IDENTIFYING THE RADIO BUBBLE NATURE OF THE MICROWAVE HAZE

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ABSTRACT

Using seven-year data from the Wilkinson Microwave Anisotropy Probe, I identify a sharp “edge” in the microwave haze at high southern Galactic latitude (−55° < b < −35°) that is spatially coincident with the southern edge of the “Fermi haze/bubbles.” This finding proves conclusively that the edge in the gamma rays is real (and not a processing artifact), demonstrates explicitly that the microwave haze and the gamma-ray bubbles are indeed the same structure observed at multiple wavelengths, and strongly supports the interpretation of the microwave haze as a separate component of Galactic synchrotron (likely generated by a transient event) as opposed to a simple variation of the spectral index of disk synchrotron. In addition, combining these data sets allows for the first determination of the magnetic field within a radio bubble using microwaves and gamma rays by taking advantage of the fact that the inverse Compton gamma rays are primarily generated by scattering of cosmic microwave background photons at these latitudes, thus minimizing uncertainty in the target radiation field. Assuming uniform volume emissivity, I find that the magnetic field within the southern Galactic microwave/gamma-ray bubble is ≳5 μG above 6 kpc off of the Galactic plane.

Key words: Galaxy: center – ISM: bubbles – ISM: structure – radio continuum: ISM

Online-only material: color figures

1. INTRODUCTION

Recent full-sky data sets by the Wilkinson Microwave Anisotropy Probe (WMAP) and the Fermi Gamma-Ray Space Telescope have revealed the presence of a new and very large structure in the Milky Way. This emission manifests as an excess of both microwaves and gamma rays when removing Galactic diffuse emission associated with known emission mechanisms at these wavelengths and has come to be named the “WMAP haze” (Finkbeiner 2004; Dobler & Finkbeiner 2008; Dobler 2012) and the “Fermi haze/bubbles” (Dobler et al. 2010; Su et al. 2010) in the microwaves and gamma rays, respectively.

In microwaves, the haze is synchrotron emission with a brightness temperature as a function of frequency $T \propto \nu^{\beta_H}$ with $\beta_H \approx -2.5$ (Dobler 2012). This spectral dependence implies that the underlying electron spectrum (number density as a function of energy) is given by $dN/dE \propto E^{-\gamma}$ with $\gamma \approx -2$ for energies $\sim 10$ GeV. In gamma rays, the haze/bubbles is most likely due to inverse Compton (IC) scattering of the starlight, infrared, and cosmic microwave background (CMB) interstellar radiation field (ISRF). In the original discovery paper of the Fermi haze/bubbles, Dobler et al. (2010) showed that the spectrum of the gamma rays is consistent with IC emission from the same electron population responsible for the microwave haze synchrotron in both energy dependence and overall normalization. However, as shown by Dobler (2012), the existence of $\sim 1$–10 GeV IC gamma rays at high latitude where the ISRF is dominated by the CMB require electrons with energies $\sim$TeV.

Taken together, the microwaves and gammas imply that the electron spectrum is roughly a power law from $\sim 1$–1000 GeV suggesting that either the electrons have not had sufficient time to cool (the cooling time in this energy range is $\sim 10^6$–10$^7$ yr; see Su et al. 2010) or are continuously being accelerated within the haze/bubbles (e.g., Dobler et al. 2011; Mertsch & Sarkar 2012). The large volume of hard spectrum cosmic rays has made it difficult to identify an underlying origin for the haze/bubbles and there have been numerous studies exploring the possibilities from starbursts (Biermann et al. 2010), to Galactic winds (Crocker & Aharonian 2011), to jet-blown bubbles (Guo & Mathews 2012; Guo et al. 2012; Yang et al. 2012), and even co-annihilation of dark matter particles in the Galactic halo (Dobler et al. 2011).

The goal of this Letter is not to delve into the origin question any further, but rather to address one of the main discrepancies between the microwave and gamma-ray haze/bubbles; namely, the observation that (as pointed out by Su et al. 2010), the gamma-ray emission appears to have a sharp edge at latitudes $|b| \approx 50^\circ$, while the microwaves fall off in intensity closer to $|b| \approx 35^\circ$ (see Dobler 2012). In Section 2 I describe the component separation methods used to uncover both the microwave and gamma-ray haze/bubbles in WMAP and Fermi data, and in Section 3 I will show that, in fact, the microwaves also have a sharp edge at $b \approx -50^\circ$ that is spatially coincident with the edge in the Fermi emission. In Section 4 I summarize this work and describe the important implications for this microwave edge on the interpretation of the Galactic haze/bubbles.

2. METHODS

The most straightforward method for uncovering the Galactic haze/bubbles in both the WMAP and Fermi maps is via “template fitting,” which uses maps at other wavelengths to morphologically trace known emission mechanisms in the data. A simple linear regression of these templates (using an...
appropriate mask) against the data yields template amplitudes which can be used to “peel away” these foregrounds. In this Letter, the templates are fit at each frequency (energy) for the WMAP (Fermi) data implying that no constraint is put on the shape of the spectrum of each emission mechanism, though it is assumed that the spectrum does not vary significantly with position. The details of the template fitting used here can be found in Dobler & Finkbeiner (2008) and Dobler (2012) (hereafter DF08 and D12, respectively) for the microwaves and Dobler et al. (2010) for the gammas.

2.1. WMAP Analysis

For the WMAP analysis, the templates used are the Schlegel et al. (1998, SFD) dust map evaluated at 94 GHz by Finkbeiner et al. (1999, FDS), the Haslam et al. (1982) 408 MHz map, and the Finkbeiner (2003) Hα composite map. These templates are meant to trace the three primary Galactic emission mechanisms at microwave wavelengths: thermal and spinning dust (FDS), soft synchrotron (Haslam), and free–free (Hα). In addition, I include the haze and disk bivariate Gaussian templates used in D12. Because the CMB is of comparable brightness to the haze at WMAP wavelengths, I presubtract the CMB5 estimate for the haze given by DF08. Pixels for which the dust extinction at Hα is greater than 1 mag and for which the Hα intensity is greater than 10 Rayleigh are masked in the fit, as well as all point sources in the WMAP and Planck ERCSC (30 GHz to 143 GHz) catalogs. These Galactic templates are fit to the WMAP data via the regression equation $w_v = c - P \tilde{a}_v$, where $w_v$ is a map of the WMAP data at frequency $v$, $c$ is the CMB5 estimate, and $P$ is a matrix of template maps. The equation is solved for the coefficients $\tilde{a}_v = (P^T n^{-1} P)^{-1} (P^T n^{-1} w_v - c)$ where $n$ is the mean noise in a given band. The haze residual in each band is defined as $R_H(x) = w_v - c - P \tilde{a}_v + a^{H}_v \times H(x)$, where $H$ is the haze template. That is, it is the residual of the regression plus the amount of haze template removed. To account for spectral variations with position, the fit is performed independently on the regions given in D12. A composite $R_H$ is constructed from the union of those regions.

2.2. Fermi Analysis

At Fermi energies, there are three main sources of diffuse gamma-ray emission from the Galaxy: bremsstrahlung, IC, and $\pi^0$-decay. The latter component is the dominant emission mechanism at high latitudes. For the purpose of comparing the haze/bubbles in Fermi to the WMAP emission, this Letter concentrates on the extreme high southern Galactic latitudes, $b < -35^\circ$. High northern latitudes are contaminated by dust-correlated emission in both the microwaves (likely spinning dust; see Draine & Lazarian 1998; Dobler et al. 2009) and the gammas ($\pi^0$-decay) and make a clear separation of the haze/bubbles emission difficult in both data sets.

Because the $\pi^0$s are created via collisions of cosmic-ray protons with the interstellar medium (ISM), I use the SFD map of dust column density as a template for this emission since it is a reasonable tracer of dust and gas in our Galaxy. It is important to note that this template is an integrated column density while $\pi^0$ emission is proportional to the ISM density times the proton number density, and so line-of-sight effects render the SFD map an imperfect tracer of $\pi^0$ emission. This has dramatic effects at low latitudes as pointed out by Dobler et al. (2011); however for $b < -35^\circ$ as is used here, a simple two-template (SFD plus bivariate Gaussian; see Dobler et al. 2010) description of the data is sufficient to isolate the Fermi haze/bubbles emission.

As in Dobler et al. (2010) the fit minimizes the log-likelihood, $\ln L = \sum_i [k_i \ln \mu_i - \mu_i - \ln(k_i!)]$, where $k_i$ is the map of observed counts at pixel $i$, $\mu_i$ is a synthetic counts map given by $\mu(E) = S(E) \times \text{mask} \times \text{exposure}$, and $S(E)$ is the synthetic sky map $S(E) = b_{\text{SFD}} \times S_F + b_H \times H + b_{\text{uni}}$. This log-likelihood is minimized over the template amplitudes $b_{\text{SFD}}, b_H$, and $b_{\text{uni}}$ (a spatially uniform contribution) for pixels outside of the mask and for $b < -35^\circ$. I emphasize that this is not meant to represent a perfect model for the diffuse emission from our Galaxy, but rather serves to effectively isolate the Fermi haze/bubbles emission so that it can be morphologically compared to the microwave emission. For a thorough analysis of Galactic diffuse emission observed by Fermi see The Fermi-LAT Collaboration (2012). Last, the analysis was also redone using the Fermi diffuse model (gll_iem_v02.fits) as opposed to the SFD map as a template and the results are not significantly changed.

3. RESULTS

Directly comparing the haze/bubbles residuals at high latitude will involve weighted stacking of $R_H$ in multiple WMAP bands, and so it is useful to estimate the extent to which the spectrum of the microwave emission is affected by the CMB bias described in DF08. This bias comes from the fact that any CMB estimate used in Section 2 will inherently have some residual foregrounds after cleaning emission from the Galaxy, and since that CMB estimate is presubtracted with a fixed CMB spectrum, this imprints a bias on the inferred haze spectrum (see DF08). The CMB estimate used here is generated by the linear combination of the WMAP data that minimizes the variance in unmasked pixels of $c = \sum_j \xi_j w_j$, where $w_j$ is the WMAP data minus the FDS prediction for thermal dust emission in each band and $\sum_j \xi_j = 1$ for $w_j$ in thermodynamic $\Delta T$ units.

This last constraint on $\xi$ has the consequence that the measured spectrum cannot be used to infer the true spectrum. That is, while the amplitude of the bias can be estimated (DF08), the exact bias cannot be known. However, it is possible to answer the question: for a foreground with a given true spectrum $T_{\text{true}}(\nu) \propto \nu^\beta_{\text{true}}$, what would be the inferred spectral index $\beta_{\text{inferred}}$? This $\beta_{\text{inferred}}$ is shown as a function of $\beta_{\text{true}}$ in Figure 1. Despite the very large possible CMB bias, for a true spectral index of $\beta_{\text{true}} = -2.5$, the inferred spectral index when comparing K to Ka band would only be biased by $\delta \beta = -0.015$ given the CMB5 coefficients $\xi = (0.11, -0.48, 0.12, 0.16, 1.09)$. The implication is that the spectrum measured by DF08 and D12 for the microwave haze $T_H(x) \propto \nu^{\beta_H}$ with $\beta_H \approx -2.5$ is likely not significantly biased and the underlying electron population is very close to $dN/d\xi \propto \nu E^{-2.4}$.

The full-sky residuals $R^W_H$ and $R^F_H$—the haze/bubbles in WMAP and Fermi data—are shown in Figure 2 and illustrate several of the key characteristics noted in previous studies: scaling $R^W_H \propto \nu^{1.5}$ yields roughly equal brightness indicating a $T \propto \nu^{-2.5}$ spectrum (Dobler & Finkbeiner 2008), $R^W_H$ and $R^F_H$ are roughly spatially coincident at low latitudes (Dobler et al. 2010; Su et al. 2010), at $1^\circ$ smoothing $R^W_H$ appears to fade quickly below $b = -35^\circ$ (Dobler 2012), and $R^F_H$ appears to

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\footnote{All gamma-ray results in this Letter are derived with 1.6 year Fermi maps constructed as described in Dobler et al. (2010).}

\footnote{Planck Collaboration 2012, which utilize large frequency coverage to eliminate this bias.}

\footnote{http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html}
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Dobler

-3.5 -3.0 -2.5 -2.0
true spectral index $\beta$

$\delta \beta$ (inferred minus true)
$\delta \beta = -0.015$
$\beta = -2.5$
$
\nu_0 = 23 \, \text{GHz}, \quad \nu_1 = 33 \, \text{GHz}$

Figure 1. Difference between the inferred and true spectral index as a function of the true index for the CMB estimate used in this Letter. The inferred haze spectrum measured by Dobler & Finkbeiner (2008) and Dobler (2012) is $\beta_H \approx -2.5$. Since the CMB bias for a $T \propto \nu^\beta$ foreground with $\beta \approx -2.5$ is only 0.015, the measured spectrum is not significantly biased.

(A color version of this figure is available in the online journal.)

have a sharp “edge” at $|b| \sim 50^\circ$ (Su et al. 2010). The lack of a similar edge in the WMAP data at $b \sim -50^\circ$ has led to some ambiguity about whether the WMAP haze and the Fermi haze/bubbles are in fact the same structure. However, creating the weighted stack of the WMAP emission $R^K_H + (\nu_{Ka}/\nu_K)^{2.5} \times R^K_{Ka}$ and smoothing to 2° (i.e., the same smoothing as the Fermi map) reveals an edge in the microwave haze that appears coincident with the southern edge in the gamma-ray bubbles.

To assess the significance of this feature, I zoom in on the extreme southern latitudes with $b < -35^\circ$ in Figure 3 (corresponding to heights >6 kpc above the GC), and a clear sharp edge is evident in both the gamma rays and the microwaves. As noted in Su et al. (2010) the center of the Fermi bubble at these latitudes is roughly $\ell \sim -4; 5$. Binning the sky into polar bins centered on the bubble center ($\ell_{cen}, b_{cen}$) = ($-4;5, -35^\circ$), integrating annuli with unmasked pixel latitudes $<-35^\circ$ (see the figure), and plotting as a function of distance from the bubble center, the lower left panel of Figure 3 shows the southern Fermi bubble edge described in Su et al. (2010). The same plot generated with the microwaves also shows a clear edge that is spatially coincident with the Fermi bubble edge, located at roughly $r = 17^\circ$ from the bubble center. For the 2° smoothing shown here, the statistical significance of the edge identified in this way is high for both the $K$-band microwave haze/bubbles and the $K/Ka$-band weighted stack (a null test calculated by setting $(\ell_{cen}, b_{cen}) = (-180^\circ, -35^\circ)$ shows no evidence for an edge at the Galactic anti-center). Finally, by integrating a uniform brightness, infinitely sharp edge (smoothed to 2° and with the same mask) in the same way, Figure 3 shows that the Fermi and WMAP bubbles are consistent with having a sharp edge.

Figure 2. Top row: the microwave haze in the WMAP $K$ and $Ka$ band smoothed to 1°. As noted in Dobler (2012), the microwaves seem to fade quickly below $b \approx -35^\circ$ in contrast to the Fermi haze/bubbles (lower left) which continue down to $b \approx -50^\circ$. The Fermi residual is just the difference between the data and the Fermi diffuse model for visualization (see Section 2). However, when smoothing the WMAP data to 2° and stacking with weights given by $(\nu/\nu_K)^{2.5}$ it can be seen in the lower right panel that there is an edge in the microwaves at $b \approx -50^\circ$ as well.

(A color version of this figure is available in the online journal.)
Figure 3. Top left: the southern Fermi bubble at latitudes $b < -35^\circ$ where the edges are most discernible in the gammas. Top right: the same region but for the WMAP K-band haze/bubbles smoothed to $2^\circ$. There is a clear spatial correspondence between the Fermi haze/bubbles and the WMAP haze, including an edge at high latitudes. Taking the center of the emission to be $(\ell, b)_{cen} = (-4.5, -35.0)$ (dashed white line) and plotting the intensity of the gammas and microwaves as a function of distance from the center (i.e., integrating over the angular bins shown in dotted lines in the upper right panel) reveals an unambiguous detection of an edge at high latitudes that is spatially coincident with the edge in the Fermi haze/bubbles as shown in the bottom left panel. This emission is well fit by a flat brightness profile with a sharp edge at $r \sim 17^\circ$ from the center (performing the same annular bin using $\ell_{cen} = 180^\circ$ yields no such feature). Lower right: the same but integrating over radial bins (for two ranges in $r$) as a function of angular bin.

Figure 4. Same as the bottom panels of Figure 3, but using the Fermi diffuse model in the template fit.

While this is a clear detection of an edge in the WMAP haze, there is angular dependence in the microwave emission that is not readily apparent in the gamma rays. Figure 3 shows the emission as a function of annulus angle both inside and outside the haze/bubbles ($r < 20^\circ$ and $r > 20^\circ$ from $(\ell_{cen}, b_{cen})$) in the lower right panel and indicates an “arm” of emission in the microwaves for annular angles less than $\sim 30^\circ$. No such arm is evident in the gamma rays. For annular angles greater than $30^\circ$ there is no other clear structure present in the microwaves though the microwave bubble emission is detected in each angular bin (i.e., there is an excess of emission interior to the microwave edge compared to exterior). Figure 4 shows the same results, but using the Fermi diffuse model template in the fit. While the overall amplitude of the gamma-ray signal is slightly lower, the edge is still spatially coincidence with the edge in microwaves.
The Galactic plane), which argues for a leptonic (IC) rather than hadronic (CMB) origin. However, above http://galprop.stanford.edu/).

in Figure 3.

favored by the detection of the microwave haze at and inconsistent with a hadronic scenario, which is also dis-

Figure 5 shows the spectrum of the Fermi haze/bubble for $b < -35^\circ$ and within $r < 17^\circ$ of the bubble center for four different spectral estimates: using the SFD map or the Fermi diffuse model in the template fit and estimating the spectrum via unmasked pixels in $dE/\nu$ or $K_H$. Below $\sim 4$ GeV, the four different types of spectral estimates differ, indicating a systematic bias in the derived spectrum due to imperfect template approximations and/or brighter, softer components leaking into the residuals. However, above $\sim 4$ GeV, the spectra are all consistent with IC from electrons scattering predominantly off of CMB photons and having a spectrum $dN/\nu \propto E^{-2}$ (i.e., the same as that required to make the $T \propto u^{-2.5}$ microwave haze spectrum). Interestingly, this spectrum of the “cap” of the bubble is somewhat softer than that found by Dobler et al. (2010) and Su et al. (2010) who include lower latitudes, in agreement with the IC scenario (since the higher energy optical and IR components of the ISRF have lower amplitude at high latitudes) and inconsistent with a hadronic scenario, which is also dis-favored by the detection of the microwave haze at $b < -35^\circ$ in Figure 3.

The IC intensity $I(n_e, R)$ is a function of the electron number density $n_e = dN/\nu dE$ and the ISRF intensity $R$ while the synchrotron brightness $T_{\text{syn}}(n_e, B)$ depends on $n_e$ and the magnetic field $B$ (Blumenthal & Gould 1970; D12). Thus, assuming the same $n_e = N_0 \times E^{-2}$ is responsible for both signals and given the above ISRF estimate, combining the microwave and gamma-ray data in Figure 3 provides a measurement of $B$. A uniform volume emissivity model integrated along the line of sight yields $B \sim 5 \mu G$ within the southern bubble. Although uncertainty in the spatial distribution of the electrons within the bubble and the specific magnetic field geometry are likely at the factor two level, this represents the first estimate of the magnetic field within a radio bubble using complimentary microwave and gamma-ray emission.

4. SUMMARY

Using seven-year WMAP data to isolate the microwave haze and comparing this to the Fermi haze/bubbles at southern Galactic latitudes less than $-35^\circ$, I have presented the detection of a sharp edge in the microwave haze that is coincident with the southern Fermi bubble edge. This microwave bubble edge is evident when smoothing the haze to $2^\circ$ in both the $K$-band WMAP data and a stack of the $K$ and $Ka$ band weighted by $\nu^{-2.5}$, where $\nu$ is the microwave band. I have also shown explicitly that, for the CMB estimate used in this study as well as Dobler (2012), the $\nu^{-2.5}$ spectrum of the microwave haze/bubbles is not significantly biased by systematics indicating that the electrons responsible for generating this synchrotron have a number density as a function of energy $dN/\nu dE \propto E^{-2}$, in excellent agreement with the IC interpretation of the gamma rays.

The detection of an edge in the microwave haze $\sim 50^\circ$ off the plane and coincident with the Fermi haze/bubbles has several important consequences. First, it proves conclusively that the microwave haze and the Fermi bubbles are the same structure observed at multiple wavelengths. Second, given the vastly different experiments, the detection of an edge in microwaves proves that the edge in gamma rays is real and not due to processing artifacts or low photon counts in the maps generated by Dobler et al. (2010) and Su et al. (2010). Finally, the sharp edge, coupled with the hard spectrum of the emission, suggests a transient event for the origin of the microwave haze, indicating that it is a separate component of diffuse emission in our Galaxy and not merely a spatial variation in the spectral index of the disk synchrotron.

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5 For this calculation, the Porter et al. (2008) ISRF estimates were used (see http://galprop.stanford.edu/).