HIGH GALACTIC LATITUDE INTERSTELLAR NEUTRAL HYDROGEN STRUCTURE AND ASSOCIATED (WMAP) HIGH-FREQUENCY CONTINUUM EMISSION

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ABSTRACT

Spatial associations have been found between interstellar neutral hydrogen (H i) emission morphology and small-scale structure observed by the Wilkinson Microwave Anisotropy Probe (WMAP) in an area bounded by $l = 60^\circ, 180^\circ$ and $b = 30^\circ, 70^\circ$, which was the primary target for this study. This area is marked by the presence of highly disturbed local H i and a preponderance of intermediate- and high-velocity gas. The H i distribution toward the brightest peaks in the WMAP Internal Linear Combination (ILC) map for this area is examined, and by comparing with a second area on the sky it is demonstrated that the associations do not appear to be the result of chance coincidence. Close examination of several of the associations reveals important new properties of diffuse interstellar neutral hydrogen structure. In the case of the high-velocity cloud MI, the H i and WMAP ILC morphologies are similar, and an excess of soft X-ray emission and Hα emission have been reported for this feature. It is suggested that the small angular scale, high-frequency continuum emission observed by WMAP may be produced at the surfaces of H i features interacting one another, or at the interface between moving H i structures and regions of enhanced plasma density in the surrounding interstellar medium. It is possible that dust grains play a role in producing the emission. However, the primary purpose of this report is to draw attention to these apparent associations, without offering an unambiguous explanation as to the relevant emission mechanism(s).

Subject headings: cosmology: miscellaneous — ISM: general

1. INTRODUCTION

Examination of the Wilkinson Microwave Anisotropy Probe (WMAP) images immediately fires the imagination, especially the summary image that has received so much publicity, the so-called internal linear combination (ILC) map. It was produced after subtraction of suspected Galactic components from the five-channel observations carried out by WMAP and then combining the data. But do the remaining structures in the ILC map truly reveal the fingerprints of processes that took place shortly after the universe was born? On close inspection, certain features in the WMAP ILC map (hereafter the ILC map) look hauntingly familiar to those who have spent their careers studying Galactic interstellar neutral hydrogen (H i) structure. This can be recognized in a visual comparison of the ILC image referenced above and the all-sky H i column density map. Several extended areas of excess emission at high Galactic latitudes ($b > 30^\circ$) are present in both maps; for example, in the areas around Galactic longitude and latitude $(l, b) = (170^\circ, 80^\circ)$, which exhibit extensive intermediate- and high-velocity H i, and around $(l, b) = (160^\circ, -35^\circ)$. Also, a striking area of extended ILC structure that reaches from $(l, b) = (230^\circ, 0^\circ)$ through $(l, b) = (315^\circ, -35^\circ)$ has a counterpart in the H i data, where a tongue of emission follows roughly the same axis, emerging from the Galactic disk H i at $(l, b) = (255^\circ, -15^\circ)$ and stretching through $(l, b) = (310^\circ, -35^\circ)$. These apparent associations initiated a closer look at the H i structure and ILC data for several areas of sky. If the ILC small-scale structures correspond to cosmological signals, absolutely no associations with H i structure, other than those due to pure chance, should be found.

The thrust of this paper is to highlight the fact that a close relationship between ILC and H i structures appears evident in the data. This deserves closer attention. Lagache (2003) has examined the relationship between WMAP structure and interstellar H i by considering the H i emission integrated over all velocities as a function of position and suggests that excess WMAP emission may be associated with small, transiently heated dust particles. In the data presented below, the apparent associations are found by examining H i area maps produced by integrating over limited velocity ranges as opposed to the total H i content. Small-scale H i features due to relatively weak and narrow emission profile structure tend to become lost when maps of integrated H i content are plotted.

In §2 the data and analysis are described. In §3 several of the most informative examples of close correspondences and morphological associations between H i and ILC structure are presented. In the discussion in §4 reference is made to possible dust-related emission mechanisms that may be invoked to account for the associations, and a geometric model for producing the apparent morphological associations is outlined. In the conclusions in §5 the hope is expressed that others will be motivated to seek confirmation (or otherwise) of the claims made here.

2. DATA AND ANALYSIS

The goal of the present study was to determine whether parallels exist between small angular scale ($1^\circ$–$2^\circ$) Galactic H i structure and high radio-frequency continuum emission features observed by WMAP. Neutral hydrogen emission profile data with an angular resolution of $0.6^\circ$ were obtained from the Leiden-Dwingeloo sidelong-corrected H i Survey (Hartmann & Burton 1997), as well as the more extensive Leiden-Argentina-Bonn (LAB) All-Sky Survey (Kalberla et al. 2005). In our study the distribution of the H i brightness was initially plotted as a function of Galactic longitude and latitude $(l, b)$ maps every $10$ km s$^{-1}$ in velocity, integrating over a $10$ km s$^{-1}$-range. The focus of the first phase of this study is region A, bounded by $l = 60^\circ$ and $180^\circ$, $b = 40^\circ$ and $70^\circ$, for which 25 maps covering the velocity range $-200$...

1. See G. Hinshaw et al. (2006) at http://lambda.gsfc.nasa.gov.
2. See http://www.astro.uni-bonn.de.
| No. (1) | ILC Temp. (2) | H $\times$ Velocity (3) | H $\times$ Amplitude (4) | Angular Offset (5) |
|---------|---------------|-------------------------|--------------------------|-------------------|
| 1       | 139.6         | 0.227                   | -5                       | 37                |
| 2       | 139.6         | 0.227                   | 5                        | 139.6             |
| 3       | 174.4         | 0.223                   | -95                      | 175.0             |
| 4       | 160.3         | 0.218                   | -115                     | 163.0             |
| 5       | 176.1         | 0.212                   | -5                       | 176.5             |
| 6       | 140.3         | 0.202                   | -45                      | 140.3             |
| 7       | 172.3         | 0.199                   | -65                      | 168.2             |
| 8       | 174.0         | 0.182                   | -125                     | 171.5             |
| 9       | 174.0         | 0.182                   | -15                      | 173.1             |
| 10      | 177.2         | 0.182                   | -105                     | 175.5             |
| 11      | 168.1         | 0.180                   | -125                     | 167.0             |
| 12      | 168.1         | 0.180                   | -25                      | 168.2             |
| 13      | 174.7         | 0.172                   | -15                      | 175.5             |
| 14      | 174.4         | 0.172                   | -5                       | 174.0             |
| 15      | 101.8         | 0.169                   | -5                       | 100.8             |
| 16      | 78.2          | 0.168                   | -5                       | 78.5              |
| 17      | 82.3          | 0.168                   | -15                      | 80.0              |
| 18      | 165.7         | 0.168                   | -125                     | 167.0             |
| 19      | 165.7         | 0.168                   | -15                      | 165.9             |
| 20      | 91.5          | 0.166                   | -135                     | 91.0              |
| 21      | 170.2         | 0.165                   | -55                      | 170.0             |
| 22      | 135.4         | 0.164                   | -45                      | 135.9             |
| 23      | 151.2         | 0.162                   | -165                     | 152.3             |
| 24      | 172.6         | 0.161                   | -15                      | 173.3             |
| 25      | 112.3         | 0.159                   | -87                      | 112.8             |
| 26      | 62.6          | 0.157                   | -15                      | 63.5              |
| 27      | 165.6         | 0.155                   | -15                      | 166.2             |
| 28      | 65.0          | 0.155                   | -115                     | 64.5              |
| 29      | 68.6          | 0.150                   | -145                     | 66.6              |
| 30      | 93.2          | 0.166                   | -5                       | 94.0              |
| 31      | 121.6         | 0.150                   | -140 to -110             | See text          |
| 32      | 113.4         | 0.149                   | -15                      | 115.4             |
| 33      | 89.3          | 0.146                   | -170                     | 89.0              |
| 34      | 158.8         | 0.145                   | -55                      | 157.5             |
| 35      | 94.6          | 0.143                   | -165                     | 94.7              |
| 36      | 77.0          | 0.143                   | -25                      | 79.0              |
| 37      | 117.0         | 0.138                   | -85                      | 117.5             |
| 38      | 78.2          | 0.138                   | -25                      | 77.0              |
| 39      | 62.6          | 0.137                   | -15                      | 61.1              |
| 40      | 167.3         | 0.136                   | -135                     | 167.0             |
| 41      | 172.8         | 0.132                   | -5                       | 172.0             |
| 42      | 174.7         | 0.131                   | -55                      | 172.7             |
| 43      | 163.8         | 0.130                   | -125                     | 162.1             |
| 44      | 131.8         | 0.128                   | -75                      | 131.0             |
| 45      | 125.2         | 0.127                   | -65                      | 123.9             |
| 46      | 138.7         | 0.126                   | -55                      | 139.3             |
| 47      | 166.3         | 0.125                   | -45                      | 165.8             |

**TABLE 1**

**TARGET AREA ASSOCIATIONS**

*Amplitude (9) and ILC Temp. (2) are not explicitly shown in the table.*
to +50 km s\(^{-1}\) with respect to the local standard of rest were produced.

The H\(_i\) and ILC data in the form of \(l, b\) maps were visually examined in a manner akin to blink comparison using a transparent overlay of the ILC data to search for apparent associations between small-scale structures. The Galactic H\(_i\) sky is filled with small-scale structure evident in such \(l, b\) maps (e.g., see Hartmann & Burton 1997), so that any attempt to compare with small-scale structure found in the ILC data, which also consists of many small peaks of order 1\(^{\circ}\)–2\(^{\circ}\) across, will lead to chance agreements in position. This was tested (to first order) by also comparing the ILC map for the region A data with the H\(_i\) \(l, b\) maps for region B, chosen as \(l = 180^\circ - 300^\circ\), \(b = 40^\circ - 70^\circ\). This is located symmetrically opposite the Galactic anticenter with respect to region A. To this end, 20 H\(_i\) maps from \(-120\) to +80 km s\(^{-1}\) at 10 km s\(^{-1}\) intervals were produced to cover the extent of the Galactic H\(_i\) emission in region B.

For regions A and B, lists of the brightest ILC peaks were produced. For region A this included all 51 ILC peaks with amplitudes \(\geq 0.100\) mK. For region B, 51 peaks were also used whose amplitudes are \(\geq 0.117\) mK. The centers and amplitudes of the ILC and the apparently associated H\(_i\) peaks were recorded and the angular separations between the ILC and apparently associated H\(_i\) peaks calculated. The same was done for two lists of 51 negative-amplitude ILC peaks for regions A and B whose amplitude limits are \(\leq -0.131\) and \(\leq -0.144\) mK, respectively.

### 2.1. Statistics of the Apparent Associations

The morphologies of both H\(_i\) and ILC structures are complex, yet distinct brightness features of a small angular extent of order 1\(^{\circ}\)–2\(^{\circ}\) are common in both classes of data. To derive a rough estimate of the likelihood of finding chance associations between ILC and H\(_i\) peaks, it is possible to calculate how likely it is that one of \(N_{\text{peaks}}\) in the ILC map will coincide by chance with one of \(N_{\text{H}\_i\_peaks}}\) in the H\(_i\) maps for the same area, \(A\), assuming both to be randomly distributed on the sky.

The number, \(N\), of H\(_i\) peaks expected to lie by chance within a distance \(r\) of any ILC peak, that is, within an area of order \(\pi r^2\) deg\(^2\) centered on the ILC peak, is given by

\[
N = \pi r^2 A^{-1} N_{\text{peaks}} N_{\text{H}\_i\_peaks}}.
\]  

This is a first-order approach to the problem and ignores an edge effect that will be introduced for large separations, \(r\), which reduces the effective area, \(A\), to be entered in equation (1). At small separations this is a minor correction. This estimate is in any case limited for several other reasons. For example, the two classes of structure are treated as being random on the sky, which is not so for H\(_i\), because it is known to be filamentary. The apparent associations that are found (see Table 1 below) are also spread over all velocities with associations at anomalous velocities relatively overrepresented in region A. In addition, no account is taken of morphological similarities between the two types of structure other than to search for sets of closed contours on a scale of 1\(^{\circ}\)–2\(^{\circ}\). Morphological similarities reported in § 3.3 below are difficult to quantify in a formal manner, but in any event would reduce the likelihood of chance associations.

For each of the H\(_i\) maps, about 10–15 contour levels were plotted, and the number of peaks, defined as sets of closed contours with dimensions of order 1\(^{\circ}\)–2\(^{\circ}\), was counted on each of the H\(_i\) maps. A given H\(_i\) peak on one contour map can usually be followed over at least two or three adjacent maps for H\(_i\) at velocities outside \(\pm 20\) km s\(^{-1}\) with respect to the local standard of rest. In one case the relevant H\(_i\) peak could be followed over as many as eight maps (i.e., \(80\) km s\(^{-1}\)). Furthermore, low-velocity H\(_i\) \((-20\) km s\(^{-1}\) \(< v < 20\) km s\(^{-1}\)), narrow emission-line components of order 6 km s\(^{-1}\) wide tend to appear in only one contour map, integrating over a 10 km s\(^{-1}\) width. On average, each H\(_i\) peak is identified in two adjacent velocity maps so that the value of \(N_{\text{H}\_i\_peaks}}\) is half of the number found in all the H\(_i\) + b \(l, b\) maps used in the analysis.

In the case of region A, about 452 obvious H\(_i\) peaks in the 25 area maps were counted, which sets \(N_{\text{H}\_i\_peaks}} = 226\). For region B the H\(_i\) is more highly concentrated at low latitudes and low velocities, and fewer H\(_i\) peaks were counted in the 10 km s\(^{-1}\) wide H\(_i\) maps at \(b > 40^\circ\). Using the same criterion, that on average an H\(_i\) peak can be followed over two adjacent H\(_i\) maps, \(N_{\text{H}\_i\_peaks}} = 130\) is used in the calculations.

### 2.2. The Angular Distribution of Apparent Associations

In Figure 1 the distribution of the angular offsets in 0.2\(^{\circ}\) bins between ILC and H\(_i\) features for a number of data comparisons are shown. Figure 1a presents the histogram of angular separations...
between ILC and H\textsc{i} peaks when the ILC peaks for region A are compared to the H\textsc{i} data for region A. It shows a clear excess at small angular separations with the peak occurring at about 0.8°, only slightly larger than the beamwidth. Beyond 1° separation, the values fall below expectations for chance associations indicated by a dashed line, which represents equation (1). Of the 51 ILC peaks in region A, some 60 associations make up the histogram. As will be discussed below, this carries a clue to the nature of the phenomenon producing the associations.

A similar excess of offsets between ILC and H\textsc{i} peaks with small angular separations is seen in Figure 1b for region B, which shows the results obtained by overlaying the ILC data on the H\textsc{i}
maps for the same area. The numbers involved are smaller than for region A, with the bulk of the H\textsc{i} concentrated at low velocities.

An estimate of the significance of the apparent associations found in Figures 1a and 1b can be obtained by overlaying the ILC data for region B on the H\textsc{i} peaks for region A, and vice versa. Figure 1c shows what is found when the region B ILC peaks are overlaid on region A H\textsc{i} maps. Figure 1d shows the converse. Neither plot shows evidence for systematic small-scale angular offsets other than might be expected from chance.

Finally, negative ILC peaks and H\textsc{i} structure were compared. Figure 1e shows the results found by overlaying region A negative-amplitude peaks on region A H\textsc{i} maps, and Figure 1f shows the results derived by overlaying region B negative ILC peaks on H\textsc{i} data for the region B. Figure 1g plots the results obtained when comparing the negative ILC peaks for region B with the H\textsc{i} for region A, and Figure 1h shows the converse. None of these four plots show convincing evidence for systematic small-scale angular offsets other than might be expected from chance.

Another way to summarize these results is to compare the total number of cases of close associations at small angular separations. For example, for those offset by 1.1° or less, region A contains 41 cases, compared to the 23 estimated from chance according to equation (1), which compares to 20, 17, and 21 cases for the plots in Figures 1c, 1e, and 1g, which are independent estimates of what is to be expected due to chance associations. Similarly, for region B the direct comparison produces 22 cases of small offsets compared to 13 predicted by chance, with the other three comparisons summarized in Figures 1d, 1f, and 1h, producing 10, 9, and 6, cases respectively. This suggests that the close associations found in region B are also significant.

These plots point to the possibility that the ILC continuum peaks are located at the boundaries of Galactic H\textsc{i} emission features, which implies at the interface between H\textsc{i} structures and surrounding plasma, or at the interface between colliding H\textsc{i} structures.

3. CASE STUDIES OF ASSOCIATED H\textsc{i} AND CONTINUUM STRUCTURES

If the close associations between ILC and H\textsc{i} structures found especially in region A are indeed significant, then they should be expected to reveal underlying aspects of interstellar gas dynamics that may allow the cause of the relationships to be understood. That would then remove the study from the realm of statistics to that of interstellar physics.

The cases outlined below emerged from the study of an extended version of region A with the latitude boundary set to 30°. Table 1 lists the apparent associations with an identifying number for the ILC peak given in column (1) and its Galactic coordinates (in degrees) in columns (2) and (3). The peak ILC brightness temperature in mK is given in column (4). Column (5) gives the center velocity in km s\(^{-1}\) with respect to the local standard of rest of the H\textsc{i} map used to determine the positions of the relevant H\textsc{i} feature; hence −95 km s\(^{-1}\) refers to the H\textsc{i} map, integrating from −100 to −90 km s\(^{-1}\). Columns (6) and (7) give the Galactic coordinates for the H\textsc{i} peak, with the amplitude in units of K km s\(^{-1}\) in column (8). The angular offset in degrees between associated peaks is given in column (9).

Table 1 includes 64 ILC peaks with amplitudes ≥0.100 mK. All but two of these appear to have associated H\textsc{i} peaks, yet the table includes 83 entries for H\textsc{i} associated with the remaining 62 ILC peaks. This is consistent with multiple H\textsc{i} structures being involved in creating some of the continuum emission peaks. In those directions where the most dramatic associations between ILC and H\textsc{i} structure were noted, the H\textsc{i} data were examined in more detail by using H\textsc{i} maps made by integrating over 5, 2, or 1 km s\(^{-1}\) and latitude-velocity b, r plots with a view to obtaining further insights into the nature of the possible relationship between the two forms of emission.

In most of the plots below, the ILC data are shown as contours overlaid on the H\textsc{i} morphology plotted using inverted gray-scale shading, and these examples are offered because they each reveal something interesting and unexpected about the nature of interstellar matter. This is regarded as highly significant because these directions would never have been chosen for closer study if it were not for the apparent associations with the continuum emission peaks highlighted in the ILC map.

3.1. Source 25 at (l, b) = (112.3°, 57.8°): Directly Overlapping H\textsc{i} and Continuum Features

Figure 2a shows the brightness of a high-velocity (v ≤ −100 km s\(^{-1}\)) H\textsc{i} feature, source 25 from Table 1, centered at −118 km s\(^{-1}\), integrated over 5 km s\(^{-1}\) (peak value 51 K km s\(^{-1}\)). Figure 2b shows the brightness of an intermediate-velocity (between −100 and −30 km s\(^{-1}\)) H\textsc{i} feature centered at −87 km s\(^{-1}\), integrated over 5 km s\(^{-1}\) (peak value 47 K km s\(^{-1}\)). By using Gaussian analysis of the H\textsc{i} profiles every 0.5° in latitude and longitude across the peaks, the coordinates of the centers of the H\textsc{i}
structures were accurately derived and found to be identical in latitude (to <0.1°) and also identical to the latitude center of the ILC peak. The centers of two $H\text{I}$ features are identical in longitude, but offset from the ILC peak by 0.3°, half the beamwidth used in the $H\text{I}$ studies.

Examination of the latitude-velocity $b$, $v$ plot at $l = 112°$ for this feature revealed no significant $H\text{I}$ emission at $-100$ km s$^{-1}$ between the two peaks seen in Figures 2a and 2b. However, a marked lack of low-velocity $H\text{I}$ emission around zero velocity is revealed. (Low velocity is defined as between $+30$ and $-30$ km s$^{-1}$.) Figure 2c shows the integrated $H\text{I}$ content over the velocity interval $-8$ to $+2$ km s$^{-1}$ with the continuum contours overlaid. The peak in the ILC structure is clearly colocated with a lack of low-velocity $H\text{I}$. Also at low velocities an $H\text{I}$ peak at $(l, b) = (115°, 57°)$ is associated with a secondary peak in the continuum emission. Further relationships emerge when the integrated $H\text{I}$ emission between $-130$ and $-120$ km s$^{-1}$ is examined (Fig. 2d). Two $H\text{I}$ maxima at $(l, b) = (113°, 55°)$ and $(115°, 54°)$ overlap $H\text{I}$ minima seen in Figure 2c.

These plots suggest a direct relationship between high- and intermediate-velocity $H\text{I}$ and a distinct minimum in low-velocity $H\text{I}$, with all of them related to the presence of an ILC continuum emission peak. This contrasts with those models that would place the high-and intermediate-velocity $H\text{I}$ at very different distances, well removed from local $H\text{I}$. For example, Wakker (2001) places the high-velocity gas at distances of several kiloparsecs with the intermediate-velocity $H\text{I}$ at about 1 kpc, both of which contrast with the realm of high-latitude, low-velocity $H\text{I}$, which is local at distances of order 50–100 pc. Blaauw & Tolbert (1966) originally noted that intermediate-velocity $H\text{I}$ has a relative lack of low-velocity gas is a hallmark of that area of sky encompassed by region A, which places them both within about 100 pc of the Sun. Here we find striking evidence in Figure 2 that $H\text{I}$ structure in all three velocity regimes is related, something that would not have been noticed but for the apparent association with a significant peak in the ILC structure. This implies that $H\text{I}$ gas in all three velocity regimes in this direction is local. (The possibility that small-scale, intermediate-velocity structure is associated with a lack of low-velocity gas has been briefly noted by Burton et al. [1992], as well as Kuntz & Danly [1996], without their following up on the implications.)

3.2. Sources 11 and 31 Centered at $(l, b) = (119.5°, 57°)$ and the Association between High- and Low-Velocity $H\text{I}$

Figure 3a shows the high-velocity gas integrated between $-140$ and $-110$ km s$^{-1}$ associated with two ILC continuum peaks, 11 and 31 (Table 1) identified in Figure 3b. The ILC peaks are linked by a ridge of emission straddled by two $H\text{I}$ features (peak amplitudes 22 K km s$^{-1}$), whose morphologies closely follow the continuum radiation contour lines. Gaussian analysis of the $H\text{I}$ profiles in a 0.5° grid for the entire area covered in Figure 3a was carried out and allowed the center velocities of the two $H\text{I}$ components to be determined. They are $-127$ and $-118$ km s$^{-1}$ for the northern and southern peaks, respectively. The Gaussian analysis also allowed the $H\text{I}$ column density for two other features to be mapped, shown in Figures 3b and 3c. Their presence was recognized in a set of $H\text{I}$ emission profiles at $l = 120°$ shown in Figure 3d. Most striking is a component at $-8$ km s$^{-1}$, that is seen only at $(l, b) = (120°, 57°)$. It has a peak column density of $7 \times 10^{18}$ cm$^{-2}$, and its morphology is plotted in Figure 3b, which shows that it is located precisely on the saddle in the continuum contours between two peaks. Even more striking is the fact that it is unresolved in angle.

Figure 3c shows the column density plot for the $-17$ km s$^{-1}$ feature evident in Figure 3d, again based on the results of the Gaussian analysis of the area profiles (peak column density $19 \times 10^{18}$ cm$^{-2}$). The location of this component also appears related to the presence of the continuum ridge, with the southern peak located at the position of the HV peak that nestsles in the indentation (or pinch) in the continuum emission ridge. At this stage of the analysis, no clear relationship between intermediate-velocity $H\text{I}$ structure and other features in the area of Figure 3 has been noted. However, very weak positive velocity $H\text{I}$ emission is also found toward this structure, but it will require confirming observations to determine whether it is real.

The plots in Figure 3 represent the second example of a close relationship between $H\text{I}$ structures at low and high velocities, with each of them related to the presence of an ILC feature. In addition, the discovery of the angularly unresolved, low-velocity, high Galactic latitude emission peak is unprecedented and deserving of observations at much higher angular resolution.

3.3. Continuum Source 33 at $(l, b) = (89.3°, 34.5°)$ and Associated High-Velocity $H\text{I}$

Figure 4 illustrates the dramatic association between ILC emission peak 33 (Table 1) and $H\text{I}$. Here nine inverted gray-scale images of the $H\text{I}$ at different velocities are overlaid by a contour map of the ILC structure. All the $H\text{I}$ plots are single-channel maps (1 km s$^{-1}$ wide) and the peak brightness temperatures are of order 0.8 K, except for the map at $-200$ km s$^{-1}$, where the peak is 0.3 K and at $-150$ km s$^{-1}$, where it is 1.1 K. The limits of the associated $H\text{I}$ emission are $-135$ km s$^{-1}$, at the same location as the peak at $-140$ km s$^{-1}$, and $-205$ km s$^{-1}$. The $H\text{I}$ centroid of emission shifts in velocity as it follows the ridge of the ILC emission feature, with a bifurcation of the $H\text{I}$ peak starting at $-170$ km s$^{-1}$ to produce two components that “move” along opposite sides of the continuum ridge as the velocity is increased.

A preliminary attempt to sketch the structure revealed in these $H\text{I}$ maps at smaller velocity intervals suggests a twisted pattern around an axis defined by the continuum radiation, possibly related to helical magnetic field structure around this axis. Higher resolution $H\text{I}$ data are desirable to untangle the $H\text{I}$ structure in this fascinating area. Note that the map of total $H\text{I}$ in these directions carries no hint of the existence of the structure seen in Figure 4, because it is very faint compared to low-velocity gas in this area of sky.

Examination of $b$, $v$ plots and emission profile data for this area reveal further details that are relevant to understanding the apparent relationship between $H\text{I}$ and ILC features. This is illustrated in Figure 5a, in which several $H\text{I}$ emission profiles cutting across the continuum feature seen in Figure 4 are shown. In a manner similar to that reported in § 3.2 above, a distinct additional component, in this case at $-40$ km s$^{-1}$, emerges in one of the profiles. Its morphology integrated between $-42$ and $-38$ km s$^{-1}$ is shown in Figure 5b as an inverted gray-scale image (peak value 6.7 K km s$^{-1}$) with the same ILC contours shown in Figure 4 overlaid. Figure 5c illustrates in contour map form how closely this intermediate-velocity $H\text{I}$ structure (contours from 3 K km s$^{-1}$ in steps of 0.05 K km s$^{-1}$) mimics the continuum contours seen in Figure 5b. Their axes are aligned to better than 5°. This $H\text{I}$ component is clearly associated with the continuum, as well as the $H\text{I}$ structure at high velocities seen in Figure 4.

Further examination of the $b$, $v$ contours reveals a phenomenon also found for the $H\text{I}$ continuum association noted in § 3.1 (Fig. 2) above, a dearth of low-velocity emission where the anomalous velocity $H\text{I}$ structure shows a peak. This is
illustrated in Figure 5d, where the integrated H\textsc{i} emission from 
$-5$ to $+15$ km s$^{-1}$ (peak 36 K km s$^{-1}$) is shown. A distinct mini-
num (36 K km s$^{-1}$) compared to the maximum value in this
plot (112 K km s$^{-1}$) in the low-velocity integrated H\textsc{i} emission
is found at the location of the peak in the intermediate-velocity
H\textsc{i} emission at $-40$ km s$^{-1}$. This, in turn, coincides with the
location of continuum source 32 and the HV structure seen in
Figure 4.

3.4. Close-up View of HVC MI

Figure 6 shows the inverted gray-scale image of the H\textsc{i} bright-
ness associated with the high-velocity cloud MI integrated over
the velocity range $-140$ to $-100$ km s$^{-1}$. The double H\textsc{i} peaks
are offset from and parallel to a pair of ILC peaks, sources 19 and
57. A third ILC peak, source 43, is also associated with a weak
H\textsc{i} feature; see Table 1. This main double H\textsc{i} feature is well known
and corresponds to the high-velocity cloud HVC MI.

A crucial clue as to the likely cause for associations between
the small-scale H\textsc{i} and high-frequency continuum structures is
found in a report of excess soft X-ray emission toward HVC MI
found by Herbstmeier et al. (1995). Their Figure 7a has been
adapted to correspond to the data in Figures 6a and 6b and is shown
as Figure 6c, where the contours correspond to the H\textsc{i} emission
from HVC MI, similar to the data in Figure 6a. The shaded pixels
overlaid correspond to areas of excess soft X-ray emission. Fur-
thermore, Tufte et al. (1998) have reported excess H\textsc{ii} emission at

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several positions toward HVC MI. The close spatial relationship seen in Figure 6c between the X-ray hot spots and the H\textsc{i} and the high-frequency continuum emission observed by WMAP, as well as the presence of H\textsc{ii} emission, contains critical clues that should lead to understanding the nature of the associations between H\textsc{i} and weak, high-frequency continuum emission. It is predicted that the high-velocity cloud MII, a companion to MI but located outside region A, will show a similar relationship between H\textsc{i} and ILC structures. (The outcome of this prediction will be discussed in a future report.)

In Figure 6d the ILC contours are overlaid on the low-velocity H\textsc{i} data. Again, a relative lack of LV emission, here integrated between $-5$ and $+5$ km s$^{-1}$, is seen to be closely associated with the continuum and H\textsc{i} structure at high velocities. The H\textsc{i} column...
density is 1.8 K km s$^{-1}$ for the minimum, compared to 6.2 K km s$^{-1}$ for the maximum, at the top left of Figure 6d.

4. DISCUSSION

Several authors have considered the possibility that excess WMAP emission may be produced by spinning dust grains, in turn possibly associated with H i. For example, Davies et al. (2006) note that the spectrum of the low WMAP frequency data is consistent with such a model. In contrast, Banday et al. (2003) find evidence in earlier Cosmic Background Explorer (COBE) data of a component in the continuum emission with a dustlike morphology, but with a synchrotron-like spectrum. Larson & Wandelt (2004) have suggested that both the ILC data positive and negative peaks do not have sufficient amplitude to be accounted for by a cosmological interpretation of the data, which implies that some other mechanism may be playing a role in generating the observed signals. In a specific case involving the detection of anomalous microwave emission toward the Perseus molecular cloud, Watson et al. (2005) present the hypothesis that dipole emission from spinning dust grains can account for the spectrum of the continuum emission in the range 10–50 GHz. An extensive literature exists concerning the possible role of spinning dust grains as the cause of continuum emission in the frequency range of the WMAP experiment. This includes Draine & Lazarian (1998), Finkbeiner et al. (2002), Schlegel et al. (1998), and de Oliveira-Costa et al. (2004). An alternative mechanism for producing low-density electrons possibly capable of generating high-frequency radio emission involves a plasma physical phenomenon suggested by Verschuur (2007).

In general, many high-latitude ILC peaks listed in Table 1 for extended region A have a corresponding, closely spaced H i peak found in two or more l, b maps made at 10 km s$^{-1}$ intervals. The typical angular offset is approximately $0.8^\circ$ (Fig. 1a). Including the cases below $b = 40^\circ$ in the statistics makes no difference to the distribution seen in Figure 1a. Angular offsets of order $1^\circ$ between parallel H i, dust, and H$\alpha$ filaments have been reported by Verschuur et al. (1992).

Based on the above results, it is suggested that the ILC peaks are associated with H i structures that are interacting (probably colliding) with other H i structures, or interacting with regions of...
enhanced plasma density in surrounding interstellar space through which the H\textsc{i} is moving. In one case illustrated above, two H\textsc{i} features at distinctly different velocities are coincident in position at the location of the ILC peak (Fig. 2). In other cases, two H\textsc{i} features at (nearly) the same velocity straddle a continuum emission peak in position, for example, as shown in Figure 3. Depending on the geometry of the situation, positional coincidence will only be observed in those directions where a collision between two H\textsc{i} features (clouds) occurs along the line of sight. However, where the H\textsc{i} features are interacting while moving along an axis oriented at some angle to the line of sight, the continuum emission peak will be observed as offset from the H\textsc{i} peak(s).

A number of clues that may help account for the physics underlying the production of continuum emission at the surface of moving H\textsc{i} structures exist in the literature. For example, as was described in § 3.4, Herbstmeier et al. (1995) report excess soft X-ray emission at the boundary of HVC MI, where the ILC continuum structure is prominent (Fig. 6). On a larger scale, Kerp et al. (1994) find evidence for widespread soft X-ray emission over much of region A toward the high-velocity structures, but the angular resolution of their data does not allow for closer comparison with our results. Furthermore, Tufte et al. (1998) found the H\textalpha emission high-velocity clouds MI and MII, as well as other high-velocity features. This raises tantalizing questions as to the emission mechanism that could produce the continuum radiation. If it involves the formation of dust at the (shocked) interface between the H\textsc{i} and surroundings by a mechanism involving spinning dust grains such as has been proposed by Draine & Lazarian (1998), the presence of both excess H\textalpha and soft X-ray emission will also have to be taken into account.

Lagache (2003) has searched for associations between H\textsc{i} and WMAP peaks, but confined his study to the total H\textsc{i} content as a function of position. In the examples above, the amplitudes of the H\textsc{i} peaks show a relationship to the ILC peaks that varies widely.
and in many cases, such as for the $\text{H}_i$ features shown in Figures 4 or 5, is invisible in maps of total $\text{H}_i$ content over the relevant areas. Land & Slosar (2007) also studied the relationship between $\text{WMAP}$ peaks and $\text{H}_i$ structure, but considered only direct, point-to-point associations, which are in fact relatively rare. Far more likely are small angular offsets between peaks in the two forms of emission.

Another interesting, possibly related phenomenon, has been found by Liu & Zhang (2006), who studied the cross-correlation between $\text{WMAP}$ and Energetic Gamma-Ray Experiment Telescope (EGRET) $\gamma$-ray data and concluded that an unknown source of radiation, most likely of Galactic origin, is implied by their analysis. Such a source would produce foreground residuals that need to be removed in order to minimize their role in confusing the cosmological interpretation of the $\text{WMAP}$ data. Perhaps the source of this unknown radiation of Galactic origin is to be found in processes occurring at the surfaces of Galactic $\text{H}_i$ structures moving through interstellar space and/or interacting with one another.

Based on what is found in these examples, it is possible that where two $\text{H}_i$ features are interacting (colliding), current sheets are created in which particle acceleration may underlie the production of the continuum emission observed by $\text{WMAP}$. Excess electrons at these interfaces may initially be introduced through the process described by Verschuur (2007) and references therein.

To pursue this study this further, $\text{ILC}$ structure should be compared with $\text{H}_i$ maps integrated over smaller velocity ranges than the $10$ km s$^{-1}$ used in this overview, and higher angular resolution $\text{H}_i$ observations of some of the most interesting $\text{H}_i$ features shown in Figures 2–6 are desirable. It is hoped that research into the relationships between interstellar $\text{H}_i$ morphology and high-frequency radio emission observed by $\text{WMAP}$ will be stimulated by this work.

5. CONCLUSIONS

The goal of this study was to determine whether evidence exists to suggest that small-scale structure in the $\text{WMAP}$ $\text{ILC}$ data and $\text{H}_i$ are related. To that end, the map of $\text{ILC}$ structure guided the study and not only led to the discovery of what appear to be highly significant spatial relationships between the two data sets, but also drew attention to unexpected properties of the Galactic $\text{H}_i$ that turned out to be especially interesting and relevant to accounting for the associations.

In region A clear associations have been found between small-scale structure maps of $\text{WMAP}$ and Galactic $\text{H}_i$ features identified in maps in which the $\text{H}_i$ is integrated over $10$ km s$^{-1}$. In region B a similar excess of associated features was noted. In contrast, no significant associations are found when comparing the $\text{ILC}$ data for one region with the $\text{H}_i$ data for the other region, nor when the minima in the $\text{ILC}$ data are treated as peaks. This argues that the apparent associations found in region A are not due to chance. While studying the data for region B in which the $\text{H}_i$ is more concentrated at low velocities and latitudes, it became clear that $\text{H}_i$ maps at smaller velocity intervals should be used in the search for associations. A future report will describe such work, together with extensive studies of structures at high latitudes in the southern Galactic hemisphere.

Taken as an ensemble, the spatial associations between $\text{H}_i$ and $\text{ILC}$ emission peaks point to the existence of one or more processes occurring in interstellar space capable of generating weak continuum radiation observed by $\text{WMAP}$. The radiation appears to originate at the surfaces of dynamic and interacting $\text{H}_i$ structures. Where this interaction is viewed along the direction in which the $\text{H}_i$ is moving, the radio continuum structure will overlap in position, but where the $\text{H}_i$ has a transverse component of motion (much more common), the two forms of emission will appear closely offset on the sky.

Of particular significance is the fact that the associations between $\text{ILC}$ and $\text{H}_i$ structure discussed here led to the discovery that $\text{H}_i$ structures in the three velocity regimes (high, intermediate, and low) are physically related to one another, which places them at a common distance from the Sun, probably of order $100$ pc.

Rigorous studies of the apparent associations between $\text{ILC}$ and $\text{H}_i$ structures should make use of the full $\text{LAB}$ survey spectral resolution of $1$ km s$^{-1}$ to produce $\text{H}_i$ maps integrating over $2$ km s$^{-1}$ velocity intervals, a limit set by what is known about low-velocity $\text{H}_i$ emission-line structure.

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REFERENCES

Banday, A. J., Dickinson, C., Davies, R. D., Davis, R. J., & Gorski, K. M. 2003, MNRAS, 345, 897
Blauuw, A., & Tolbert, C. R. 1966, Bull. Astron. Inst. Netherlands, 18, 405
Burton, W. B., Bania, T. M., Hartmann, D., & Yuan, T. 1992, in Evolution of Interstellar Matter and Dynamics of Galaxies, ed. J. Palous, W. B. Burton, & P. O. Lindblad (Cambridge: Cambridge Univ. Press), 25
Davies, R. D., Dickinson, C., Banday, A. J., Jaffe, T. R., & Gorski, K. M. 2006, MNRAS, 370, 1125
de Olivieria-Costa, Teigmak, M., Davies, R. D., Gutiérrez, C.M., Lasenby, A. N., Rebolo, R., & Watson, R. A. 2004, ApJ, 606, L89
Draine, B. T., & Lazarin, A. 1998, ApJ, 494, L19
Finkbeiner, D. P., Schlegel, D. J., Frank, C., & Heiles, C. 2002, ApJ, 566, 898
Hartmann, D., & Burton, W. B. 1997, Atlas of Galactic Neutral Hydrogen (Cambridge: Cambridge Univ. Press)
Herbstmeier, U., Melboul, O., Snowden, S. L., Hartmann, D., Burton, W. B., Mortiz, P., Kalberla, P. M. W., & Egger, R. 1995, A&A, 298, 606
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnaud, E. M., Bajaja, E., Morras, R., & Poppel, W. G. L. 2005, A&A, 440, 775
Kerp, J., Lesch, H., & Mack, K.-H. 1994, A&A, 286, L13
Kuntz, K. D., & Danly, L. 1996, ApJ, 457, 703
Lagache, G. 2003, A&A, 405, 813
Land, K., & Slosar, A. 2007, preprint (astro-ph/0706.1703v1)
Larson, D. L., & Wandelt, B. D. 2004, ApJ, 613, L85
Liu, X., & Zhang, S.-N. 2006, ApJ, 636, L1
Schlegel, D. J., Finkbeiner, D. P., & Davies, M. 1998, ApJ, 500, 525
Tufte, S. L., Reynolds, R. J., & Haffner, L. M. 1998, ApJ, 504, 773
Verschuur, G. L. 2007, IEEE Trans Plasma Sci., 35, 759
Verschuur, G. L., Rickard, L. J., Verter, F., Pound, M. W., & Leisawitz, D. 1992, ApJ, 390, 514
Walker, B. P. 2001, ApJS, 136, 463
Watson, R. A., Rebolo, R., Rubiño-Martín, J. A., Hildebrandt, S., Gutiérrez, C.M., Fernández-Cerezo, S., Hoyland, R. J., & Battistelli, C. M. 2005, ApJ, 624, L89