lazarian & Draine 2000).

None of these requirements are met by the current paper, so our interpretation of the observed excess is only tentative. During the next few years, however, dramatically improved data will become available.

5.2. Prospects

There are compelling reasons to pursue this project with an interferometer in the southern hemisphere, such as the Cosmic Background Imager (CBI; Padin et al. 2001). The synthesized beam is 5'–8', well matched to the 6' of the IRAS (Beichman et al. 1988) map as reprocessed SFD98. CBI has 10 channels from 26 to 36 GHz providing spectral information with high sensitivity. Many prospective targets

⁵ The data are available at <http://amundsen.swarthmore.edu/SHASSA/>.

are in the southern half of the sky toward the Galactic center. The frequency coverage is not ideal for separation of free-free from spinning dust, but the high sensitivity (41 μ K in 900 s for the highest resolution configuration) should allow clean detections and easy comparison with the Jonas, Baart, & Nicolson (1998) Rhodes/HartRAO survey at 2.326 GHz for free-free removal. The Degree Angular Scale Interferometer (DASI; Halverson et al. 1998) has many of the same properties but a larger beam of about 20', and is therefore more appropriate for comparison with the Rhodes/HartRAO data (20').

The recently launched *Microwave Anisotropy Probe* (MAP; Bennett et al. 1997) has full-sky coverage at 22, 30, 40, 60, and 90 GHz with beams of 56', 41', 32', 21', and 14' (FWHM), respectively. These data will complement the interferometer data nicely. With data from these projects, a decisive detection of spinning dust emission may be possible in the near future.

6. CONCLUSIONS

We have explored a far-IR-selected sample of dust clouds spanning a wide range of IR color temperature, column density, and ionization fraction. Our target selection procedure rejected the radio-bright H II regions as poor targets because free-free was expected to overwhelm spinning dust emission. In spite of this prejudice, one H II region (from the LPH catalog of diffuse H II regions in Lockman, Pisano, & Howard 1996) made the list and provided a very significant detection. A dark cloud, L1622, was also detected and found inconsistent with free-free emission at a lower confidence. This is the first detection of a rising spectrum source at 8–10 GHz consistent with spinning dust. The amplitude of this emission per H atom apparently varies by a factor of at least 30, somewhat more than theoretically expected. Some adjustment of model parameters will be needed to explain the brightness of LPH 201.663+1.643, but the current model of Draine & Lazarian could possibly accommodate the new data (B. T. Draine 2001, private communication). Note that magnetic dipole emission from ferromagnetic or ferrimagnetic grains (Draine & Lazarian 1999) is substantially weaker than the observed signal from LPH 201.663+1.643, but significant contributions from such a mechanism cannot currently be ruled out.⁶ Other

attempts have been made to explain the large variation using 12 μ m emission as a tracer of the small grain population (de Oliveira-Costa et al. 2001). We caution that the interpretation of these data must remain tentative until a larger sample meeting the criteria in § 5 can be obtained.

Cold neutral clouds are an obvious target choice for future work because free-free emission is likely to be subdominant in them. Diffuse ionized gas also appears to be an excellent target, since ion-dust interactions are effective at spinning up the grains. As long as the density is low, as in the LPH list (Lockman et al. 1996), H II regions may be the optimal targets for future work with DASI, CBI, and MAP.

This measurement is rather tenuous, as was the discovery of Galactic radio emission 60 years ago (Reber 1940). The signal was immediately interpreted as free-free (Heney & Keenan 1940) but was later recognized as synchrotron radiation. Those emission mechanisms are now essential tools for ISM research in the Milky Way and distant galaxies. With the expected increase in astronomical capability at microwave frequencies in the near future, we anticipate that spinning dust will make a useful addition to this toolbox.

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⁶ Because this emission may be $\sim 30\%$ polarized for aligned grains of strongly magnetic material, polarization measurements would be helpful.

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