INTERACTING GALACTIC NEUTRAL HYDROGEN FILAMENTS AND ASSOCIATED HIGH-FREQUENCY CONTINUUM EMISSION

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ABSTRACT

Galactic H\textsc{i} emission profiles in an area where several large-scale filaments at velocities ranging from $-46$ km s$^{-1}$ to 0 km s$^{-1}$ overlap were decomposed into Gaussian components. Eighteen families of components defined by similarities of center velocity and line width were identified and related to small-scale structure in the high-frequency continuum emission observed by the Wilkinson Microwave Anisotropy Probe (WMAP) Internal Linear Combination (ILC) map of Hinshaw et al. When the center velocities of the Gaussian families, which summarize the properties of all the H\textsc{i} along the lines of sight in a given area, are used to focus on H\textsc{i} channel maps the phenomenon of close associations between H\textsc{i} and ILC peaks reported in previous papers is dramatically highlighted. Of particular interest, each of two pairs of H\textsc{i} peaks straddles a continuum peak. The previously hypothesized model for producing the continuum radiation involving free–free emission from electrons is re-examined in light of the new data. By choosing reasonable values for the parameters required to evaluate the model, the distance for associated H\textsc{i}–ILC features is of order 30–100 pc. No associated H\textsc{ii} radiation is expected because the electrons involved exist throughout the Milky Way. The mechanism for clumping and separation of neutrals and electrons needs to be explored. It is concluded that the small-scale ILC structure originates in the local interstellar medium and not at cosmological distances.

Key words: ISM: atoms – ISM: clouds

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1. INTRODUCTION

In three previous reports (Verschuur 2007a: Paper I; Verschuur 2007b; Verschuur 2010: Paper II) 108 close associations between foreground galactic neutral hydrogen (H\textsc{i}) features and small-scale structures found in the Wilkinson Microwave Anisotropy Probe (WMAP) Internal Linear Combination (ILC) map of Hinshaw et al. (2007) were discussed. The ILC data represent the signal observed by WMAP in the 23–94 GHz frequency range from the cosmic microwave background (CMB) after the contributions from foreground signals produced by, for example, galactic continuum radiation and emission from interstellar dust and ionized hydrogen regions have been removed. The structure that remains is believed to represent small-scale structure intrinsic to the CMB that originated soon after the big bang. Such structure is thus taken to represent primeval concentrations of matter at distances of order 4500 Mpc that may act as the future seeds for clusters of galaxies.

In stark contrast, structure found in area maps of the 21 cm emission from interstellar H\textsc{i} at velocities of order 100 km s$^{-1}$ with respect to the local standard of rest represent spectral line radiation that originates within a few hundred parsecs of the Sun. Given the range of line-of-sight velocities of the interstellar H\textsc{i} gas in the region of sky discussed below, which is of order 150 km s$^{-1}$, and given the velocity resolution of the spectral line observations, 1.3 km s$^{-1}$ for the data we have used, this implies that the H\textsc{i} structure seen on the sky can be plotted at a hundred distinct velocities, each map showing peaks that are slightly different from the others. However, H\textsc{i} maps at single velocities represent the H\textsc{i} brightness produced by overlapping components along the line of sight and do not allow for the unequivocal identification of the physical properties of the individual components. That requires detailed analysis of the profile shapes, which is discussed below.

If the two types of radiation, structure in the CMB as found in the ILC data and H\textsc{i} emission profiles, originate at the vastly different distances referred to above there should be no relationship whatsoever between the two types of structures as seen projected on the sky. But that is not what is found, as reported in Papers I and II. The two types of structures appear to be associated, not in a one-to-one positional agreement, but with individual pairs of H\textsc{i}–ILC peaks mostly slightly offset from one another in angle on the sky, on average by about 0.8.

At issue is whether these close associations are due to chance. To some extent, this was dealt with in Papers I and II. However, the task of proving that associations are statistically significant is difficult because while only one ILC area map is used, those data have to be compared to structures seen in as many as 100 H\textsc{i} velocity maps. To reduce the number of H\textsc{i} area maps that have to be examined, it is hypothesized that if the H\textsc{i} emission profiles are decomposed into Gaussians and families of components identified, far fewer area maps, in this case of H\textsc{i} column density of specific clouds, would have to be studied.

The goal of the present study is therefore to reduce the task of examining large numbers of H\textsc{i} maps for comparison with the ILC data without losing information about the nature of the H\textsc{i} small-scale structure. To this end a Gaussian analysis of the H\textsc{i} profiles over a given area was carried out and a number of families of H\textsc{i} features identified. The physical parameters of these families contain information about all the H\textsc{i} along the line of sight in the area of sky under investigation and thus they will most clearly reveal H\textsc{i} cloud structure.

In Paper II it was argued that a possible mechanism for generating high-frequency continuum radiation in the local interstellar medium that would produce the appearance of structure in the ILC data is free–free emission from clouds of electrons produced by localized ionization of hydrogen. However, no associated H\textsc{ii} radiation is found, a point brought
to our attention by G. Hinshaw (2012, private communication). That would imply that the model fails. However, in light of what is found in the bulk of the analysis to follow, the mechanism is re-considered.

In Section 2 some of the H\textsc{i} data used in this study are displayed and in Section 3 the Gaussian analysis is described. In Section 4 the results of sorting Gaussian components into families are presented and their morphological relationship to the high-frequency continuum emission structure is shown in Section 5. The apparent failure of the previously suggested model for producing the high-frequency continuum radiation is considered in Section 6. The discussion section in Section 7 shows that the model does work when it is recognized that the necessary electrons already exist in the interstellar medium. Conclusions are offered in Section 8.

2. THE DATA

The H\textsc{i} spectral line data used in this paper were drawn from the Leiden–Argentina–Bonn (LAB) All-Sky H\textsc{i} Survey (Kalberla et al. 2005) performed with a 0.6 beam width and a 1.3 km s\textsuperscript{-1} velocity resolution.

To describe the context of the work to follow, Figure 1 displays five H\textsc{i} contour maps of brightness temperature in a 3.3 km s\textsuperscript{-1} bandwidth as a function of galactic coordinates, longitude (GLON or $l$) and latitude (GLAT or $b$), for an area bordered by $l = 70^\circ$ and $110^\circ$ and $b = 50^\circ$ and $70^\circ$. Such maps were produced and examined at 2 km s\textsuperscript{-1} intervals from +14 km s\textsuperscript{-1} to −70 and then every 4 km s\textsuperscript{-1} to −160 km s\textsuperscript{-1} with respect to the local standard of rest. Contour levels are shown in the captions. The velocities of these displayed examples were chosen to illustrate several key points in the analysis to follow.

Figure 1(a) shows the H\textsc{i} brightness centered at a velocity of −46 km s\textsuperscript{-1}. A curving filamentary feature can be followed from $(l, b) = (100^\circ, 70^\circ)$ to $(l, b) = (78^\circ, 50^\circ)$. It will be referred to as Filament Alpha. A weak extension from $(l, b) = (85^\circ, 57^\circ)$ to $(l, b) = (71^\circ, 50^\circ)$ suggests that filaments may be overlapping in the area around $(l, b) = (87^\circ, 59^\circ)$. In the data of Hartmann & Burton (1997, p. 131), Filament Alpha can be followed well beyond the bounds of Figure 1(a). Figure 1(b) shows the H\textsc{i} morphology at −36 km s\textsuperscript{-1}. The H\textsc{i} distribution in the center is dominated by two peaks to be called South Pair. They appear to lie on Filament Alpha. However, other structure suggests that the picture may be more complex.

Figure 1(c) shows H\textsc{i} brightness at −30 km s\textsuperscript{-1}. A part of a twisted S-shaped filament, named Gamma, runs across the center of the area terminating in a bright feature at $(l, b) = (103^\circ, 61^\circ)$ before turning south. The elongated peak at $(l, b) = (89^\circ, 56^\circ)$ appears to be an extension to this velocity of the southern component of South Pair. Figure 1(d) shows the H\textsc{i} brightness at −13 km s\textsuperscript{-1} and a pair of peaks at $(l, b) = (91^\circ, 62^\circ)$ lies on Filament Delta that stretches to the lower-right corner of the area. These two peaks will be referred to as North Pair and they are located where Filament Delta crosses Filament Gamma.

Figure 1(e) shows the H\textsc{i} brightness at +1 km s\textsuperscript{-1}. The bright H\textsc{i} feature at $(l, b) = (87^\circ, 60^\circ)$ lies on a complex filamentary feature labeled Beta and is located where Filament Beta overlaps Alpha; that is, between the two components of South Pair seen in Figure 1(b).

Figure 1(f) shows the positive amplitude ILC peaks and the two areas labeled 1 and 2 marked by dashed lines are the boundaries within which Gaussian fitting was carried out. The first-year ILC data used here are the same set used in Papers I and II drawn from Hinshaw et al. (2007), effective beam width 1°, mapped as contours from +0.02 mK in steps of 0.03 mK. A visual comparison of the ILC data with this sample of H\textsc{i} maps shows associations between the two types of features. A concentration of low-velocity (LV) H\textsc{i} in the region of enhanced ILC emission seen around $(l, b) = (80^\circ, 57^\circ)$ is obvious. To avoid the complexity manifest in that region, the present study was limited to Areas 1 and 2.

Figure 2 shows channel maps for these two areas at the velocities indicated in the caption with the same ILC contours shown in Figure 1(f) overlain. The velocities were chosen based on the average velocities of individual Gaussian component families to be discussed below. Figure 2(a) shows low-level H\textsc{i} features that precisely skirt the boundary of extended ILC structure. Figure 2(b) shows the H\textsc{i} features labeled South Pair straddling an ILC peak and Figure 2(e) shows North Pair. What is striking is that without exception the small-scale H\textsc{i} peaks are associated with and closely offset from equally small-scale ILC features. This offset between the two types of radiation is what was reported in Papers I and II. However, only one of the associations reported in Paper I, Source 16 at $(l, b) = (101^\circ, 59^\circ)$, is seen here. Its H\textsc{i} signature is evident in Figures 2(e) and (f). In Paper I the center velocity of S16 was listed as −5 km s\textsuperscript{-1}, but that analysis used area maps made every 10 km s\textsuperscript{-1} covering a bandwidth of 11.3 km s\textsuperscript{-1}. Figure 2(f) shows its peak to be at −9 km s\textsuperscript{-1} and illustrates that more is learned about H\textsc{i}–ILC associations when these narrower channel maps are used. While Paper I only revealed one pair of associations in this area, because it only considered the brightest ILC peaks, the maps in Figure 2 reveal at least nine more closely spaced associations with no cases of direct overlap, which is true for most of the 108 pairs listed in Papers I and II.

At this point the analysis could end because Figure 2 clearly confirms what was found in other sections of sky as outlined in Papers I and II. In general, small-scale structure in the high-frequency background continuum radiation maps observed by WMAP as revealed in the ILC data is associated with, but slightly offset from, structure in galactic H\textsc{i} emission. However, noting associations reveals nothing substantive about the physical properties of the H\textsc{i} being observed; for example, what are the volume densities and temperatures of the H\textsc{i} and what process could give rise to the associated high-frequency continuum emission? As the next step in this process, the efficacy of using Gaussian analysis to understand the H\textsc{i} properties was explored to determine whether this clarifies the underlying physics that might, in turn, help us to understand the nature of the emission process giving rise to the high-frequency continuum radiation.

3. GAUSSIAN ANALYSIS

The H\textsc{i} area maps discussed so far reveal only the amplitude of the H\textsc{i} emission at a given velocity; they reveal little about the physics or dynamics of the structures that are present. H\textsc{i} emission profiles usually consist of multiple Gaussian components produced by concentrations of H\textsc{i} along the line of sight or by motion or temperature variations within coherent sub-features within a given volume of space. Each Gaussian is characterized by a peak brightness temperature, $T_B(\text{max})$, a center velocity, $v_c$, and a line width, $W$, the full width at half-maximum brightness. The area maps in Figures 1 and 2 represent the total of the brightness temperatures at any given velocity that is produced by overlapping components. The goal of the present study translates to untangling the Gaussian structure to identify the properties of the overlapping components.
Figure 1. Contour maps of the H\textsubscript{i} brightness in a 3.3 km s\textsuperscript{−1} band centered at the following velocities. (a) At \(-46\) km s\textsuperscript{−1}, contours 0.5:1.5@0.2, 1.7:7.7@1 K km s\textsuperscript{−1}. The bright filamentary feature that curves from the upper left to the lower center is referred to as Filament Alpha and it shows a weak parallel strand below \(b = 57^\circ\).

(b) At \(-36\) km s\textsuperscript{−1}, contours 1.5@0.8, 7:20@3, 26:40@6 K km s\textsuperscript{−1}. The central pair of features is referred to as South Pair, see the text. (c) At \(-30\) km s\textsuperscript{−1}, contours 1:4@1, 7:28@3 K km s\textsuperscript{−1}. The curved feature at the center is referred to as Filament Gamma in the text. (d) At \(-13\) km s\textsuperscript{−1}, contours 1.5@1, 7:17@2 K km s\textsuperscript{−1}. The diagonal feature is referred to as Filament Delta in the text. It encompasses a pair of peaks around \(l, b = (92^\circ, 62^\circ)\) called North Pair, see the text. (e) At +1 km s\textsuperscript{−1} in the upper frame, contours 4:7@1, 10:22@3, 26:42@4 K km s\textsuperscript{−1}. The diagonal feature is referred to as Filament Beta in the text. (f) The ILC amplitudes for the area displayed as contours 0.02:0.17@0.03 mK. The two areas over which Gaussian analysis was performed are indicated by the dashed lines and numerals 1 and 2, see the text.
The hypothesis that the H\textsc{i} component line shape is Gaussian rests on the assumption that motions within any mass of H\textsc{i} will show a random velocity distribution that can be described by a Gaussian function. However, Gaussian analysis of H\textsc{i} profiles is difficult because a given solution may not be unique and that means that relatively few researchers have ventured into the realm of such analyses. The challenge has been discussed by Verschuur (2004), Verschuur & Peratt (1999), and Verschuur & Schmelz (2010). The algorithm used in the present Gaussian decomposition of LAB profiles was described by Verschuur (2004). A crucial difference between this approach and the totally automated analysis used by, for example, Haud (2000) and subsequently by Haud & Kalberla (2007) is that in the present study each profile and the associated Gaussian fit is examined visually to assure that the results are consistent. The problem is that the Gaussian fitting algorithm is set to minimize residuals and false minima can be found for a set of Gaussian components that bear no relationship to the profiles in their immediate vicinity. While other researchers may have attempted to design their algorithms to take in account neighboring solutions, in our experience that is not necessarily sufficient, as will illustrated with examples to follow.

Gaussian decomposition of H\textsc{i} profiles in the present study was performed for Areas 1 and 2 (Figure 1(f)) using profiles every 1° in $l$ and 0°.5 in $b$. At the latitude of these areas (60°) this created a uniform sampling grid of 588 profiles separated in real angle of 0°.5 in both coordinates. The Gaussian decompositions allowed the fitting of up to nine components although very few profiles actually required that many.

During the analysis it became clear that Gaussian decomposition is subject not only to the presence of noise but is especially vulnerable to non-noise-like low-level (interference?) features found even in the baseline areas of the LAB profiles where no H\textsc{i} is present. In some profiles these showed a negative amplitude. When they occurred at a velocity at the edge of a profile, the properties of the component fit that included the relevant velocity range could be dragged to apparent line widths that were either higher or lower than those found for similar components in neighboring profiles. This problem could only be identified by visually examining the Gaussian fits. Obviously there is no way
to detect the presence of such non-noise-like deviations within the velocity range of the H\textsubscript{i} emission itself, which contributes to noise in the values of the derived component parameters. Visual examination of each Gaussian fit compared to neighboring profiles allows the distortion produced by these non-noise structures near the profile edges to be recognized and the algorithm was then run with a different initial setting to produce results consistent with neighboring profiles. In several profiles small interference spikes in only one channel were present and in two profiles single-channel negative spikes that could be confused with narrow absorption lines occurred at velocities that also contributed to producing spurious Gaussian parameters. These obvious cases were dealt with by canceling the problem spike in a given channel. It is highly doubtful that an automatic Gaussian analysis could deal with these problems unless it used advanced AI techniques.

To initiate the search for the best-fit Gaussians for any given profile, the results for an adjacent solution were used. When the results of a given initialization were clearly inconsistent with the trends observed in surrounding profiles, the profile was re-initialized using another of the adjacent Gaussian fits. Note that while the process of fitting Gaussian components to individual profiles is inherently noisy, the data for an ensemble of fits do produce coherent patterns in column density maps that allow families of components to be recognized and mapped.

A pervasive, underlying broad-line width component is the signature of every profile, both at LV and IV. Its width is predominantly about 33 km s\textsuperscript{-1}. However, after the initial analysis and sorting of families of Gaussian and making maps of the H\textsubscript{i} column densities in Area 2, a systematic error was recognized that was readily rectified. The data showed that the broad components often manifested line widths of order 24 km s\textsuperscript{-1} in addition to the 33 km s\textsuperscript{-1} regime. When maps of the narrow line width components were made it was found that the dominant one, called LV1, to be discussed below, was absent in those directions where 24 km s\textsuperscript{-1} wide components were found. Thus the initially produced area map of the H\textsubscript{i} column density for LV1 had holes in the directions where the Gaussian fitting routine had found a solution involving a broad component of order 24 km s\textsuperscript{-1} wide.

The profiles in those direction were therefore reconsidered and it was found that a significantly better fit could be obtained by initializing the algorithm using the nearest solutions in which the 33 km s\textsuperscript{-1} lines were present. Thus the 24 km s\textsuperscript{-1} components turned out to be the result of a self-perpetuating fit that produced false minima. The relevant profiles were
rerun and subsequent mapping of component LV1, using the better Gaussian fits, did not show any holes. In fact LV1 is found to be pervasive, as are the underlying broad components of order 33 km s\(^{-1}\) wide, see tables below for details. This unfortunate state of affairs and its rectification is highlighted because automated Gaussian fitting programs are subject to the problem of false minima in residual phase space and future attempts to duplicate the present study should pay close attention to the result for given profiles to make sure no such systematic effects creep in. Fortunately, such effects stamp their presence in otherwise ordered column density maps, which allows their presence to be recognized.

Figure 3 illustrates several examples of Gaussian fitting to a variety of profiles at the positions indicated. Figure 3(a) shows a profile defined by a single, underlying broad component with line width \(W = 36.2 \text{ km s}^{-1}\) at \(v_c = -8.9 \text{ km s}^{-1}\). The profile just 1° away in longitude shown in Figure 3(b) reveals the presence of a second underlying broad component at intermediate velocity (IV) \(v_c = -30.0 \text{ km s}^{-1}\) with \(W = 35.1 \text{ km s}^{-1}\) while the other is at LV centered at \(v_c = +0.7 \text{ km s}^{-1}\) with \(W = 33.9 \text{ km s}^{-1}\). The separation on the sky of these two profiles is 0.5 in true angle and serves to illustrate the tremendous amount of structure found in the H\(\text{I}\) distribution. Figure 3(c) shows two broad underlying components whose presence is easy to discern because they manifest so clearly in the wings of the overall profile. The broad IV component has \(W = 35.1 \text{ km s}^{-1}\) while the LV broad component has \(W = 34.8 \text{ km s}^{-1}\).

The profile displayed in Figure 3(d) is notable because of the presence of a narrow component at the center of the profile, only 3.4 km s\(^{-1}\) wide. The underlying broad components for this profile are 37.5 km s\(^{-1}\) wide at IV and 37.2 km s\(^{-1}\) wide at LV. In adjacent profiles the amplitude of the H\(\text{I}\) emission between velocities of \(-80\) and \(-30\) km s\(^{-1}\) produced an almost straight line slope and solutions were only obtained by painstakingly using the surrounding profiles to find a fit consistent with the trends in the data around those positions. It seems very unlikely that an automated program would find solutions to such a profile. Figure 3(e) shows an extremely bright and narrow center component 3.0 km s\(^{-1}\) wide at \(-17.2\) km s\(^{-1}\), which is part of component family LV13, see below. The associated
components that were sorted into 18 distinct families most of which were recognized in both Areas 1 and 2. The sorting of Gaussians into families was usually straightforward because of clear continuity in center velocity and/or line width that could be followed across many adjacent profiles. When the data were gathered into families and plotted as area maps, the presence of components that had not been assigned to the correct family was quickly apparent. They could then be assigned to the appropriate family and the resulting maps show a high degree of order, as will be discussed in the context of examining all the data, below.

4. SORTING GAUSSIANS INTO PARAMETER FAMILIES

Gaussian analysis of 288 profiles yielded 3706 Gaussian components that were sorted into 18 distinct families most of which were recognized in both Areas 1 and 2. The sorting of Gaussians into families was usually straightforward because of clear continuity in center velocity and/or line width that could be followed across many adjacent profiles. When the data were gathered into families and plotted as area maps, the presence of components that had not been assigned to the correct family was quickly apparent. They could then be assigned to the appropriate family and the resulting maps show a high degree of order, as will be displayed below. Only six components could not be fit into any of the families and may be regarded as noise in the data.

Table 1 summarizes the key properties of component families for Area 1 and Table 2 applies to Area 2. Column 1 gives the name of the family, Column 2 lists the number of Gaussians used for Area 1 and Table 2 gives the number of Gaussians used for Area 2. Column 3 lists the average center velocity, $v_c$, for the family, and Column 4 gives its average line width, $\Delta v$. Column 5 gives the peak $N_H$ value, in units of $10^{18}$ cm$^{-2}$.

Table 1

| Name      | No. of Gaussians | Avg. Center Vel. (km s$^{-1}$) | Avg. Line Width (km s$^{-1}$) | Peak $N_H$ ($10^{18}$ cm$^{-2}$) |
|-----------|------------------|-------------------------------|-------------------|-------------------------------|
| Broad LV  | 273              | $-5.0 \pm 3.1$               | $33.3 \pm 2.0$    | 92.4                          |
| Broad IV  | 273              | $-35.8 \pm 6.4$              | $33.1 \pm 2.2$    | 59.7                          |
| LV1       | 273              | $-1.5 \pm 2.6$               | $14.7 \pm 2.3$    | 91.6                          |
| LV2       | 169              | $-0.2 \pm 2.1$               | $5.8 \pm 2.3$     | 57.9                          |
| LV3       | 46               | $-0.4 \pm 3.1$               | $4.1 \pm 2.1$     | 22.6                          |
| LV4       | 95               | $-5.1 \pm 1.3$               | $7.8 \pm 2.3$     | 43.3                          |
| LV5       | 32               | $-12.2 \pm 2.7$              | $9.2 \pm 3.8$     | 33.1                          |
| LV6       | 41               | $+9.1 \pm 2.7$               | $8.1 \pm 3.1$     | 31.4                          |
| LV11      | 44               | $-27.3 \pm 2.7$              | $10.7 \pm 4.2$    | 38.4                          |
| LV12      | 52               | $-19.2 \pm 2.5$              | $9.8 \pm 2.8$     | 50.6                          |
| LV13      | 48               | $-19.1 \pm 3.3$              | $5.1 \pm 1.9$     | 31.7                          |
| LV14      | ...              | ...                           | ...               | ...                           |
| IV-A      | 216              | $-38.6 \pm 3.9$              | $14.7 \pm 2.9$    | 141.3                         |
| IV-B      | 107              | $-38.2 \pm 4.8$              | $7.0 \pm 2.8$     | 129.5                         |
| IV-C      | 50               | $-35.3 \pm 2.9$              | $5.0 \pm 2.4$     | 41.6                          |
| IV-D      | ...              | ...                           | ...               | ...                           |
| IV–HV     | 24               | $-73.6 \pm 5.4$              | $16.0 \pm 4.4$    | 24.1                          |
| HV        | ...              | ...                           | ...               | ...                           |

Table 2

| Name      | No. of Gaussians | Avg. Center Vel. (km s$^{-1}$) | Avg. Line Width (km s$^{-1}$) | Peak $N_H$ ($10^{18}$ cm$^{-2}$) |
|-----------|------------------|-------------------------------|-------------------|-------------------------------|
| Broad LV  | 315              | $-5.2 \pm 3.9$               | $32.5 \pm 2.4$    | 58.3                          |
| Broad IV  | 315              | $-46.6 \pm 4.6$              | $33.0 \pm 2.5$    | 61.3                          |
| LV1       | 315              | $-0.5 \pm 2.3$               | $14.8 \pm 2.2$    | 58.3                          |
| LV2       | 74               | $-2.7 \pm 2.4$               | $6.3 \pm 3.0$     | 20.9                          |
| LV3       | ...              | ...                           | ...               | ...                           |
| LV4       | 76               | $-7.5 \pm 1.6$               | $7.6 \pm 2.9$     | 38.4                          |
| LV5       | 76               | $-12.4 \pm 3.8$              | $9.3 \pm 2.9$     | 26.0                          |
| LV6       | 40               | $+5.4 \pm 3.4$               | $8.7 \pm 4.2$     | 29.2                          |
| LV11      | 54               | $-27.9 \pm 2.9$              | $13.4 \pm 3.5$    | 30.3                          |
| LV12      | 55               | $-21.7 \pm 3.1$              | $9.8 \pm 3.3$     | 40.8                          |
| LV13      | ...              | ...                           | ...               | ...                           |
| LV14      | 48               | $-25.7 \pm 5.6$              | $3.6 \pm 1.4$     | 31.1                          |
| IV-A      | 281              | $-48.0 \pm 4.9$              | $14.7 \pm 3.0$    | 48.7                          |
| IV-B      | 145              | $-45.7 \pm 5.4$              | $7.4 \pm 2.4$     | 24.6                          |
| IV-C      | 24               | $-38.2 \pm 6.2$              | $6.6 \pm 1.9$     | 10.3                          |
| IV-D      | 40               | $-54.6 \pm 3.5$              | $9.7 \pm 3.8$     | 25.3                          |
| IV–HV     | 50               | $-77.8 \pm 7.4$              | $21.0 \pm 6.1$    | 22.8                          |
| HV        | 48               | $-109.3 \pm 12.6$            | $24.6 \pm 5.3$    | 32.3                          |
| Other     | 6                | $-64.9 \pm 3.8$              | $8.6 \pm 3.0$     | 8.8                           |

broad components are 27.8 km s$^{-1}$ wide at $-47.8$ km s$^{-1}$ and 36.8 km s$^{-1}$ wide at $-5.0$ km s$^{-1}$.

Figure 3(f) shows a profile where the peak brightness temperature at IV and LV are maxima for the entire mapped area. The underlying broad components have $W = 30.6$ km s$^{-1}$ at IV and $W = 32.0$ km s$^{-1}$ at LV. The fact that both peaks reach maxima here is an indication that the structures at IV and LV are directly related, as will be discussed in the context of examining all the data, below.
(full-width, half-maximum), $\bar{W}$, both with one standard deviation errors. Column 5 lists the peak column density found for a given family. Table 3 summarizes all the family data. Column 1 is again the family name, Column 2 is the total H\textsc{i} column density summed over all the members of that family in both Areas and Column 3 is the fraction of the total column density for a given family. The average column density of the family is given in Column 4 and the peak value is shown in Column 5, which corresponds to the value in either Table 1 or 2. Of these component families, three (broad LV, broad IV, and LV1) were found in all directions, although for some of the broad IV features the amplitudes are so low as to be comparable to the peak-to-peak noise in the data.

For all the broad components listed in Tables 1 and 2, which includes 1176 cases, $\bar{W} = 33.1 \pm 1.1$ km s\textsuperscript{-1}. A simple test was performed to show that this large line width is not an artifact of the observing beam width encompassing velocity gradients within the beam to produce the higher line width values. H\textsc{i} profiles obtained by Verschuur (2013) toward a high-velocity (HV) H\textsc{i} feature known as A0 using the Green Bank Telescope (9.1 beam width) were Gaussian analyzed and the results compared with a similar decomposition of profiles from the LAB survey toward the same feature. Both sets of data revealed an underlying broad component about 22 km s\textsuperscript{-1} wide with two peaks at $33 \pm 2$ km s\textsuperscript{-1}. In general, it is not simply an artifact of lower angular resolution that generates the 33 km s\textsuperscript{-1} component. It is notable that the present study did not reveal any convincing evidence for components that could be associated with a so-called WNM, of warm neutral medium, at 8000 K, which would produce line width of order 20 km s\textsuperscript{-1}. However, the data in Table 2 show that for two component families labeled IV–HV and HV the average line widths are in the 20 km s\textsuperscript{-1} regime. That is a property of anomalous velocity H\textsc{i}, not the gas at lower velocities. (In an unrelated and as yet unpublished study of the Gaussian component structure of HV clouds by the author, the LAB data show that a component of order 22 km s\textsuperscript{-1} wide is common and also that another component about 34 km s\textsuperscript{-1} wide is present in many cases. In some directions, the H\textsc{i} emission profile can be fit by only one Gaussian, which is then found to be either about 22 or 34 km s\textsuperscript{-1} wide.)

When compared to Gaussian line width data obtained from totally unrelated studies, the numerical value for the broad component line width is striking. Verschuur & Schmelz (2010) gathered together line width data in their Table 2 pertaining to an underlying broad-line-width background component reported in nine published papers by various researchers as well as their own data that together produced $\bar{W} = 33.7 \pm 2.4$ km s\textsuperscript{-1}. This is essentially identical to the value of $33.1 \pm 1.1$ km s\textsuperscript{-1}, in the present study. Several other families listed in Tables 1 and 2 include 1139 components with a weighted average line width of 14.6 ± 1.2 km s\textsuperscript{-1}. Again, this value is significant when compared to the results summarized by Verschuur & Schmelz (2010) in their Table 3 of 13.9 ± 0.9 km s\textsuperscript{-1}. For completeness, 10 entries in Tables 1 and 2 have $\bar{W}$ values between 4.1 and 8.1 km s\textsuperscript{-1} involving 923 components for a weighted average line width of 5.7 ± 0.6 km s\textsuperscript{-1}. The remaining 339 components have average line widths between 8.7 and 10.7 km s\textsuperscript{-1} to produce a weighted average line width of 9.6 ± 1.3 km s\textsuperscript{-1}.

5. The Relationship Between the H\textsc{i} Component Families and ILC Peaks

The H\textsc{i} column density maps for the families of components are next plotted and compared with ILC data. What will become apparent is that a great deal more remains to be revealed about the crucial H\textsc{i} structure in future higher resolution studies.

Figures 4(a)–(c) show the morphology of the families of H\textsc{i} components at IVs from −48 to −35 km s\textsuperscript{-1} that encompass the emission from South Pair at the right-hand side. The ILC peak at $l, b = (88.5, 58.5)$ bridges the space between the major peaks in the H\textsc{i} defining South Pair. A fourth IV component at $-55$ km s\textsuperscript{-1} seen in Figure 4(d) is associated with ILC peaks at the top left of the area. It is striking that South Pair is clearly defined by H\textsc{i} components with three distinct line widths (see Table 1). The Gaussian analysis does not reveal the greater extent of Filament Alpha in these H\textsc{i} column density maps since column density is given by the product of line width and amplitude. An intrinsically narrower yet bright feature may not stand out against a background of somewhat wider components, even if it is a member of the same family. The presence of three distinct component families with different line widths at the location of the northern half of South Pair may be indicative of the contributions from three distinctly different filaments whose existence can be inferred by close examination of Figure 1.

Figure 5 shows area maps of the H\textsc{i} column densities for the families with $\bar{W}$ between −26 and −19 km s\textsuperscript{-1}, LV11, 12, 13, and 14, compared to the ILC contours. Figure 5(a) shows the patchy morphology of LV11; its brightest peak appears to be associated with North Pair and another ILC peak at the left-hand edge of the map around $l = 100^\circ$ is found in the region of more complex ILC structure. The members of the LV11 family were identified by similarities in line width. Figure 5(b) shows the morphology of LV12 that is clearly related to the presence of the ILC peaks. Its average line width is similar to LV11 but its center velocities are very different (Table 1). Figure 5(c) shows LV13 and 14 combined since their morphologies smoothly blend although their velocities show a considerable change from Area 1 to Area 2 (see Tables 1–3). Again, H\textsc{i} column density peaks are clearly associated with ILC peaks. When combined in
Figure 4. H\textsubscript{i} column density distributions for families of Gaussian components at intermediate velocities with the WMAP contours overlain, the same contour levels as in Figure 1(c). (a) IV-A. (b) IV-B. (c) IV-C. (d) IV-D. See the text.

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

Figure 5(d), these four H\textsubscript{i} component families are located where several filaments intersect or overlap (see Figures 1(c)–(e)) and the overall feature in Figure 5(d) thus manifests variations along its length of center velocities and line widths. Together these patterns imply that a great deal of complexity is hidden from view because of the poor angular resolution of the available data. This is borne out by the H\textsubscript{i} profiles in the region of North Pair. They are extremely complex (see, for example, Figure 3(d)), which makes the task of confidently identifying families of line widths in this area very difficult. What remains true, however, is that the H\textsubscript{i} column density maps reinforce the notion that H\textsubscript{i} and ILC structures are related, as is so clearly evident in Figure 2.

Figure 6 shows the morphology of the LV components. Figure 6(a) plots the ILC contours on a map of component family LV1 that is found throughout the area and is therefore a pervasive background or “field” component. Its morphology is not obviously related to the presence of ILC structure. Figure 6(b) shows the morphology of LV2, which is part of Filament Beta (Figure 1(e)) and this segment of filamentary structure is clearly related to the presence of the ILC peak where it appears to terminate at \((l, b = 88^\circ, 58^\circ)\), but examination of Figure 1(e) suggests it then curves back and away to the west from that terminus.

The high-frequency continuum radiation creating the ILC peak in South Pair originates in a volume of space where the two filaments Alpha and Beta overlap. Also, very striking is the fact that where the H\textsubscript{i} peak in IV-A \((\tau_c = -38.6 \text{ km s}^{-1})\) overlaps LV3 \((\tau_c = -0.4 \text{ km s}^{-1})\) at \(l, b = (87^\circ.0, 59^\circ.5)\) the H\textsubscript{i} brightness of both the IV and LV component is by far the greatest for the area mapped. The relevant profile is shown in Figure 3(f). This is strong circumstantial evidence that H\textsubscript{i} at very different velocities is somehow interacting and hence at the same distance. This phenomenon that H\textsubscript{i} at very different velocities is directly associated was also found in several areas described in Paper I. Figure 6(c) shows the morphology of LV3 and its properties are so similar to LV2 that they could well be combined, yet they appear to represent two distinct families in one filamentary feature.

The other three frames in Figure 6 show the H\textsubscript{i} column density maps for the remaining LV component families and the fact that the majority of the structures, albeit patchy, seem to be associated with immediately adjacent ILC features suggests that there is more to be learned from higher resolution H\textsubscript{i} mapping.
The H\textsubscript{i} associated with S16 discussed above can be seen in Figures 6(d) and (e) and in this display is less dramatic than found in Figures 2(e) and (f).

For completeness, Figure 7 gathers together the column density maps for the remaining component families. Figure 7(a) shows the H\textsubscript{i} morphology for the LV broad-line-width component and Figure 7(b) is the same for the IV broad-line-width family. There is some indication for diagonal features but these area maps are not readily related to the ILC structures. An exception is the bright patch just to the south of the North Pair ILC feature in Figure 7(a). It contributes to the pattern seen in Figure 2(b), center frame. Examination of the H\textsubscript{i} profile in this direction again shows it to be extremely complex, similar to the profile in Figure 3(d), and the complexity can only be untangled using higher resolution H\textsubscript{i} data.

The final two frames in Figure 7 refer to component families that were not carefully mapped because their brightness temperatures are very low, barely above peak-to-peak noise in some cases. The case of component IV–HV ($v_c = -78$ km s\textsuperscript{-1}) is shown in Figure 7(c). In some directions its spectrum is well separated from the bulk of the H\textsubscript{i} emission in velocity while in other directions it overlaps the wings of the H\textsubscript{i} emission from the bulk of the IV gas. Yet, its peak column density lies toward the North Pair ILC peak. Finally, Figure 7(d) shows the column density map for weak HV H\textsubscript{i}, called component HV ($v_c = -109$ km s\textsuperscript{-1}), which favors other peaks in the ILC map.

5.1. What the Gaussian Mapping Reveals

Overall, the goal of mapping Gaussian components with a view to clarifying the relationship between H\textsubscript{i} and ILC peaks has done little to reveal a more edifying picture. Instead the picture has become more complex. On the one hand, there is strong evidence that H\textsubscript{i} at very different velocities appears to be involved where ILC peaks are located, and on the other hand those interactions are complex and somehow give rise to the small-scale structure in the high-frequency continuum radiation found in the ILC map. The patterns seen in the H\textsubscript{i} area maps displayed in Figure 2 are also found in the component maps, Figures 4–7, so the area maps at specific velocities determined by Gaussian family average velocities may be the most effective...
way to identify close associations between H\(_i\) and small-scale ILC structure. This reduces the task from having to sort through 60–100 H\(_i\) channel maps to find associations to considering only a dozen or so data sets determined by the identification of Gaussian families. Bear in mind that the H\(_i\) column density maps of the ensemble of component families contain between them information about all the H\(_i\) found over the total line of sight through any given area.
5.2. A Note on the Statistics of Associations

In Paper I an attempt was made to show that the association between H\textsc{i} and slightly offset ILC features was significant. In Paper II it was shown that there is no evidence for widespread direct positional associations, which was never claimed in any case. Yet the question remained as to whether the near positional associations discussed here and in Papers I and II are significant or due to chance.

Interstellar H\textsc{i} structure is seen all over the sky and so is the structure revealed by ILC data. However, for any given area of sky as many as 100 H\textsc{i} area maps at velocities separated by 2 km s\(^{-1}\) need to be studied and the likelihood of chance associations becomes large. At the same time, the data discussed above and in Papers I and II show that no two examples of associations are identical. Providing convincing statistical arguments that a given association between an H\textsc{i} feature and one found in the ILC data is significant may be impossible. There is no a priori standard for defining an association that can be tested for statistically. Instead we must rely on looking at the actual data that show the associations clearly.

Seen from another perspective, the entire sky is filled with small-scale structure found in the high-frequency continuum emission observed by WMAP as revealed in the ILC map, which was produced after possible sources of intervening radiation had been removed (Hinshaw et al. 2007). But interstellar H\textsc{i} structure also covers the entire sky and that was not taken into account in the production of the ILC map. There would have been no a priori reason for doing so. While random coincidences in position between ILC and H\textsc{i} peaks are to be expected, this is not what is found. In general, apparently associated ILC and H\textsc{i} features are offset from one another by a small amount, on average 0\(^{\circ}\)8, as stated in Paper II, and estimated to be closer to 1\(^{\circ}\) for the patterns seen in Figure 2.

6. THE APPARENT FAILURE OF THE PREVIOUS MODEL

The area maps presented in Figure 2 reveal the presence of several sets of associated H\textsc{i}–ILC features. In Paper II it was
suggested that the continuum radiation is produced by free–free emission from electrons interacting with electrons and that the excess electrons are produced by the ionization of hydrogen atoms where H\textsc{i} features interact. It was also noted that for the emission mechanism to account for the data, the continuum sources would have to be unresolved in the WMAP survey in order for the presence of the phenomenon to have been missed in the original ILC analysis of the WMAP data.

For the present data, an order-of-magnitude calculation can be performed. For example for North Pair using the H\textsc{i} column density of the associated peak of $67 \times 10^{18}$ cm$^{-2}$ (Figure 5(d)), it is possible to calculate (using the formula derived in Paper II, see Equation (1), below) the degree of ionization required to produce the observed ILC peak of 0.08 mK. For a distance of 100 pc, an electron excitation temperature of 8000 K, a source width of 0:2, and a depth along the line of sight equal to that width, the fractional ionization required is 0.45. The electron density that is implied is 28.3 cm$^{-3}$ and the corresponding emission measure (given that the path length is known for a given distance) should produce H\textalpha emission at a level of 125 R in the 1$^\circ$ beam of the WHAM survey of Haffner et al. (2003). However, examination of the WHAM data reveals no such structure. The maximum emission measure over the relevant area of sky is 0.7 R, barely above a 0.5 R background level. Therefore, the hypothesis that the continuum peaks in the ILC data are due to free–free emission from electrons produced through localized ionization of the H\textsc{i} in the galactic disk, as suggested in Paper II, fails. No combination of parameters (distance, angular size, aspect ratio, and excitation temperature) can account for both the observed continuum emission level and the lack of H\textalpha signal. But what, then, is the source for the high-frequency continuum radiation if the associations seen in Figure 2 are real?

7. DISCUSSION

The original goal of this project was to determine the properties of two pairs of H\textsc{i} features in directions where filaments cross and at which locations peaks in the ILC data were found. As a result of mapping families of Gaussian components in the area, the H\textsc{i} distribution was found to be more complex than the impression garnered from examining up to 100 area maps of brightness temperature at specific velocities at 2 km s$^{-1}$, for example. Instead the average velocities of the Gaussian families are used to focus attention on specific H\textsc{i} channel maps the relationship between H\textsc{i} structure and ILC structure emerges in dramatic detail (see Figure 2). In fact, Figures 2 and 4–7 confirm the claims made in Papers I and II that close associations between small-scale H\textsc{i} and ILC features are real. However, it is not immediately clear how the high-frequency continuum emission is generated in local interstellar space (local because the H\textsc{i} data discussed here are at high galactic latitudes of 60$^\circ$ and the velocities imply a galactic origin). As this discussion proceeds it will become increasingly obvious that we are venturing into uncharted territory. The most fundamental issue that has yet to be resolved is at what angular scale both the H\textsc{i} and the ILC structures can be claimed to be resolved. Given that uncertainty it will be shown below that it is nevertheless possible to obtain an apparently good fit to the data using the model proposed in Paper II.

A solution requires that several questions be answered. First, given that the free–free emission from electrons appears to work quite well as outlined in Paper II, other than the absence of associated H\textalpha radiation, what might be the source of electrons so as to avoid the H\textalpha dilemma? Second, what mechanism is operating to cause the H\textsc{i} and the electrons to cluster? Also, why would the neutrals and electrons cluster in slightly offset directions? Lastly, if a source of electrons can be identified and a mechanism for clustering suggested, is it still possible to account for production of the high-frequency continuum radiation through invoking free–free emission from electrons?

7.1. Source of Electrons

It is well known that free electrons exist everywhere in interstellar space, as inferred from pulsar dispersion measures and radio source rotation measures. Average electron densities along path lengths of hundreds to thousands of parsecs are estimated to be in the range 0.03–0.3 cm$^{-3}$ (see, for example, Wood & Linsky 1997; Allen et al. 1990; Lyne et al. 1985). Unfortunately, essentially nothing is known about the clumping of these electrons along a given line of sight. In contrast, the clumping of the H\textsc{i} is its most basic characteristic, producing morphologies such as seen in Figure 1. Using the data in Table 3 the average H\textsc{i} column density for the 588 lines of sight included in the study is $123 \times 10^{18}$ cm$^{-2}$. Assuming a typical path length of 100 pc the average H\textsc{i} volume density is 0.41 cm$^{-3}$. An average electron density of 10% of the H\textsc{i}, that is 0.04 cm$^{-3}$, lies in the range interstellar electron density from pulsar dispersion measure data. This offers a first-order approach to determining whether a reasonable set of parameters can be found that can be used with the electron bremsstrahlung model to account for the observed amplitudes of the high-frequency continuum signals found in the ILC data.

7.2. Application of the Theory

From Equation (12) in Paper II, the brightness temperature, $T_B(\nu)$, of the high-frequency continuum radiation at a frequency $\nu$ produced by free–free emission from (cold) electrons with an excitation temperature, $T_e$, is given by

$$T_B(\nu) = 1.86 \times 10^{17} \nu^{-2} T_e^{-0.5} \ln(4.7 \times 10^{10} T_e/\nu) \times f^2 N_H(\theta_o AL)^{-1} K,$$

where $N_H$ is the observed H\textsc{i} column density in units of $10^{18}$ cm$^{-2}$ and the electron density is expressed as a fractional degree of ionization, $f$. The angular width of the electron enhancements (or cloud) on the sky is $\theta_o$ and $A$ is the aspect ratio, the depth of feature relative to its width. $L$ is the distance in parsecs.

In order to evaluate Equation (1), several assumptions have to be made and then, based on what is found, the direction of future research may be indicated. The electron excitation temperature is set to 100 K, the typical kinetic temperature of interstellar neutral hydrogen, bearing in mind that the data show no evidence for a WNM at 8000 K (line width 20 km s$^{-1}$) as noted in Section 4. An angular width of the small-scale ILC features has to be assumed since the structures considered above are usually about 1$^\circ$ across, which is the resolution of the ILC map. Thus it is fair to assume that the sources of high-frequency continuum radiation are unresolved on this scale. (Others with access to high-resolution observations of the high-frequency continuum radiation should look into this issue; e.g., those who use the Planck spacecraft data.) In order to explore whether Equation (1) works, the model amplitudes are calculated for the two ends of the WMAP band, 23 and 94 GHz, and then averaged.
Figure 8. Distance required to match the ILC amplitude for two cases indicated as a function of the electron column density expressed as a fraction of the associated \( \text{H} \) peak. The curves represent the values derived for different assumed angular widths of unresolved features. The dashed line square is the suggested regime where the model calculations, Section 7.2, give reasonable distances for reasonable values of the parameters required to evaluate Equation (1), see the text.

Equation (1) is applied to the two cases of close associations between \( \text{H} \) and ILC peaks, North Pair and South Pair, and it is used to determine the distance at which it can account for the observed ILC positive amplitudes as a function of the required degree of ionization of the associated \( \text{H} \) column density (as a first-order approach to the data). The results are shown in Figure 8. For example, if the angular scale of the unresolved ILC peak in South Pair is 0.1 then the solid line in Figure 8 so labeled indicates that for a range of electron densities equal to 0.10–0.17 times the associated \( \text{H} \) peaks, the distance of the source required to produce the observed ILC amplitude of 0.12 mK would be between about 30 and 100 pc. The calculation used the peak \( \text{H} \) column density for IV-A as the guide to the column density of the associated electron cloud. It remains to be determined just what value should be used given that there are several distinct \( \text{H} \) families of line widths involved in this direction (see Figure 4). But to first order the model does match the data. The difference between this calculation and the one reported in Section 6 is that the electron temperature is not 8000 K as would be expected from localized ionization of \( \text{H} \) but closer to 100 K consistent with the temperature of the cold hydrogen atoms.

The fact that the curves in Figure 8 for North Pair and South Pair appear to encompass a region of phase space that is reasonable as regards the required electron column densities and distances, for the 100 K regime, indicates that the possibility that the ILC structures are indeed located in the galactic disk relatively close to the Sun should be seriously considered. But what mechanism would simultaneously act to clump the neutrals and the electrons and have them physically separated yet closely associated in space.

7.3. On the Clumping and Separation of Electrons with Respect to \( \text{H} \)

Figure 1 shows clear evidence for the presence of several large-scale filaments of \( \text{H} \) in the area under consideration and Figure 2 shows that \( \text{H} \) and ILC features over the target area for this study are connected and offset from one another. These are observational facts that have to be recognized. There appear to be several ways in which electrons and neutrals could become spatially separated in interstellar space, although none have been formally studied for such an environment. The options are only briefly mentioned here.

In a completely different astrophysical situation, namely the solar environment, many papers have dealt with a phenomenon called the first ionization potential (FIP) effect. It is used to account for the spatial separation either in layers in the solar atmosphere, or along flux tubes, of various atomic species. The FIP effect is invoked to account for solar abundance variations that are otherwise difficult to comprehend. A number of references that indicate how the FIP effect may be important include Raymond (1999), Laming (2009), and Schmelz et al. (2012). Another way of considering this is to recognize that the offset between the \( \text{H} \) and ILC peaks is one of e/H abundance variations in interstellar space, either along a given filament or between adjacent volumes of space.

A little known instability occurring within flux tubes is described by Marklund (1979), who suggested that if an electric field is present in a plasma permeated by a magnetic field and has a component perpendicular to the field, the \( \mathbf{E} \times \mathbf{B} \) force will cause electrons and ions, but not neutral particles, to migrate to the axis of a flux tube. As Peratt & Verschuur
(2000) note, because of different ionization potentials of various atomic species and cooling within the filaments, ionic species will then separate within a flux tube. This mechanism, akin to the FIP effect, also has the seeds for separating the H\textsc{i} from the electrons.

Another possibility for separating electrons and neutrals may involve interacting magnetically controlled filaments. Figure 1 shows two H\textsc{i} features, South Pair, which straddle a high-frequency continuum source, as displayed in Figure 4(a). In that same direction the data indicate that a number of filaments of H\textsc{i} intersect (see Figure 1). This raises the interesting possibility that magnetic reconnection may play a role in creating pockets of H\textsc{i} that are pulled away from a central X-neutral point where magnetic fields, likely to be present in the filaments, are reconnecting. The continuum radiation revealed in the ILC data is then being produced at the X-neutral point. Unfortunately, the necessary theory to help account for the data invoking magnetic reconnection does not yet appear to exist. Priest & Forbes (2000) note that the answer to the question of what actually happens to the particles at the X-point as regards energies and spectra, and how magnetic energy is converted to heat, kinetic energy, and particle energy, is largely unknown. They state that “These apparently simple questions have not yet been answered fully [and] the answers are likely to be highly complex” (p. 461). In this context they list at least 12 possible types of reconnection that may play a role. While their work also focused on events in this context they list at least 12 possible types of reconnection that may play a role. While their work also focused on events in this context they list at least 12 possible types of reconnection that may play a role. While their work also focused on events in this context they list at least 12 possible types of reconnection that may play a role.

The Gaussian mapping reveals details in the H\textsc{i} morphology of several components at widely different velocities, from 0 km s\textsuperscript{-1} to −109 km s\textsuperscript{-1}. In an area named North Pair, two H\textsc{i} features straddle an ILC source that is located at the point of overlap of two filaments at velocities of order −30 and −13 km s\textsuperscript{-1}. Similarly, in an area named South Pair, two H\textsc{i} peaks straddle an ILC peak and here the H\textsc{i} consists of three families of components at IVs around −36 km s\textsuperscript{-1}, with average line widths of 14.7, 7.0, and 4.6 km s\textsuperscript{-1} found where H\textsc{i} filaments at distinctly different velocities, around 0 km s\textsuperscript{-1} and −38 km s\textsuperscript{-1}, overlap.

The previously hypothesized mechanism for producing the high-frequency continuum radiation from interacting H\textsc{i} features in interstellar space involving free–free emission from electrons (Verschuur 2010) is re-examined in light of the new data. It is found to account for the existence of the small-scale ILC peaks if the sources are located from 30 to 100 pc from the Sun. The pervasive presence of interstellar electrons is revealed in observations of pulsar dispersion measures, and to fit the model the cold electrons have to be clumped on scales that are similar to those seen in the H\textsc{i} distribution with densities from 10\% to 25\% of the immediately adjacent H\textsc{i} peaks. Associated H\alpha radiation at the location of the ILC peaks is not expected because the source of electrons does not require the localized ionization of H\textsc{i} as was hypothesized in Paper II. (Note that in the presence of a small degree of ionization in the interstellar medium a magnetic field can be frozen into the neutral gas through collisions between electrons, ions, and neutrals. This means that the dynamics of the magnetic field and the neutral gas are coupled. This phenomenon is extensively considered in the study of interstellar H\alpha gas dynamics and the concept dates back to an early paper by Kahn & Dyson 1964.)

In order to determine unequivocally whether or not the claimed associations are real, higher resolution observations are required. For example, Planck data should be compared with high-resolution H\textsc{i} observations obtained with suitably large radio telescopes, provided attention is focused on high-latitude regions where the confusion created by having too much H\textsc{i} in the beam is minimized. In the meantime caution should be exercised in drawing far-reaching cosmological conclusions from the ILC data that may be compromised by the presence of intervening galactic sources of high-frequency continuum radiation.

Since the onset of work on the associations between H\textsc{i} features and peaks in the ILC data, the manner in which the H\textsc{i} data have been considered has evolved. In Paper I, associations were found by comparing ILC data with structure found in H\textsc{i} area maps produced at 10 km s\textsuperscript{-1} intervals, each covering an effective velocity range of 1.3 km s\textsuperscript{-1}. In Paper II, H\textsc{i} data were displayed in velocity maps made with a 3.3 km s\textsuperscript{-1} effective bandwidth plotted every 2 km s\textsuperscript{-1} in velocity. These revealed the presence of the H\textsc{i}–ILC associations more clearly. The present study shows that when maps of the column density of H\textsc{i}
Gaussian component families are compared to ILC features, the relationship becomes even more revealing. It is suggested that this form of analysis be used in future studies of the relationship between galactic H\textsc{i} features and small-scale structure in high-frequency continuum radiation.

The work presented here and in Papers I and II does not negate the excellent work done by Hinshaw et al. (2007) in removing from the raw data obtained by WMAP contributions from known galactic sources of high-frequency radiation. However, they did not consider the possibility that otherwise undetected clumps of electrons in interstellar space could produce low levels of continuum radiation through free–free emission from those electrons, as considered in Section 7.2 and outlined in detail in Paper II. Our conclusion is that the small-scale structure reported by Hinshaw et al. (2007) is real but that it originates within a few hundred parsecs of the Sun and not at cosmological distances.

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