

ON THE APPARENT ASSOCIATIONS BETWEEN INTERSTELLAR NEUTRAL HYDROGEN STRUCTURE AND (WMAP) HIGH-FREQUENCY CONTINUUM EMISSION

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ABSTRACT

Galactic neutral hydrogen (H I) within a few hundred parsecs of the Sun contains structure with an angular distribution that is similar to small-scale structure observed by the *Wilkinson Microwave Anisotropy Probe* (WMAP). A total of 108 associated pairs of associated H I and WMAP features have now been cataloged using H I data mapped in 2 km s^{-1} intervals and these pairs show a typical offset of 0.8° . A large-scale statistical test for a direct association is carried out that casts little additional light on whether these small offsets are merely coincidental or carry information. To pursue the issue further, the nature of several of the features within the foreground H I most closely associated with WMAP structure is examined in detail and it is shown that the cross-correlation coefficient for well-matched pairs of structures is of order unity. It is shown that free-free emission from electrons in unresolved density enhancements in interstellar space could theoretically produce high-frequency radio continuum radiation at the levels observed by WMAP and that such emission will appear nearly flat across the WMAP frequency range. Evidence for such structure in the interstellar medium already exists in the literature. Until higher angular resolution observations of the high-frequency continuum emission structure as well as the apparently associated H I structure become available, it may be difficult to rule out the possibility that some if not all the small-scale structure usually attributed to the cosmic microwave background may have a galactic origin.

Key words: cosmic background radiation – ISM: structure

Online-only material: color figures

1. INTRODUCTION

The interpretation of the distribution of the small-scale structure observed by the *Wilkinson Microwave Anisotropy Probe* (WMAP), as epitomized by the summary prepared from the five-frequency data in what is called the *Internal Linear Combination* (ILC) map, forms a cornerstone of modern cosmology. The ILC map has been presented by Hinshaw et al. (2007) and has gone through several iterations, referred to there. The key aspect of the ILC map is that the observed structure appears to be consistent with the existence of sound waves in the early moments of the universe, as summarized in the shape of the so-called acoustic spectrum.

It was disturbing to the present author to discover that some of the small-scale structure in the ILC data appeared to be closely associated with small-scale structure in the distribution of interstellar neutral hydrogen (H I) emission in the Galaxy (Verschuur 2007a, hereafter Paper I; Verschuur 2007b). If these associations were to be regarded as anything other than mere coincidence they would imply that a previously unrecognized process occurring in interstellar space is capable of generating the structure in the high-frequency continuum emission (HFCE) observed by WMAP. That, in turn, would imply that the cosmological interpretation of the ILC structures would be affected.

An immediate criticism of Paper I was produced by Land & Slosar (2007) who searched for one-to-one correspondence between H I and ILC features. However, that did little to either confirm or invalidate our earlier discussions, which were based on the discovery that peaks in the two forms of emission are closely associated but generally offset by a small angle. This claim will be re-examined through a statistical test for a point-to-point correlation between the two forms of emission in narrow bands of H I emission. When H I structure is mapped with a velocity resolution of 3 km s^{-1} at intervals of 2 km s^{-1} , this

produces area maps at 200 different velocities between -200 and $+200 \text{ km s}^{-1}$. (All velocities are given with respect to the local standard of rest (LSR).) It is the apparent association between ILC structure and H I features in these velocity maps that reveals the possibility that there exist physical processes occurring in interstellar space capable of creating the observed HFCE. The question that must then be considered is whether there is any possibility that such processes can occur in the interstellar medium. It will be shown that unresolved structures containing excess electron density could, in principle, give rise to the HFCE at the levels observed by WMAP. Evidence for structures of the required angular scale, particle density, and temperature already exists in the literature.

The present analysis elaborates on the work reported in Paper I where it was pointed out that toward H I “cloud” MI there is a close association between ILC and H I structure as well as excess soft X-ray emission reported by Herbstmeier et al. (1995). MI is one of two H I features at anomalous velocities discovered by Mathewson (1967) that came to be named MI and MII, the former at velocities around -110 km s^{-1} and the latter at about -80 km s^{-1} . In the case of both MI and MII, associated H α emission has been reported by Tufte et al. (1998). In Paper I, it was predicted that a similar relationship between ILC, H I, and X-ray structure found for MI would also be manifested in MII. The prediction is confirmed.

In Section 3, the new statistical test is described. In Section 4, tables of H I–ILC associations in an area of sky below MII as well as in directions of the 10 brightest ILC peaks in an area of sky encompassing all galactic longitudes between $|b| = 30^\circ$ and 70° are presented. In Section 5, the average angular separation between H I and associated ILC peaks found in Paper I and in the body of this paper are discussed. In Section 6, the prediction made in Paper I that a relationship would be found between ILC structure, H I, and soft X-ray emission for MII is discussed. The results of Gaussian analysis of the profiles toward H I

features MI and MII are outlined in Section 7 in order to determine if something can be learned about the relationship of the narrowband H I features to the *ILC* structure. In Section 8, a number of the very close associations between H I and *ILC* structure in the vicinity of both MI and MII are considered and in Section 9 the results of cross-correlation calculations for several pairs of structures are presented. In Section 10, it is shown that it is theoretically possible that unresolved structure in the distribution of interstellar electrons can give rise to the high-frequency emission at the same level as observed by *WMAP*. In Section 11, a variety of data pertaining to the presence of small-scale interstellar structure is considered in the light of the present work. Discussion is offered in Section 12 followed by conclusions in Section 13.

2. DATA

The H I data used in this study were taken from the side-lobe-corrected, Leiden–Argentina–Bonn (LAB), All-Sky H I survey carried out with a beamwidth of 0.6° and bandwidths 1.3 km s⁻¹ (Kalberla et al. 2005). These data were used to produce contour maps in galactic longitude and latitude (called *l*, *b* maps) of the total H I column density as well as the brightness temperature integrated over a 3 km s⁻¹ velocity range plotted every 2 km s⁻¹ in velocity over the relevant areas of interest. During this study, it became apparent that while a 10 km s⁻¹ interval was used in Paper I, a great deal more information emerges when the emission in a 3 km s⁻¹ wide band plotted at 2 km s⁻¹ intervals is used. In addition, position–velocity plots (*l*, *v* or *b*, *v* maps) were produced when needed and in several cases individual H I emission profiles were extracted from the LAB database for the purpose of Gaussian analysis to be described.

In this report, we will use the summary *WMAP* data produced by Hinshaw et al. (2007) who combined the five-frequency data (in the range 23–94 GHz), after correcting for a number of effects including contributions from the galactic foreground, to produce the so-called *ILC* map whose angular resolution was smoothed to 1°. Structure seen in this map is generally taken to represent conditions in the early universe.

In order to understand the causes of the apparent associations between certain *ILC* and galactic H I features, observational studies should focus on those directions where the H I structure is relatively uncomplicated. This rules out all directions close to the galactic disk. Therefore, the nature of the H I–*ILC* relationship in the galactic latitude band bordered by 30° and 70° in both galactic hemispheres has been studied, the lower limit chosen to avoid the galactic disk, the upper limit set for practical purposes to avoid getting too close to the poles given that we use the rectangular galactic coordinate system of the LAB survey. The bulk of the work reported here focuses on the northern galactic hemisphere data, particularly between *l* = 160° and 210°. Examination of the data shown by Hinshaw et al. (2007) shows that this area of sky was subjected to the smallest corrections for foreground effects.

The first year *ILC* data made available to the author for the work initiated in Paper I were used for the present analysis and were supplemented by data for all longitudes between latitudes 30° and 70° for both galactic hemispheres. Note that at the high galactic latitudes to which this work is confined there are no significant differences in the morphology of the *ILC* structure between the first and third year *WMAP* results. After all, very little if any correction for foreground continuum radiation (Hinshaw et al. 2007) was applied to the high galactic latitude data other than toward the spurs of galactic continuum

emission, which lie outside the bounds of the regions considered in detail in this report.

3. LARGE-SCALE STATISTICAL TESTS

Given that nearly every (positive amplitude) *ILC* peak examined closely in Paper I and in what follows appears to be associated with an H I peak at some velocity, statistical tests to confirm or negate their significance may be moot. The point is that no amount of statistical testing can prove a negative. However, in order to determine if there is any evidence for a direct point-to-point correlation between the *ILC* and H I structure data, a simple statistical test was performed. On the one hand, the *ILC* data are available as intensities as a function of *l* and *b*. Hence, we have $I_{ILC}(l, b)$. On the other hand, the H I data are available as a function of velocity as well. Thus, the H I data are available in a data cube containing the brightness temperature, T_B as a function of *l*, *b*, and *v*. Hence, $T_B(l, b, v)$. The statistical test involves examining the product

$$P(v) = T_B(l, b, v) \cdot I_{ILC}(l, b) \quad (1)$$

at each of the velocities at which galactic emission H I over the area of interest is found. This product was calculated using H I data integrated over a 3 km s⁻¹ band (two channels) at intervals of 2 km s⁻¹ from –200 to +50 km s⁻¹ over the northern sky between the latitude limits of 30° and 70° and between –100 and +50 km s⁻¹ for the southern sky data between the same latitude limits. These limits were set by the extent of the H I emission in the two hemispheres. Furthermore, the data were divided into thirds for areas in the northern (N) and southern (S) hemispheres as follows:

Target area *l* = 60°–180° (TN or TS);

Comparison area 1 *l* = 300°–60° (C1N or C1S);

Comparison area 2 *l* = 180°–300° (C2N or C2S).

The appellation “Target Area” grew out of the work reported in Paper I which focused on that longitude range in the north.

In addition to calculating the product, $P(v)$, for a given area, comparison calculations were performed by taking the H I data for that area, say TN, and then overlaying it on the *ILC* data for each of the two comparison areas, C1N and C2N, and repeating the calculations. Thus, three sets of products are calculated for each of the areas listed above:

$$P(v)_{TN \cdot TN} = T_B(l, b, v)_{TN} \cdot I_{ILC}(l, b)_{TN}, \quad (2)$$

$$P(v)_{TN \cdot C1N} = T_B(l, b, v)_{TN} \cdot I_{ILC}(l, b)_{C1N}, \quad (3)$$

$$P(v)_{TN \cdot C2N} = T_B(l, b, v)_{TN} \cdot I_{ILC}(l, b)_{C2N}. \quad (4)$$

Similarly, three sets of products were calculated for each of the Comparison Areas 1 and 2. The entire process was repeated for the data in the southern galactic hemisphere. It is recognized that the H I and *ILC* data have different resolutions but that does not negate this search for apparent associations since the higher resolutions H I structures would appear to be encompassed by the lower resolution *ILC* data if the structures happened to overlap.

If the distribution of the *WMAP* structure and the H I peaks are random with respect to one another, a histogram of the product,

$$P(v) = T_B(l, b, v) \cdot I_{ILC}(l, b), \quad (5)$$

should show a normal distribution. If, however, there is a significant correlation between the two forms of emission within

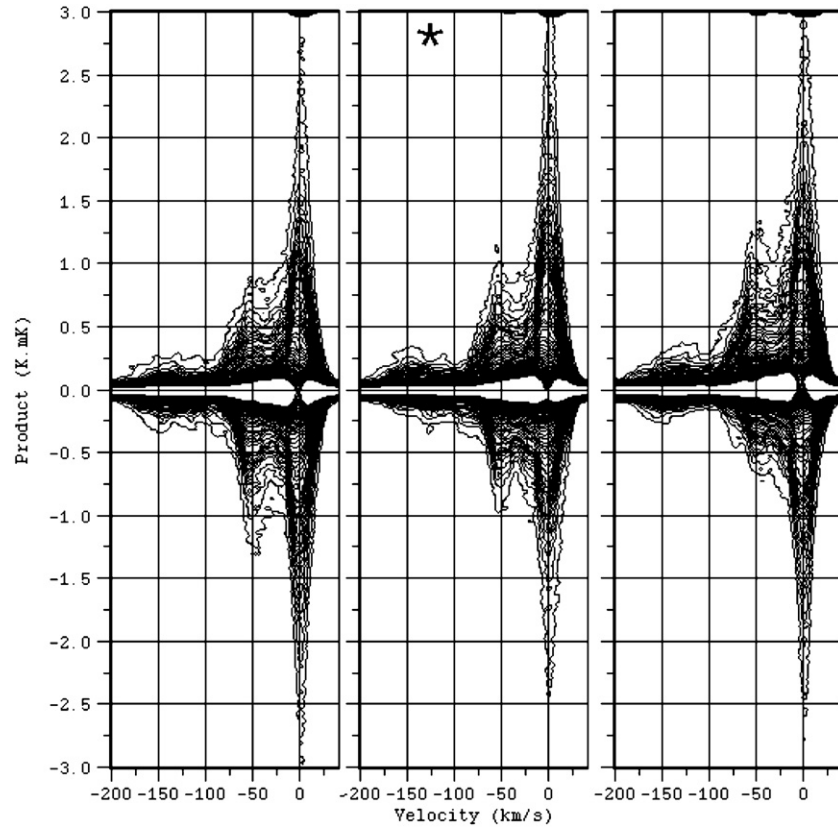


Figure 1. Examples of the statistical tests for the relationship between the H I and ILC data for the northern hemisphere Target Area. The products derived from Equations (4), (3), and (2) are shown from left to right, respectively. The product values were initially calculated in intervals of 0.01 K mK and smoothed to allow this contour map representation. Contour intervals are 2:20@2, 25:50@5, 60:300@10 K mK. The peak values inside the blank areas reach as much as 9000 K mK. The asterisk in the center plot marks the case where the H I data are compared with the ILC data for the same region. See the text for discussion of these plots.

some velocity range the histogram should show a relative excess above a normal distribution at those velocities.

Each group of three histograms covering 120° in longitude and calculated every 2 km s^{-1} in velocity produced roughly 3×10^6 data points. For display purposes, the results were plotted in contour map form for the number (N) of occurrences of the product with a given value (P) as a function of velocity. Hence, we display $N(P, v)$. For a given one-third of the area studied (according to Equations (2)(4)), three contour maps were plotted. This produced a total of nine such maps for the northern hemisphere and another nine for the southern sky data. In all, the full set of calculations involved 2.7×10^7 individual data points.

Two sets of values for the product were calculated for each data set. One considered the value of P in steps of 0.05 K mK and another over a limited range centered on zero in steps of 0.01 K mK in case those revealed more detailed structure.

In Paper I, it was claimed that there exists a relationship between ILC structure with positive values and small-scale H I structure. ILC structures that have positive values are deemed to represent directions of a small excess of high-frequency continuum radiation above the 2.738 K cosmic microwave background and negative values represent slightly cooler areas, with the range from -0.22 to $+0.22$ mK.

We have previously noted (and will discuss this further below) that there is a typical offset between H I and WMAP ILC peaks of order 0.8. If this offset were larger than the typical width of the ILC and H I structures, no correlations should make their presence known in the map of the product, $P(v)$. If, instead, there

is overlap between the contours defining structure in the two forms of emission the product, $P(v)$, should reveal the presence of such associations in certain velocity ranges.

Figure 1 shows three histogram contour maps for the H I data for the Target Area in the north (TN) when correlated with the ILC data for Comparison Area 2 (at the left), with the ILC data for the Target Area (center), and when compared with the ILC data for Comparison Area 1 (right-hand plot). The product calculations were binned in steps of 0.01 K mK in these plots. Asymmetries toward negative product values imply a correlation between the H I structure and negative ILC structure. These diagrams appear to reflect an excess of negative value signals in the ILC data in the northern strip of sky considered here. Significant cases of direct positional associations between the H I and ILC data in the center plot should show up as marked asymmetries in the value of the product over a range of velocities pertaining to the relevant H I. However, very little asymmetry is found in these plots bearing in mind that such small asymmetries as may be visible involve relatively few data points compared to the peaks in the histograms. The individual histograms are themselves seldom simple Gaussians in shape. This, too, is not surprising, since the large-scale H I and ILC structures over tens of degrees are not randomly distributed on the sky. This is evident from a visual examination of the available data. It is the small-scale associations that are of interest. For example, the slight asymmetries around -50 km s^{-1} in the left-hand and right-hand plots indicate that in some areas of sky areas of excess H I structure happens to overlap areas of predominantly either positive or negative patches of ILC structure. Thus, taken

together the data do not indicate significant overlap in position of the H I and *ILC* features at any favored velocity.

Land & Slosar (2007) have performed a statistical test using H I data integrated in velocity bands 10 km s⁻¹ wide over the whole sky and performed a search for direct correlations between *ILC* and H I structure in these velocity intervals. However, any associations that might exist between the two forms of emission would not be expected to occur at a specific velocity over large areas of sky.

The three plots in Figure 1 and the other 15 similar plots that were produced for the northern and southern galactic hemispheres between $|b| = 30^\circ$ and 70° show that convincing evidence for one-to-one associations is absent. This does not contradict the presence of associations that manifest as small angular offsets between H I and *ILC* peaks. Those are the ones that should be the focus of any further study. The point is that close associations must first be identified by actually examining the relationship between the *ILC* and H I area maps and then calculating a cross-correlation coefficient on a case-by-case basis, taking into account that the associated peaks are usually offset by a small amount and that the axis joining the offset structures do not share a common position angle over the sky.

4. NEWLY IDENTIFIED H I–*ILC* PAIRS

In this section, a number of H I–*ILC* pairs will be cataloged in an area where the apparent association between the two types of structure is very obvious, even to the naked eye when examining the relevant H I and *ILC* data, for example, the all-sky H I map found in the LAB Web site (see astro.uni-bonn.de) and the widely publicized *ILC* map (see map.gsfc.nasa.gov).

4.1. A Table of Associations in the MII Area

H I feature MII is located at $(l, b) = (185^\circ, 63^\circ)$ and its relationship to *ILC* structure was studied in the context of a larger area bounded by $l = 180^\circ$ and 210° , $b = 50^\circ$ and 70° . Figure 2(a) shows the total H I content for this area with the *ILC* contours overlain. (In this and subsequent figures, the H I data will be shown in color in the online version and as inverted grayscale in the print edition.) Figure 2(b) shows the same H I data in contour map form for visual comparison with Figure 2(a). Obviously, one cannot overlay two contour maps of this complexity in one figure and expect to learn anything by visual inspection alone. The learning comes from taking the two contour maps and examining similarities and differences between them in a “blink comparison” mode. Some readers may prefer that such a comparison be undertaken by computer, but one can only program the computer to find what one is looking for, and one cannot determine what one is looking for without first looking at the data!

4.2. A Trio of Associated Structures near MII

In Figure 2, only a few associations between H I and *ILC* peaks are obvious. This impression changes dramatically when the H I data in 3 km s⁻¹ wide bands are plotted at 2 km s⁻¹ intervals. For example, Figure 3(a) shows a very bright (relative to its environment) H I feature at $(l, b) = (201^\circ.5, 56^\circ.5)$ in the velocity range -50 to -48 km s⁻¹ which is all but invisible in the map of total column density (Figure 2). This H I peak is associated with an *ILC* peak observed by WMAP at $(l, b) = (201^\circ.2, 56^\circ.6)$ which is listed as no. 79 in Table 1. Figure 3(b) shows an elongated peak at $(l, b) = (203^\circ, 55^\circ)$ found in the H I-integrated between

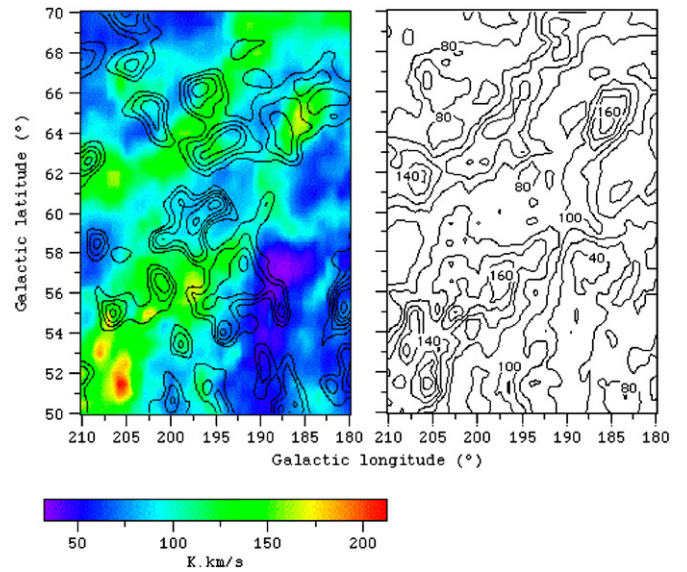


Figure 2. (a) Total H I content integrated from -150 to $+30$ km s⁻¹ for an area encompassing H I feature MII seen at $(l, b) = (184^\circ, 65^\circ)$. The *ILC* contour levels overlain are from $+0.03$ mK in steps of 0.02 mK. In order to illustrate the challenges posed by comparing *ILC* data to the H I data, Figure 1(b) displays the H I total column density data in contour map form. In the identification of H I peaks associated with specific *ILC* peaks, the H I data in contour maps were used and the positions and amplitudes determined from that database. This figure does reveal several close associations in the area around $(l, b) = (204^\circ, 55^\circ)$, which are shown in detail in Figure 3.

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

-40 and -38 km s⁻¹. Figure 3(c) shows the H I brightness integrated between $+1$ and $+3$ km s⁻¹ and it is associated with the prominent *ILC* peak at $(l, b) = (206^\circ.4, 55^\circ.0)$ listed as no. 74 in Table 1. In Figure 3(d), the H I-integrated brightness distribution in these three velocity ranges is plotted together and shows how closely the H I and *ILC* structures are correlated even if the H I is found at distinctly different velocities. Note that the slight offsets in longitude between the small angular diameter peaks in the H I and *ILC* data seen in Figure 3 are $0^\circ.3$, or half the H I beamwidth. Further details in the H I distribution in narrow velocity intervals will be discussed in Section 6–8.

4.3. A Table of Associations

The 34 brightest peaks in the *ILC* contour map have amplitudes >0.063 mK and their positions and amplitudes are given in Table 1 together with the properties of the associated H I peaks found in the narrowband maps. Column 1 assigns an identification number for the *ILC* peaks in the MII region while continuing the numbering scheme begun in Paper I, Table 1. The longitude and latitude of each *ILC* peak are indicated in Columns 2 and 3 and the amplitude of the peak in mK in Column 4. The center velocity of the 3 km s⁻¹ wide band in which the associated H I feature was recognized is given in Column 5. Columns 6 and 7 give the longitude and latitude of the relevant H I feature and its peak amplitude in K km s⁻¹ in Column 8. The angular offset in arcdegrees between associated pairs of peaks is given in Column 9.

In numerical terms 31 of the 34 *ILC* peaks in Table 1 reveal a closely spaced H I peak at some velocity when using these H I data plotted in 2 km s⁻¹ intervals. (This contrasts with only 7 of the 34 that appear to be associated in the H I map of total column density, Figure 2.) In all, 48 distinctly different H I features in the narrowband H I maps appear to be associated with these 31

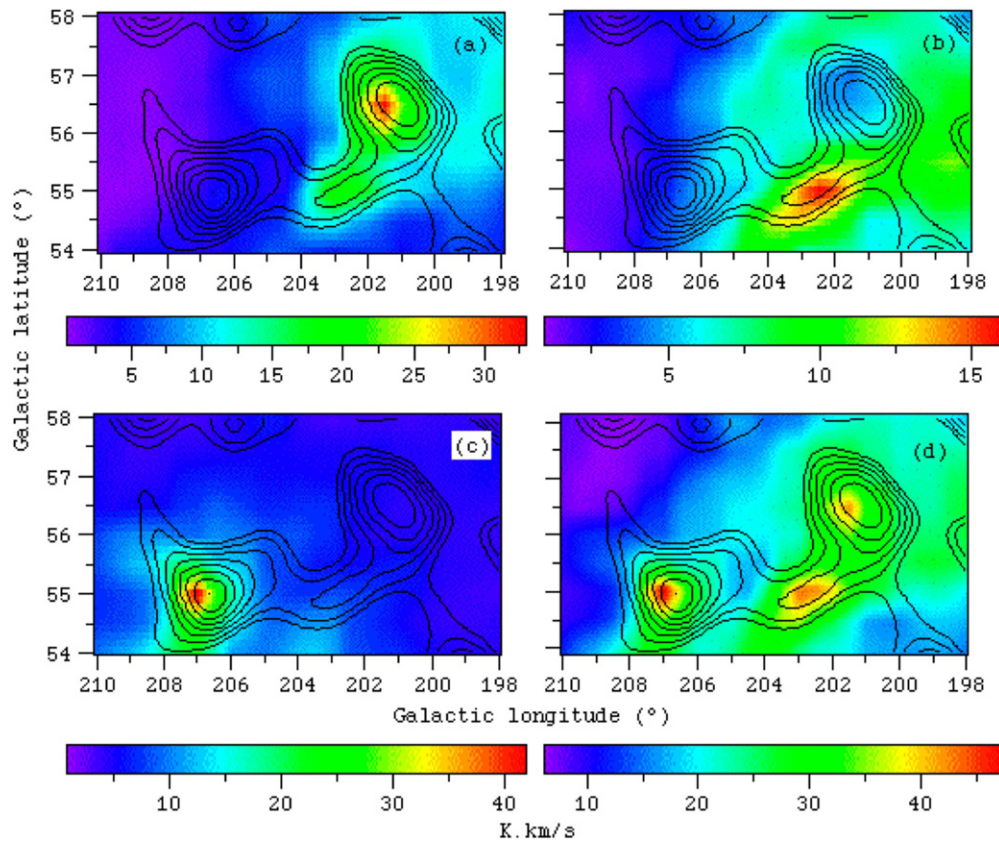


Figure 3. This illustrates how the *ILC* contours around $(l, b) = (204^\circ, 55^\circ)$ relate to the existence of three distinct peaks in the H I emission derived from data at three different velocities that are located in the area illustrated in Figure 2. (a) The H I data in the velocity range -50 to -48 km s⁻¹ are compared to the *ILC* contours. The H I structure at $(l, b) = (201^\circ, 56.6)$ is hardly visible at all in the map of total H I content in Figure 2(a) but is directly associated with the *ILC* peak, cataloged as source no. 79 in Table 1. (b) The H I data in the velocity range -40 to -38 km s⁻¹ are compared to the *ILC* contours and reveal a clear association between H I and *ILC* structure at $(l, b) = 202^\circ, 54.6$. (c) The H I data are integrated from $+1$ to $+3$ km s⁻¹ and the contours in the two forms of emission are virtually perfectly aligned. This is source no. 74 in Table 1. (d) The data in the first three plots are here combined into one plot, which shows the very high degree of association between the two forms of emission for what is clearly a complex morphology at three distinct velocity regimes.

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

ILC peaks. This is consistent with what was reported in Paper I, which shows that in many cases H I at more than one velocity is apparently involved in the production of the HFCE, possibly at the interface between interacting H I features. The average separation between paired set of H I–*ILC* peaks listed in Table 1 is 0.67 ± 0.35 , which happens to closely equal the beamwidth of the LAB H I survey.

The individual H I maps for this area between them contain 71 H I peaks defined as sets of closed contours that can be followed over adjacent velocity intervals, many of them showing small velocity gradients with changing position. About 23 of these peaks, or 32%, identified in the individual maps do not appear to have associated positive amplitude *ILC* peaks. This compares with 6% of the *ILC* peaks that do not show associated H I features.

A comparison was also carried out for the relationship between H I peaks and negative *ILC* “peaks” with very similar results. The area of Figure 2 contains 30 distinct minima with amplitudes < 0.056 mK and 18 of those appears to be associated with H I peaks. The average separation is 0.90 ± 0.34 . Given the high density of structures in the *ILC* data for this region, with clear minima separating the peaks, it is to be expected that in general the minima would tend to mimic what is found for the maxima as regards their offsets with respect to H I peaks. One way to become certain that the associations between the positive value *ILC* peaks and H I are significant is to determine

if they reveal anything new about interstellar physics. Better still would be to obtain higher resolution observation of the HFCE and the H I structure to examine their apparent relationship more closely.

4.4. The 10 Brightest *ILC* Peaks

The 10 brightest *ILC* features in the area of sky for all galactic longitudes between $b = 30^\circ$ and 70° in both the northern and southern galactic hemisphere were also examined to determine if they were associated with H I structure. All 10 sources, nine of which are found in the southern sky, are listed in Table 2 where the columns refer to the same properties as in Table 1. The numbering in Column 1 continues from the numbering used in Table 1. The velocities of the associated H I were again derived from examination of maps made at 2 km s⁻¹ intervals. Nine of the ten brightest *ILC* peaks can readily be related to the presence of H I and most of those involve H I peaks at more than one velocity, which is similar to what is found in Table 1.

5. AVERAGE SEPARATIONS OF ASSOCIATED PAIRS

The preliminary studies of possible associations between H I and *ILC* structures discussed here and in Paper I so far includes 108 close pairs. (An overview of the southern sky data for which we have prepared maps to continue this work

Table 1
MII Area Associations

No.	l ($^{\circ}$)	b ($^{\circ}$)	<i>ILC</i> Temp. (mK)	H I Velocity (km s $^{-1}$)	l ($^{\circ}$)	b ($^{\circ}$)	H I Amplitude (K)	Angular Offset ($^{\circ}$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
65	180.7	55.2	0.238	−93	181.5	54.0	1.6	1.28
66	195.2	60.4	0.206	−14	193.0	60.4	6.5	1.09
66	195.2	60.4	0.206	−61	196.0	60.0	7.4	0.56
67	197.2	59.6	0.195	None	...	...	...	...
68	193.5	63.8	0.188	8	194.0	63.0	9.4	0.82
69	196.8	66.2	0.178	−29	194.6	66.0	12.7	0.91
70	192	57.5	0.165	−93	192.9	58.0	1.8	0.70
70	192	57.5	0.165	−45	193.0	57.0	14.5	0.73
71	209.4	62.6	0.16	−39	208.0	62.1	23.7	0.82
71	209.4	62.6	0.16	−35	208.0	63.1	18.1	0.82
72	196.2	62.9	0.159	−65	196.0	63.6	8.6	0.71
73	194.2	54	0.159	−97	193.0	53.0	3.4	1.26
74	206.4	55	0.156	4	206.9	55.0	15.5	0.29
75	200.9	58.6	0.151	−35	201.5	59.9	10.7	1.34
76	187.4	63.8	0.148	−97	186.1	64.0	4.0	0.63
76	187.4	63.8	0.148	−12	188.0	64.0	5.0	0.33
77	190.5	56.3	0.144	−12	189.6	55.6	3.3	0.86
78	193.7	56.2	0.142	−22	193.0	55.6	6.5	0.72
79	201.2	56.6	0.139	−49	201.5	56.5	33.1	0.19
80	202.4	65.2	0.137	−57	203.6	65.6	7.3	0.64
80	202.4	65.2	0.137	−36	202.0	65.1	8.6	0.20
81	204.5	67.4	0.126	−29	205.7	66.5	16.5	1.01
82	187.7	55	0.125	−105	187.2	55.5	1.7	0.58
83	195.85	55.5	0.124	−12	196.6	55.5	5.3	0.42
84	208.4	58.5	0.122	None	...	—	...	...
85	199	53.4	0.116	−6	198.6	53.4	25.4	0.24
86	199.9	50.5	0.116	−93	198.0	51.0	2.6	1.31
87	186.15	50.4	0.113	−18	184.9	50.5	7.0	0.80
88	186.75	51.45	0.106	−35	186.5	51.5	4.9	0.16
89	182.15	51.35	0.094	12	183.5	50.5	7.2	1.18
90	189.5	52.1	0.093	−43	189.5	51.7	2.9	0.40
91	183.15	66.8	0.085	−65	183.6	65.5	8.2	1.31
91	183.15	66.8	0.085	−6	183.8	67.5	5.5	0.75
92	194.15	50.25	0.085	−18	195.6	50.5	7.0	0.96
93	181.85	64.85	0.073	−6	183.0	65.0	5.5	0.48
94	189.4	60.45	0.071	−65	189.6	60.1	5.6	0.36
94	189.4	60.45	0.071	−57	189.0	60.6	10.6	0.25
94	189.4	60.45	0.071	−6	189.0	60.6	6.5	0.22
95	196.55	52	0.069	−101	197.0	52.0	1.6	0.25
95	196.55	52	0.069	−77	195.4	52.0	3.4	0.74
95	196.55	52	0.069	−18	196.5	51.4	8.4	0.60
95	196.55	52	0.069	−6	196.5	52.5	7.8	0.45
96	191.35	54.4	0.065	None	...	...	...	...
97	205.85	57.9	0.064	0	205.0	57.9	6.2	0.45
98	190.7	66.8	0.063	−29	191.4	67.1	33.8	0.41
98	190.7	66.8	0.063	−14	189.1	66.0	5.4	1.02

reveals at least another 100 obvious close associations. Details are deferred to a later paper.) Table 3 summarizes the average angular separation between the *ILC* and H I peaks in each pair taken from three independent data sets considered so far. The first entry is obtained from Table 1 in Paper I. The second entry is from Table 1 and the third entry is from Table 2.

The striking fact that emerges from the data in Table 3 is that the average apparent angular separations between H I peaks associated with *WMAP* *ILC* peaks are all of order 0.8. This may be related to the method in which the associations were identified, which required that the H I contours defining a peak exhibit a morphology similar to the *ILC* feature for contours >0.02 mK. For cases where the separations are larger than about 2° , confusion quickly prevents an association from

being recognized. At that separation, the *ILC* amplitudes tend to become negative.

At this point, we reiterate concerns that are raised by the overall situation summarized in Table 3. In total, of the 108 *ILC* peaks 102, or 94%, show associated H I peaks. The converse is not true in that not all H I peaks show associated *ILC* structure. These cataloged associations involve H I at 152 distinct center velocities, which suggests that it could be the interaction between H I at different velocities that gives rise to the weak HFCE observed by *WMAP*. Given that the H I is pervasive and extremely patchy, this abundance of associations is not surprising and could obviously be fortuitous. The issue then becomes one of deciding whether it is possible that a previously unrecognized process in interstellar space could produce the HFCE observed by *WMAP* (see Section 10).

Table 2
Top 10 *ILC* Peaks

No.	l ($^{\circ}$)	b ($^{\circ}$)	<i>ILC</i> Temp. (mK)	H I Velocity (km s $^{-1}$)	l ($^{\circ}$)	b ($^{\circ}$)	H I Amplitude (K)	Angular Offset ($^{\circ}$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
99	171.35	−45.7	0.306	−18	171	−45.9	28.6	0.32
99	171.35	−45.7	0.306	−30	170.9	−45.5	4.2	0.37
100	184.1	−54.5	0.259	−50	181.55	−55	0.7	1.56
100	184.1	−54.5	0.259	20	185	−56	2.8	1.59
101	160.2	−58.25	0.261	−58	160	−58.45	1.2	0.23
101	160.2	−58.25	0.261	−12	161.5	−58	21.9	0.73
102	176.6	−48.95	0.259	−8	177.1	−49.45	51.3	0.60
102	176.6	−48.95	0.259	12	177.95	−49.4	63.5	0.99
103	164.75	−57.45	0.252	−6	164.1	−56.5	34.6	1.01
103	164.75	−57.45	0.252	−66	164	−57	1.3	0.60
104	93.45	−37.2	0.251	−8	93	−38	65.2	0.88
104	93.45	−37.2	0.251	8	94.5	−36.9	8.1	0.89
104	93.45	−37.2	0.251	14	92.95	−37.5	4.1	0.50
104	93.45	−37.2	0.251	24	93.5	−36.9	2.6	0.30
105	94.3	−40.8	0.249	18	94.05	−40	2.4	0.82
105	94.3	−40.8	0.249	−14	92.45	−40.9	22.6	1.40
106	179.95	−54.65	0.248	None	...	...	...	...
107	37.8	42.15	0.246	−38	37.05	42	2.2	0.58
107	37.8	42.15	0.246	−10	37.9	41.5	12.6	0.65
108	189.55	−51.5	0.244	−6	188	−52.1	58.6	1.14
108	189.55	−51.5	0.244	10	189	−51	55.8	0.61

6. A CLOSE LOOK AT THE H I–*ILC* ASSOCIATION IN THE MI AND MII AREAS

In Paper I, Figure 6, the relationship between *ILC*, H I, and excess soft-ray emission was published for MI. Those data are reproduced here in Figure 4(a) in which the shaded pixels representing the X-ray data taken from Herbstmeier et al. (1995) are plotted on a map of total H I content between velocities of -140 and -80 km s $^{-1}$ with the *ILC* contours overlain. The nature of the H I emission underlying the shaded pixels will be discussed in Section 7 because here the brightest H I features are hidden by the X-ray pixel structure. In Paper I, it was predicted that something similar would be found for MII but the data that allowed that assertion to be tested only came to hand after that paper was submitted. A similar plot for MII is shown in Figure 4(b) where the H I data were integrated between -125 and -55 km s $^{-1}$. (Note that in these two areas very little H I emission is seen at low velocities, as reported by Verschuur & Schmelz (2010, in preparation).) Again it appears that all three forms of emission are related for MII and while in MI all three are closely associated in position for MII the peaks for each type of radiation are slightly offset from the other two. If these close associations are due to anything other than pure chance then their relative location with respect to each other must surely provide information about the underlying physical processes involved in producing the HFCE and soft X-rays associated with the H I structure.

7. GAUSSIAN ANALYSIS OF H I PROFILES TOWARD MI AND MII

In order to more closely explore the possible relationship between H I and *ILC* structures revealed in the data, H I emission profiles in several areas of interest were decomposed into Gaussian components and the column densities of families of component line widths separately mapped on the sky. This Gaussian decomposition was done by paying attention to the existence of underlying component 34 km s $^{-1}$ wide that appears

to be present in most if not all directions observed to date in the northern galactic hemisphere as reported in a preliminary study by Verschuur (2007b). This broad component appears to be separately present in each of the so-called high-, intermediate-, and low-velocity regimes, hereafter referred to as HV, IV, and LV. This component is described by Verschuur & Peratt (1999) and Verschuur (2004) and is readily identified in directions of the simplest H I profiles, while Verschuur (2007b) showed that in certain directions where the H I is least complex the pervasive nature of this component is most obvious. Therefore, in the present study a Gaussian component with this width was fit to each H I profile in each velocity regime while the Gaussian fitting algorithm (Verschuur 2004) solved for the other components present.

Note that it is possible that a Gaussian decomposition of a single profile may give ambiguous results. However, when Gaussian analysis over an area is carried out, at least for relatively simple profiles, a remarkable coherence emerges when the results are considered as a whole. Verschuur (2004) and references therein focused on relatively simple profiles to avoid ambiguity. In this respect, the profiles shown in Figure 4 are in fact simple in that the three main peaks are well separated in velocity. Thus, each of those peaks is in itself simple, requiring at most three components to obtain a fit. Severe problems related to ambiguity occur when four or more components closely blend, which is not the case for the areas mapped here. A key fact that emerges from this analysis is that there is an underlying broad component of order 34 km s $^{-1}$ present in each velocity regime. Verschuur & Schmelz (2010) discuss the pervasive nature of this component which can clearly be seen in the profiles in Figures 4(a), (e), and (f). It is also worth noting that Gaussian analysis of all the profiles in the LAB survey has been carried out by Haud and described in a number of papers, see, for example, Haud & Kalberla (2007) and references therein, as well as by D. L. Nidever (2009, private communication) who used an algorithm referred to in Nidever et al. (2008). Verschuur & Schmelz (2010) have used data from both Haud

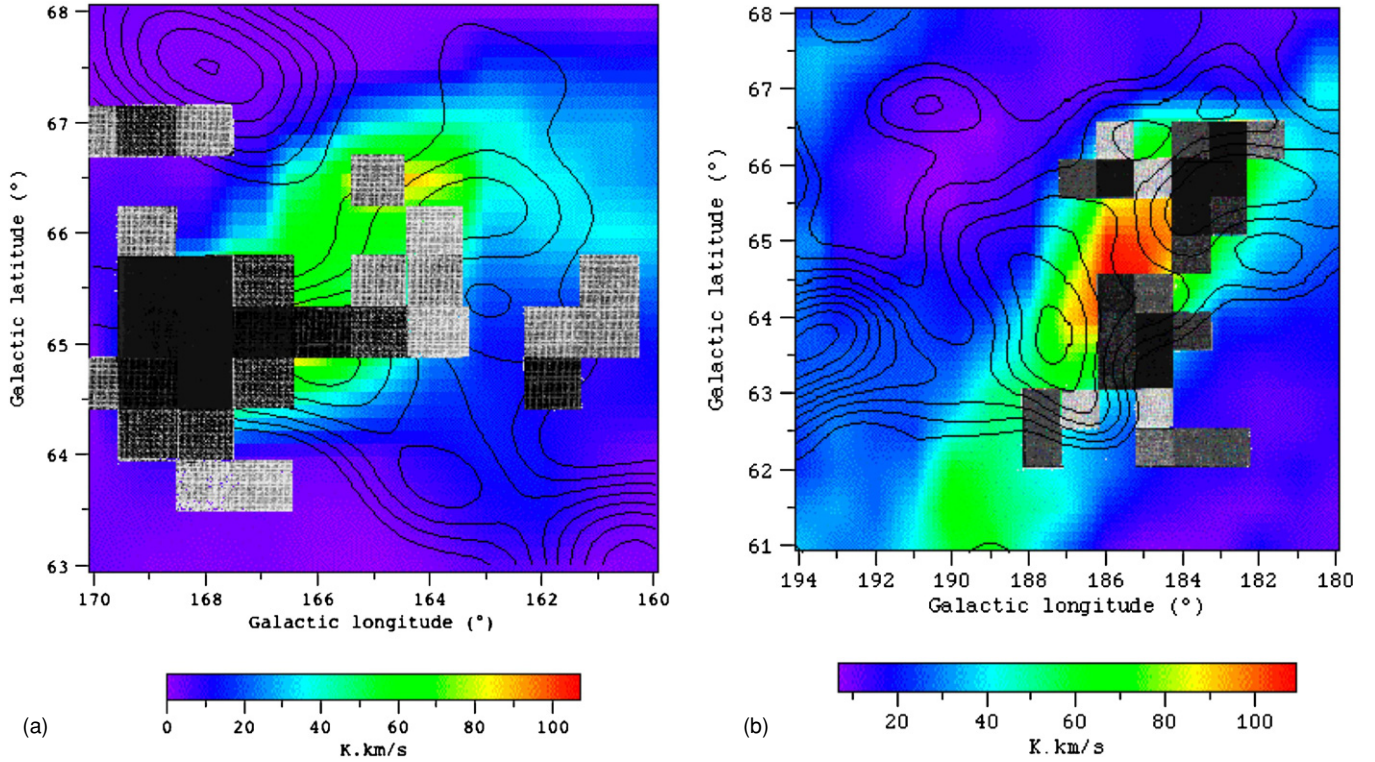


Figure 4. (a) Left-hand figure displays the total H I column density for MI integrated from -140 to -80 km s $^{-1}$ with shaded pixels indicating the presence of excess soft X-ray emission at 1/4 keV derived from the data of Herbstmeier et al. (1995). (b) The right-hand figure displays the total H I column density for MII integrated from -120 to -55 km s $^{-1}$, which covers the great majority of H I emission at any velocity in this area of sky with the ILC contours from $+0.02$ mK in intervals of 0.02 mK overlain. The shaded pixels again indicate the excess soft X-ray emission derived from Figure 7(b) of Herbstmeier et al. (1995). Note that the peaks found in all three forms of emission are slightly offset from one another in contrast to the case in (a) where they are closely aligned.

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

Table 3
Average Separations between Paired ILC–H I Peaks

Ref.	l Range	b Range	ILC Peaks (mK)	No.	Pairs	H I Peaks	Separation (°)
1	60° – 180°	30° – 70°	>0.100	64	62	83	0.93 ± 0.55
2	180° – 210°	50° – 70°	>0.063	34	31	48	0.67 ± 0.35
3	All longitudes	$ b = 30^\circ$ – 70°	>0.244	10	9	21	0.79 ± 0.40

(2010, private communication) and D. L. Nidever (2009, private communication) to show that results for a set of common profiles agree very closely and that the pervasive component does not decompose into narrow lines when observed with a $9'$ beam as opposed to the $36'$ beam of the LAB survey. Thus, the Gaussian mapping of the H I emission from MI (and MII, below) in the line width families discussed here is regarded as significant.

Figure 5 shows examples of the Gaussian decomposition for a number of directions toward MII where the presence of the broad underlying component is unambiguous. After the Gaussian fitting was completed, a number of distinct line width and velocity families were recognized in the data. These were sorted and maps made of the total column densities for each prominent category.

The average parameters for the two dominant line width components associated with MI and MII are shown in Table 4. Column 1 gives the name of the H I feature whose profiles were analyzed. Column 2 gives the derived full width at half-maximum line widths in km s $^{-1}$ averaged over the area under consideration with the 34 km s $^{-1}$ value kept fixed. Column 3 gives the average peak brightness temperature in K of the Gaussian components fit to the profiles sorted into line width

family categories, Column 4 gives the average center velocities in km s $^{-1}$ with respect to the LSR of these families, and Column 5 gives average column densities in units of 10^{18} cm $^{-2}$.

Table 4 shows that the Gaussian analysis revealed that H I emission profiles associated with MI and MII are dominated by two families of line widths, those with this width of 34 km s $^{-1}$ and another of order 21 km s $^{-1}$ wide (ranging from 18 to 26 km s $^{-1}$). The common occurrence of Gaussian components of order 34 km s $^{-1}$ wide has been discussed by Verschuur (2004) and references therein and the existence of components with widths of order 21 km s $^{-1}$ wide have been noted by Haud (2008) as well as the present author in the case of anomalous velocity H I (in preparation). It is possible that this component is due to H I at a temperature of 8000 K and this will be discussed in a future paper.

7.1. Gaussian Mapping for MI

The dominant line width families found for MI have widths of 34 and 21 km s $^{-1}$, Table 4, while two other families of line widths have average widths of 13.8 ± 2.2 and 6.3 ± 2.4 km s $^{-1}$. Figure 6(a) shows the ILC contours superimposed on a map

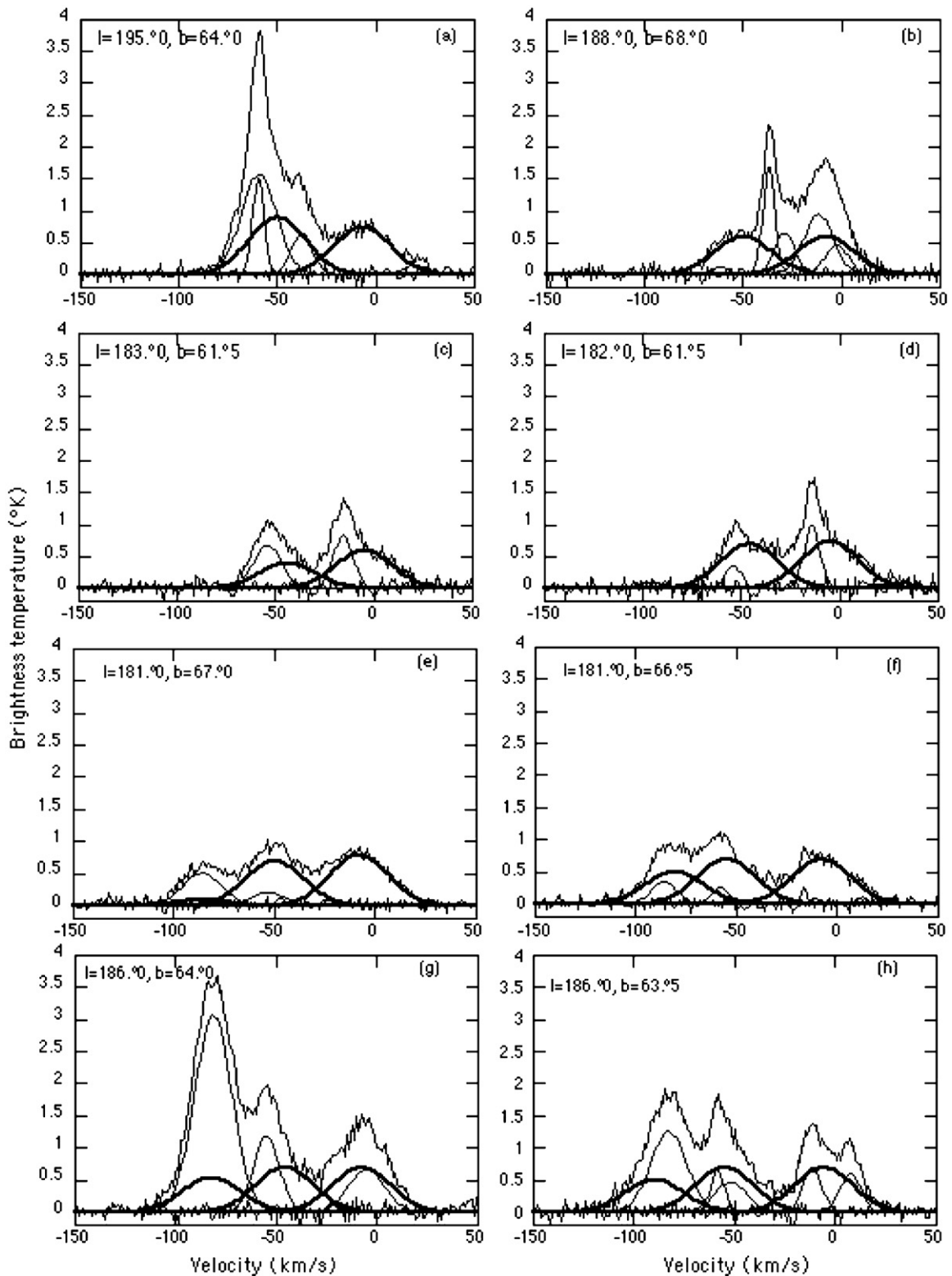


Figure 5. Eight frames showing typical profiles in the area toward MII with the Gaussians fit to those profiles. In the top four frames, no emission associated with MII is found. In the lower four frames, emission from MII can be seen around -80 km s^{-1} . The Gaussian components indicated by thick lines correspond to the underlying features with a line width of 34 km s^{-1} . At low velocities, these produce a near perfect fit to many of the observed emission profiles. In frame (g), the profile at $(l, b) = (186^\circ, 64^\circ)$ shows the manner in which the 21 km s^{-1} wide component dominates the emission from MII.

of the H I column density for the 34 km s^{-1} wide component associated with MI and Figure 6(b) shows the relationship to the H I component with a line width of order 21 km s^{-1} . In this figure, the southern H I and ILC peaks overlap nearly

perfectly while the 34 km s^{-1} wide component appears to be more prominently associated with the northern of the two ILC peaks. Tufté et al. (1998) have reported excess H α emission at five locations toward MI and these are marked in Figure 6(b)

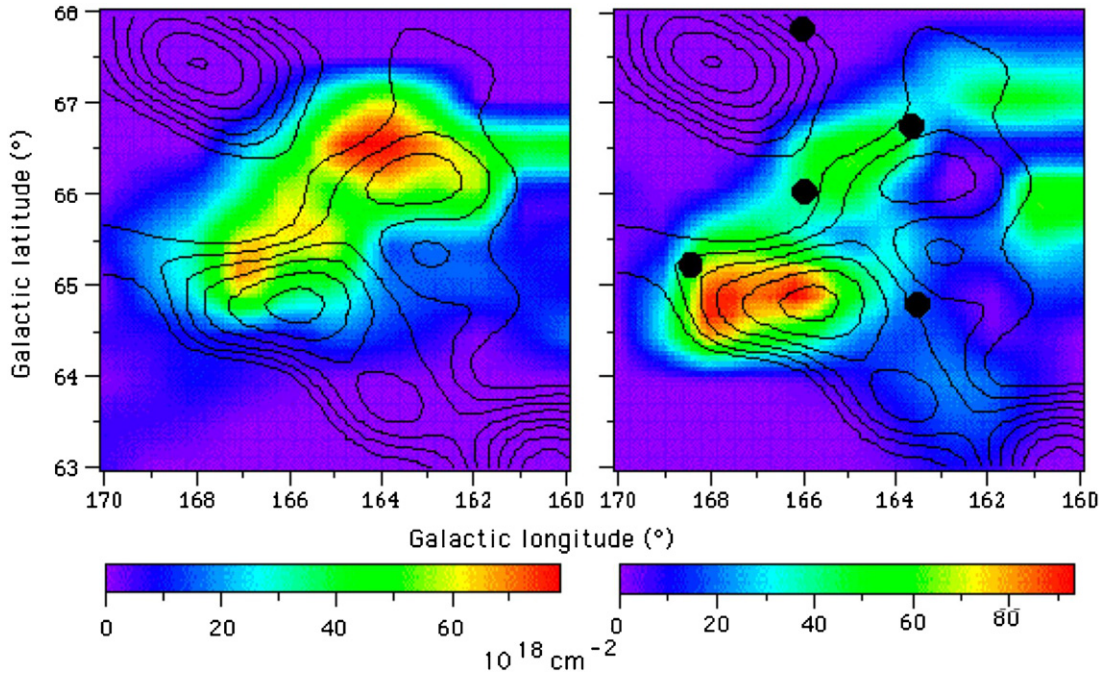


Figure 6. Left-hand figure, (a), displays the H I column density for MI for the 34 km s^{-1} wide H I component in the direction of H I feature MI compared to the *ILC* contours from $+0.06 \text{ mK}$ in intervals of 0.02 mK . The double structure in the H I is uniformly offset from the double feature in the *ILC* data. In Paper I, the total column density of the H I emission was compared with the *ILC* structure but in this plot it is evident that the physical properties of the H I associated with each of the two *ILC* peaks are distinctly different. This conclusion is reinforced in the right-hand plot, (b), showing the H I column density for components in the 21 km s^{-1} regime compared to the *ILC* contours. This component, indicative of H I at a temperature of about 8000 K , is very closely associated with the main *ILC* peak. Also shown as filled circles are directions in which Tuft et al. (1998) detected H α emission. Note that the peaks in all three categories are offset from one another. See the text.

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

Table 4
Average Properties of Gaussians for MII and MI

Source Name	Line Width (km s^{-1})	Peak Temperature (K)	Center Velocity (km s^{-1})	Column Density (10^{18} cm^{-2})
(1)	(2)	(3)	(4)	(5)
MI	34	0.42 ± 0.40	-106.5 ± 8.6	26.3 ± 24.8
MI	21.1 ± 1.6	0.76 ± 0.71	-114.2 ± 4.7	29.0 ± 27.1
Other MI	13.8 ± 2.2	0.99 ± 1.00	-117.2 ± 7.2	25.8 ± 26.7
Components	6.3 ± 2.4	0.54 ± 0.51	-117.1 ± 5.5	7.0 ± 8.8
III	34	0.32 ± 0.22	-81.6 ± 4.1	19.6 ± 13.5
III	20.2 ± 3.4	1.00 ± 0.79	-80.8 ± 5.5	35.7 ± 27.2

where it is obvious, as was also noted by those authors, that the peaks in the H α emission are offset from the associated bright H I peaks. When the two plots in Figure 6 are compared with the map of total H I contents for MI (Figure 4(a) and more specifically Figure 6(a) in Paper I) it is seen that it is the 21 km s^{-1} wide family of lines that produces the main structure with the remaining contribution to the southern H I peak coming from the H I column density map in the two narrow components summarized in Table 4. These narrower line width values are consistent with the data discussed by Verschuur & Peratt (1999). Figure 7 shows the column density maps for the two narrow components found in the emission profiles for MI. Together these associations offer a clue as to how and why the two types of emission are related, provided one accepts the suggestion that these associations are due to something other than chance. What the clues mean remains to be determined.

7.2. A Closer Look at the H I and Soft X-ray Structure for MI

The *ILC* peak in Figure 4(a) at $(l, b) = (168^\circ, 67.5^\circ)$ (listed as source no. 9 in Table 1 of Paper I) has a small X-ray structure

just to its south. This is found to identically overlap an H I feature at positive velocities between $+5$ and $+10 \text{ km s}^{-1}$ at $(l, b) = (169^\circ, 67^\circ)$ shown in Figure 8(a). In addition, an H I peak found at a velocity from -10 to -5 km s^{-1} shown in Figure 8(b) closely abuts the H I component with a 21 km s^{-1} width seen in Figure 6(b) and the relative morphology exhibits the same axial ratio for the elongated features. These data strongly hint at complex interactions between H I features at different velocities interacting with one another to produce the HFCE observed by WMAP. Also, if the low-velocity H I feature associated with the slight excess of soft X-ray emission at $(l, b) = (169^\circ, 67^\circ)$ is significant, then the association with the X-ray structure for the bulk of MI is not related to the mere presence of high-velocity gas.

7.3. Maps of H I Components Toward MII

In the area toward MII bounded by $l = 180^\circ$ and 194° , $b = 62^\circ$ and 68° , 225 H I profiles were decomposed into Gaussian components in the same way as was done for MI. Figure 9(a) shows the *ILC* contours overlain on a map of the H I column density in the 34 km s^{-1} wide component associated with MII,

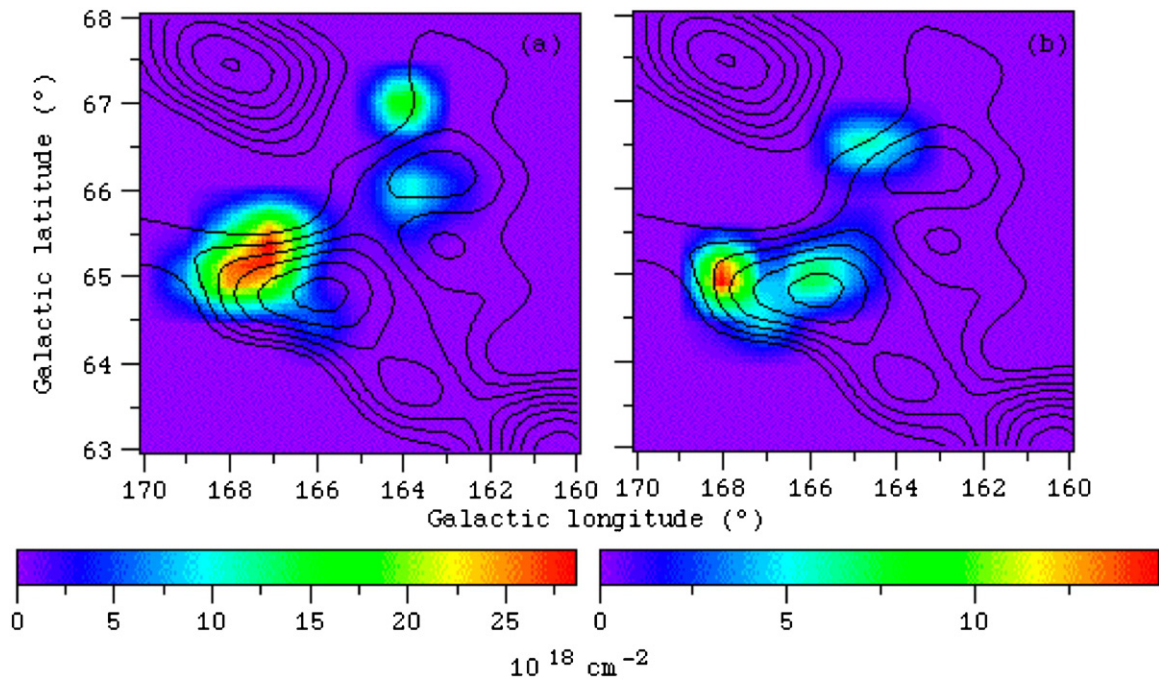


Figure 7. Two families of narrow line width components are also found toward MI and they are here plotted with respect to the *ILC* contours which are the same as for Figure 6. (a) Column density map for components with line widths between 9 and 15 km s⁻¹. (b) Column density map for narrow components with line width < 9 km s⁻¹. Both these families appear to be related to the presence of the brighter of the two *ILC* peaks associated with MI.

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

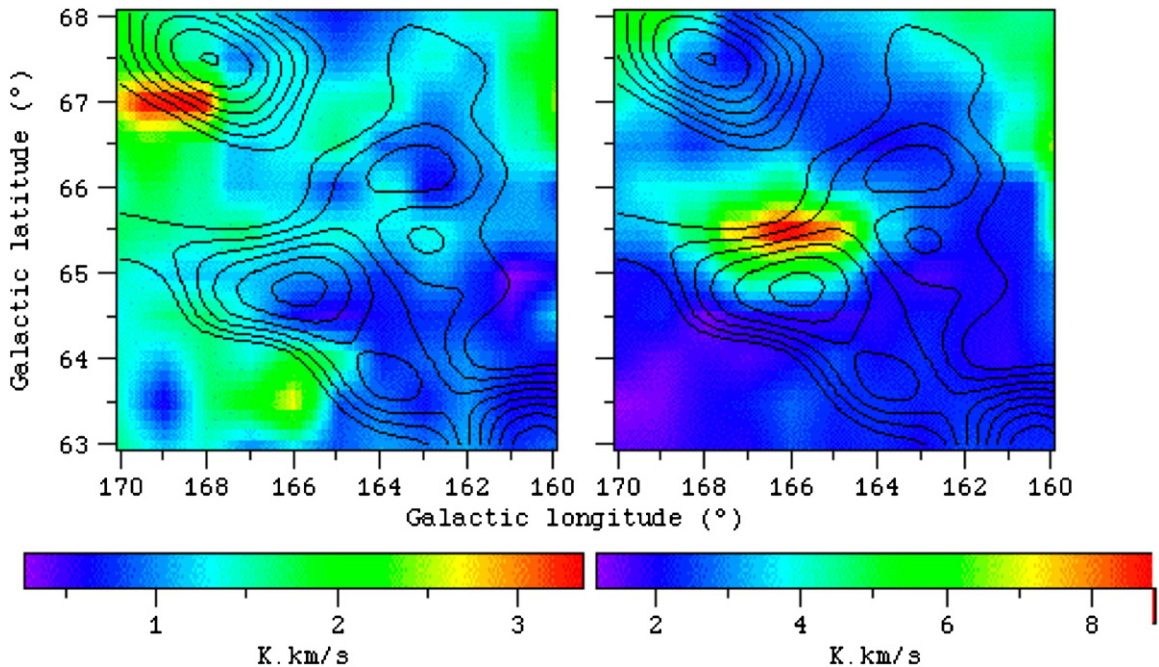


Figure 8. Two (*l*, *b*) maps for the MI area again shown with respect to the same *ILC* contours used in the previous two figures. (a) In the left-hand figure, a bright H I feature found by integrating between +5 and +10 km s⁻¹ appears to be precisely aligned with the small patch of excess soft X-ray emission seen in Figure 4(a), see the text. (b) The right-hand figure shows an H I feature found by integrating between -10 and -5 km s⁻¹ with virtually the same angular extent as the brightest *ILC* peak in this area is located just to the north of that peak by about 0'.5. This pattern of finding H I features at two distinct velocities associated with a given *ILC* peak was found to be common, and this example is particularly striking. See the text.

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

and Figure 9(b) shows the same contours compared to the component with an H I line width of order 21 km s⁻¹. Tufte et al. (1998) have reported excess H α emission at two locations toward MII. These are shown in Figure 9(b). Their direction no. 2b at (*l*, *b*) = (186°, 65°) lies on the peak in the H I map of the

21 km s⁻¹ wide feature. The velocities of the H I component and H α data are nearly identical at this position, -81.1 km s⁻¹ for the H I and -72 or -78 km s⁻¹ for each of two estimates by Tufte et al. (1998) for the H α data. The underlying 34 km s⁻¹ wide component at this position is centered at -82.3 km s⁻¹.

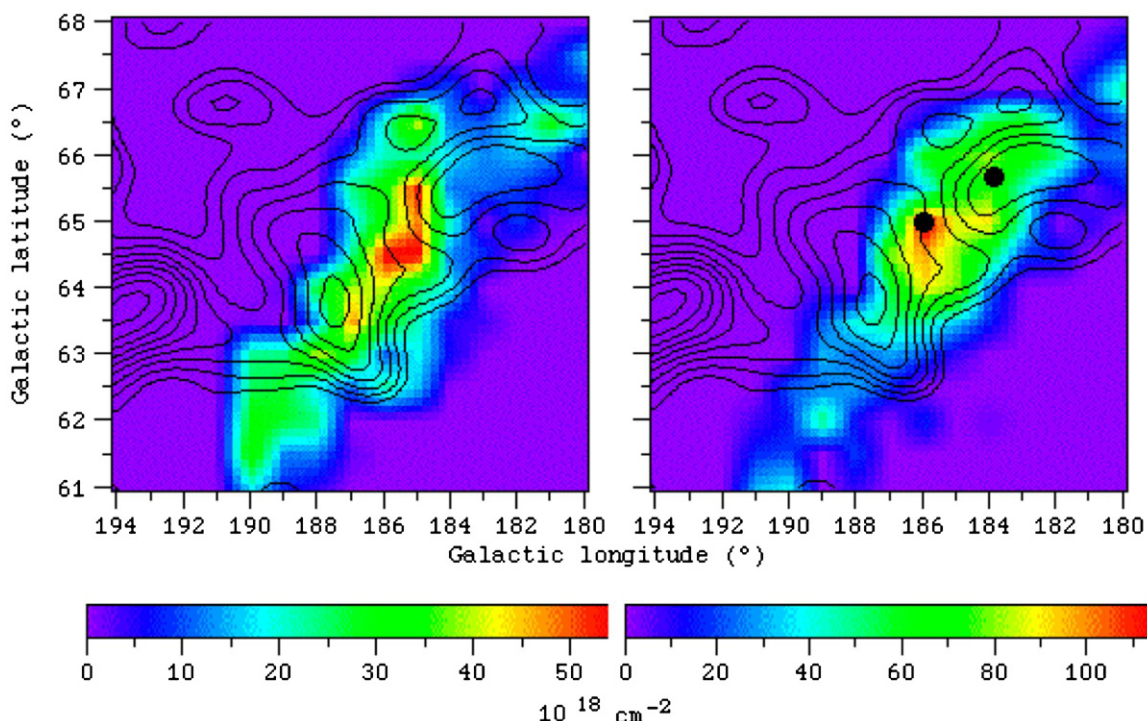


Figure 9. (a) At the left, the morphology of the column density of the 34 km s^{-1} wide H I component associated with MII compared to the *ILC* contours. (b) At the right, the morphology of the column density of a family of line widths in the 20 km s^{-1} range compared to the *ILC* contours from $+0.02 \text{ mK}$ in intervals of 0.02 mK overlain. Also shown as filled circles are directions in which Tufté et al. (1998) detected $\text{H}\alpha$ emission. Unlike the case for the data in Figure 6, here one of the $\text{H}\alpha$ detection is closely aligned to the H I.

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

Both of the two H I components mapped in Figure 9 are slightly offset from the *ILC* peak. This is also true of excess soft X-ray emission associated with MII as reported by Herbstmeier et al. (1995) shown in Figure 4(b). There is one bright *ILC* peak at $(l, b) = (193.5, 63.8)$ at the edge of the maps in Figure 4(b). It is source no. 68 in Table 1. In Figure 10, the column density of a positive velocity component in the range $+3$ to $+10 \text{ km s}^{-1}$ is compared to the *ILC* contours and it appears that the *ILC* peak is associated with an excess of positive velocity H I in this direction. This plot also shows that positive velocity H I emission appears to encompass the southern half of the *ILC* feature associated with MII.

8. ASSOCIATIONS IN THE AREA ENCOMPASSING MI AND MII

In the course of our analysis, it was found that the associations between H I and the *ILC* structures are most clearly revealed in the narrowband area maps made at 2 km s^{-1} intervals. In Paper I, a velocity range and interval of 10 km s^{-1} were used but in many directions this hides the relevant structures that cover an intrinsically smaller velocity range.

8.1. A Striking Association South of MI

An area of sky just south of MI includes several examples of the variety of associations found when small-scale features in the H I and *ILC* data are compared. Figure 11(a) shows the *ILC* contours overlain on the map of total H I content for an area bounded by $l = 180^\circ$ and 165° and $b = 45^\circ$ and 65° . Many of the pairs of associated structure listed in Paper I are located in this area but few are revealed in this map of total H I column density. Figure 11(b) compares *ILC* structure and H I data integrated

from -20 to -10 km s^{-1} in the same area. At $(l, b) = (173^\circ, 50^\circ)$ an association is visible that is listed as source no. 7 in Paper I, Table 1 but it is barely recognized and is all but invisible in the map of total H I content in Figure 11(a). It is shown in detail in Figure 12(a), which presents the brightness temperature for source no. 7 in a narrowband close-up of its area.

A Gaussian analysis was performed on 143 profiles located every 0.5 in latitude and longitude for the area bounded by $l = 176^\circ$ and 170° , $b = 48^\circ$ and 53° and again an underlying component 34 km s^{-1} wide was readily identified in most profiles for both the low- and intermediate-velocity H I. The most striking components that emerge after taking these into account is a set of narrow lines of order $3\text{--}5 \text{ km s}^{-1}$ wide with a center velocity of -19 or -20 km s^{-1} over part of the area. The H I column density of this component was mapped and the result is shown in Figure 12(b) with the *ILC* contours overlain. A near perfect overlap, especially as revealed in the morphological boundaries, is obvious.

If the narrow width of this component is interpreted as a kinetic temperature, it is in the range of $180\text{--}500 \text{ K}$. At $(l, b) = (173^\circ, 50.5^\circ)$, the narrow H I component appears to be a double. In Figure 12(b), the column density of only one of these components was used to be consistent with the Gaussian solutions in its neighborhood but if the H I column density derived from the sum of these two components is used a map of the H I column density shown in Figure 12(c) is obtained. The bright spot at $(l, b) = (172^\circ, 50.5^\circ)$ implies that an additional H I structure is present there and this argues for obtaining higher angular resolution H I profiles for this area to better track the possible relationship to the *ILC* structure. In general, the structure seen in Figure 12 suggests that in this direction the source of HFCE is related to sources associated with an

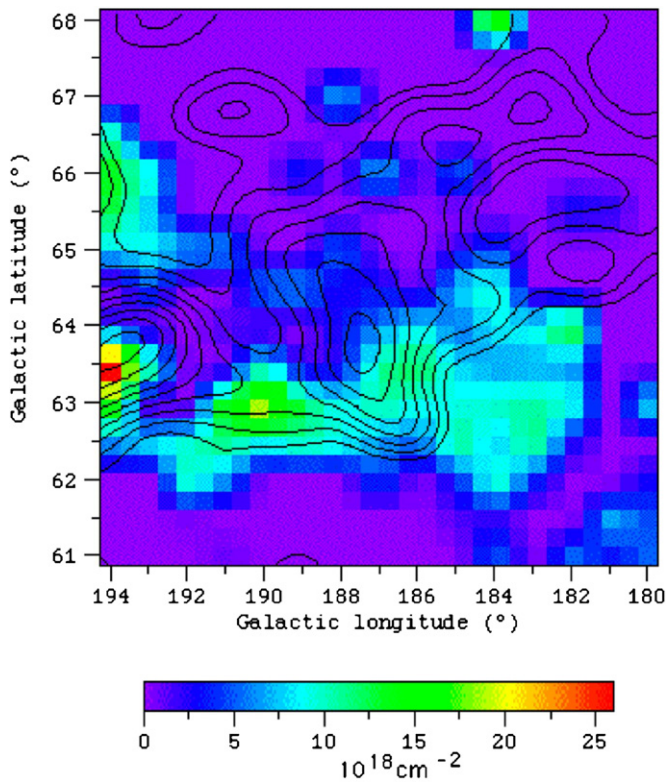


Figure 10. Gaussian analysis of the H I emission profiles in the area of M1 revealed unexpected features at positive velocities between +5 and +20 km s⁻¹. Here, the H I column density of these components is plotted with the same ILC contours as in Figure 9 overlain. It is striking that the bright peak at $(l, b) = (194^\circ, 63^\circ.4)$ appears associated with a distinct ILC peak. Also a low level of emission at these velocities borders the brightest ILC peak in the area.

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

enhanced region of H I emission from cold components of the gas.

8.2. Other Associations Near M1

Figure 13 illustrates the relationship between the ILC and H I structure for four other pairs of features in the vicinity of M1. In Figure 13(a), a very close association between H I at +2 km s⁻¹ and ILC source no. 4 in Paper I is seen. In Figure 13(b), the H I brightness temperature at +2 km s⁻¹ is shown overlain with the ILC contours for source no. 13 from Paper I, located at $(l, b) = (169^\circ.5, 46^\circ.5)$. In that paper, the positions were measured on a map made integrating over a 10 km s⁻¹ range from -10 to 0 km s⁻¹ and the offset in position between the peaks in the two forms of emission was estimated at 0.78. In the data shown in Figure 13(b), the offset determined from a map made by integrating over the narrower velocity band of 3 km s⁻¹ is zero. The difference results from the presence of velocity broadening and velocity gradients within the structure seen in the H I. Figure 13(b) also reveals another pair of associated features near $(l, b) = (173^\circ, 46^\circ)$. This was identified as source no. 24 in Paper I but the data shown here indicate that this ILC peak is slightly shifted with respect to the position given there. Figure 13(c) shows the H I at -136 km s⁻¹, which includes the ILC peak listed as source no. 40 in Paper I at $(l, b) = (167^\circ.3, 55^\circ.7)$. Clearly, the H I at this velocity, which peaks at $(l, b) = (167^\circ.3, 55^\circ.0)$, is closely associated. When the difference in angular resolution between the two types of data is taken into account, it is visually evident that these structures are nearly

identical in shape. A Gaussian mapping of these areas was not undertaken other than to determine that in these directions the H I profiles showed components with line widths of 15 km s⁻¹ for two of the peaks (from the left in Figure 13), two overlapping components 15 and 4 km s⁻¹ wide for the third peak, and two features 34 and 20 km s⁻¹ wide for the right-hand frame. Again these hint at interacting gas masses being involved.

Figure 14(a) compares the ILC contours with the H I data at -102 km s⁻¹ integrated over a 2 km s⁻¹ range. ILC source no. 2 (from Paper I) at $(l, b) = (174^\circ.4, 56^\circ.8)$ closely abuts an H I feature at $(l, b) = (175^\circ.5, 55^\circ.0)$. This association between the two forms of emission for source no. 2 is of particular interest since the boundary between the H I and the ILC peaks shows them to be unresolved at their interface. This is illustrated in Figure 14(b), which displays a cross section of the amplitudes of both the H I and ILC peaks plotted along a line joining the center of the two peaks. The equivalent half-widths at half-maximum intensity of the two features along this axis are 0.35 and 0.5, respectively, which compares with the beamwidths of 0.6 for the H I and 1° for the ILC data. These represent a case of abutting, unresolved edges. The H I feature in Figure 14(a) is centered at $b = 55^\circ.5$ and has a total width of 0.64. The ILC feature is intrinsically 1.2 wide and has a center at $b = 56^\circ.5$. The line of the interface is thus at $b = 55^\circ.8$, which is coincident with the half-maximum height of both of the observed features. These data suggest that the HFCE is being produced at the edge of the H I feature as projected on the sky. In this case, the Gaussian analysis of the peak H I profile shows overlapping components 20 and 15 km s⁻¹ wide.

8.3. The Trio of Structures

The basic data for a trio of features in the same general area was shown in Figure 3. No attempts were made to map the Gaussian component structure for these directions, largely because the H I profiles are too complex for unambiguous mapping. Gaussian analysis of the H I peaks in Figure 3 showed that the relevant components had widths of 7 and 4 km s⁻¹ for the feature in (a) and 22 and 4 km s⁻¹ in (b) while the IV H I emission profile in the direction of the H I feature in (c) was too bright to be reliably decomposed into Gaussian components.

Overall, the data discussed in this section reinforce our contention that in order to carry out a comprehensive search for associations, use must be made of H I data plotted as narrow channel maps spaced at intervals of at most 2 km s⁻¹ and preferably with high angular resolution so as to untangle the profile component structure, which so far has not shown any simple trends. It is the H I morphology observed in small velocity intervals, and the velocity structure within in the profiles, that is likely to carry the most information regarding the nature of the complex physical interactions that appear to underlie the production of HFCE in interstellar space.

9. CROSS-CORRELATION STUDIES

Given that there appear be small angular offsets between specific ILC and H I features as discussed in Sections 7 and 8, it is worth examining whether there is a statistically significant relationship when they are considered on a case-by-case basis.

In Section 3, it was shown that there is little evidence for a direct one-to-one correspondence between the ILC and H I peaks over large areas of sky. Furthermore, the close associations discussed so far do not occur in a uniform manner because the axes connecting the members of paired structures

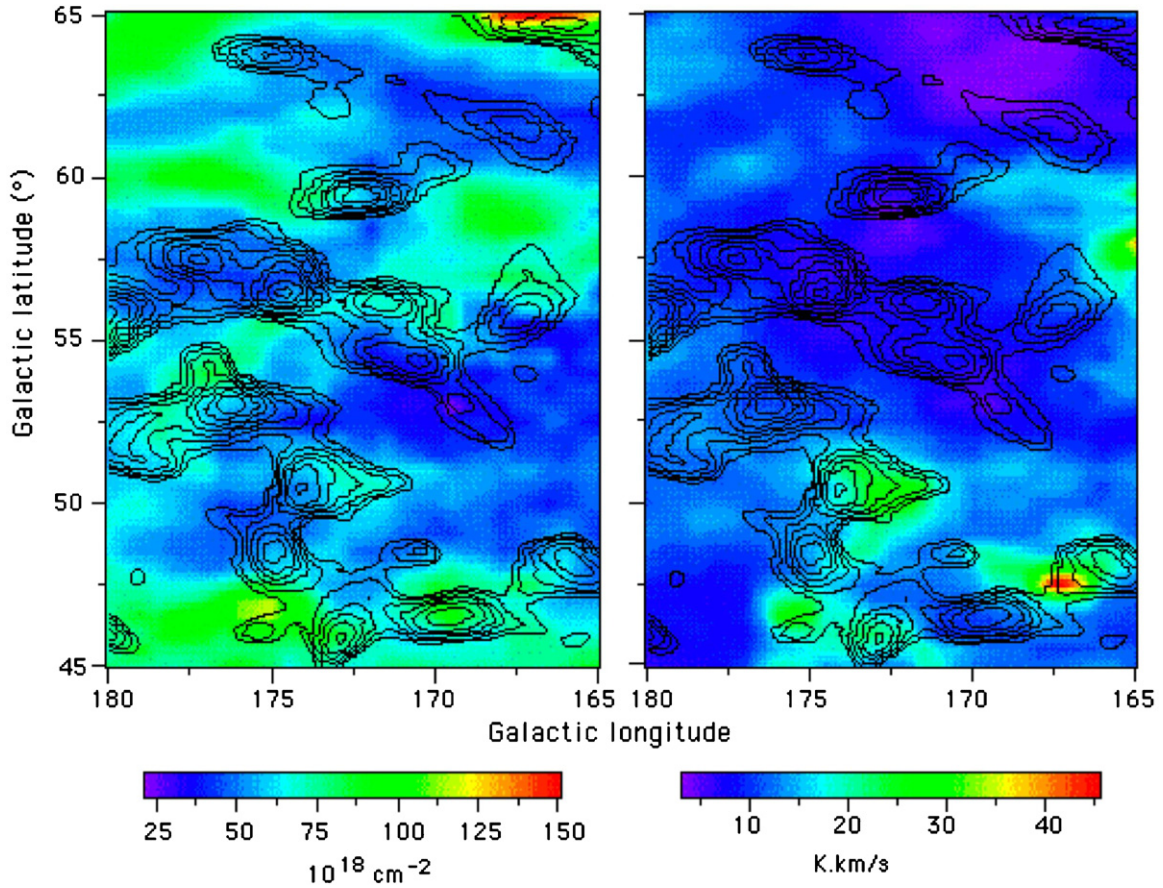


Figure 11. (a) Total H I column density for an area just below MI compared to the *ILC* contours level used before. Due to the dynamic range of this plot, few associations stand out. (b) The same area showing the integrated H I brightness from the -20 to -10 km s^{-1} at which resolution the associations begin to manifest. In Figure 12, a close-up view of the structure around $(l, b) = (173^\circ, 50^\circ.5)$ shows a very high degree of association.

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

are not oriented in the same direction on the sky. Hence no comprehensive, large-scale statistical test for a fixed position angle over large area of sky will reveal anything of significance. However, a meaningful test could be to consider individual pairs of associated features and then shift one with respect to the other in position so as to align them even if they are initially slightly offset and then derive a cross-correlation coefficient to test for first-order significance. In this regard, small offsets between the two forms of emission would be the hallmark of a form of limb brightening along one face of an H I feature, where the neutral gas interacts with the surrounding interstellar plasma, to be discussed below.

Table 5 shows the results of the correlation calculations for some of what are mostly unresolved pairs of structures discussed above and in Paper I. Column 1 gives the source name and/or references used in this work and a reference to the figure number displaying the data. Column 2 gives the velocity of the H I at which an association is claimed while Columns 3 and 4 give the magnitude of the cross-correlation coefficient when the two data sets are compared along cross sections in longitude and latitude. The values obtained using the data unshifted in position are shown followed by the values obtained when the calculation is carried out after shifting the H I data with respect to the *ILC* data by the angle indicated in order to align the peaks. Note that if two unresolved features observed with the beamwidths of $0'.6$ and $1'.0$ are perfectly coincident in position the cross-correlation coefficient would be 0.93. Thus, those cases listed in Table 5 that

show a value of R of this magnitude are in fact highly correlated, which means that the members of each associated pair have virtually the same angular dimensions. It could be argued that the method of identification of the closely associated pairs in the first place favors those that look closely similar. For example, one would tend to avoid attaching significance to finding an *ILC* feature of large angular extent next to a small H I feature, or vice versa. However, during the discovery of the associations it was not obvious that this was occurring.

10. A POSSIBLE MODEL

In this section, it is assumed that the spatially offset associations of *ILC* and H I features are significant and will consider whether free-free emission from unresolved structures in the distribution of electrons in interstellar space could give rise to HFCE. Note that contrasts with the case of free-free emission from electron-ion pairs referred to by Hinshaw et al. (2007).

10.1. Free-free Emission from Electrons

Using the form for free-free emission as given, for example, by Nitta et al. (1991), the optical depth τ_{ff} can be expressed as a function of frequency, ν , the electron temperature, T_e , the electron density, n_e , and path length, l , as follows:

$$\tau_{\text{ff}} = 9.8 \times 10^{-3} \nu^{-2} T_e^{-1.5} \ln(4.7 \times 10^{10} T_e/\nu) \int n_e^2 dl. \quad (6)$$

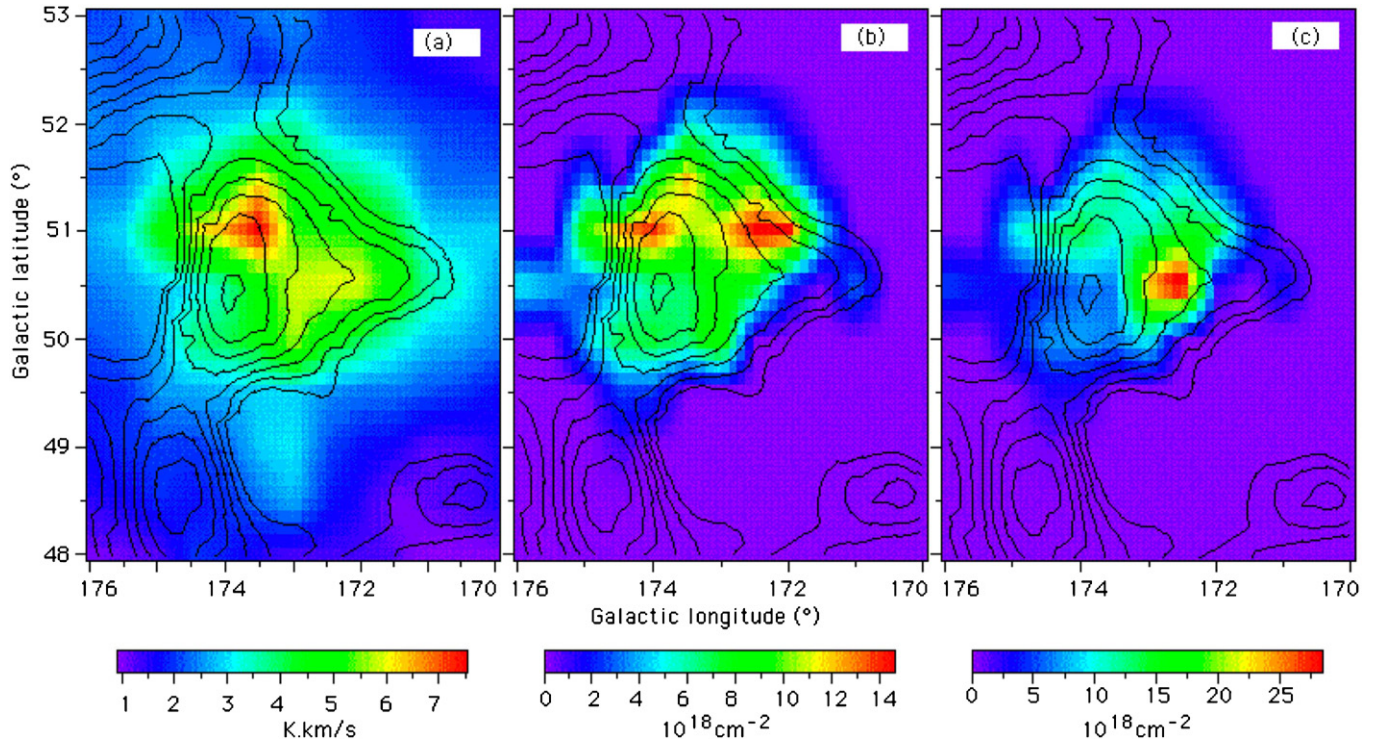


Figure 12. Three detailed views of the associated structures around $(l, b) = (173^\circ, 50^\circ.5)$ seen in Figure 11. (a) A detailed view of the association between the H I brightness at -19 km s^{-1} (integrated over a 2 km s^{-1} bandwidth) compared to the same *ILC* contours as in previous figures. This is listed as source no. 7 in Table 1 of Paper I. The outer boundary of the H I feature corresponds virtually perfectly to the *ILC* contours on three sides. (b) The H I column density found in the Gaussian analysis of a narrow line width component corresponding to the emission peak at -19 km s^{-1} is displayed with the *ILC* contours overlain. The high degree of correlation between the two forms of emission and the fact that they define the same area noted in (a) is even more striking in this plot. (c) Here, both narrow line width components found in the direction marked by the bright peak are added together. In (b) only one of those components was included but in (c) the combined value of column densities for this double Gaussian (which cannot be unambiguously separated in the available H I data) overwhelms the morphology.

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

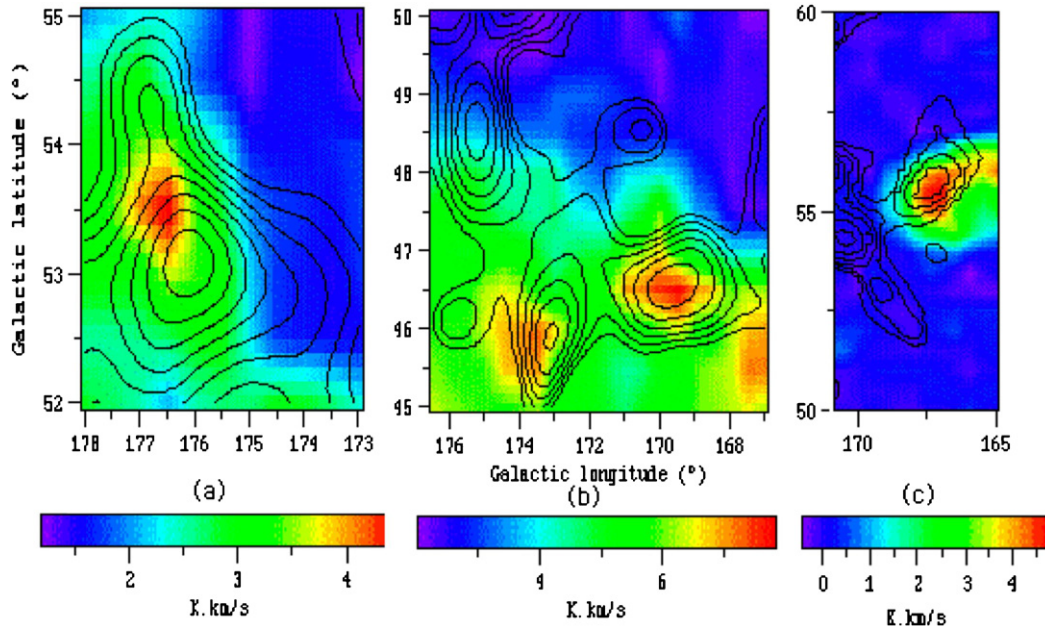


Figure 13. Four more examples in the area just south of MI that show clear associations between the *ILC* structure (same contour levels as in the previous figures) and H I emission brightness. Here, the two forms of emission are either well aligned or slightly offset by up to $0^\circ.5$. The two figure at the left ((a) and (b)) are both channel maps made at $+2 \text{ km s}^{-1}$ and the figure at the right (c) shows data at -136 km s^{-1} .

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

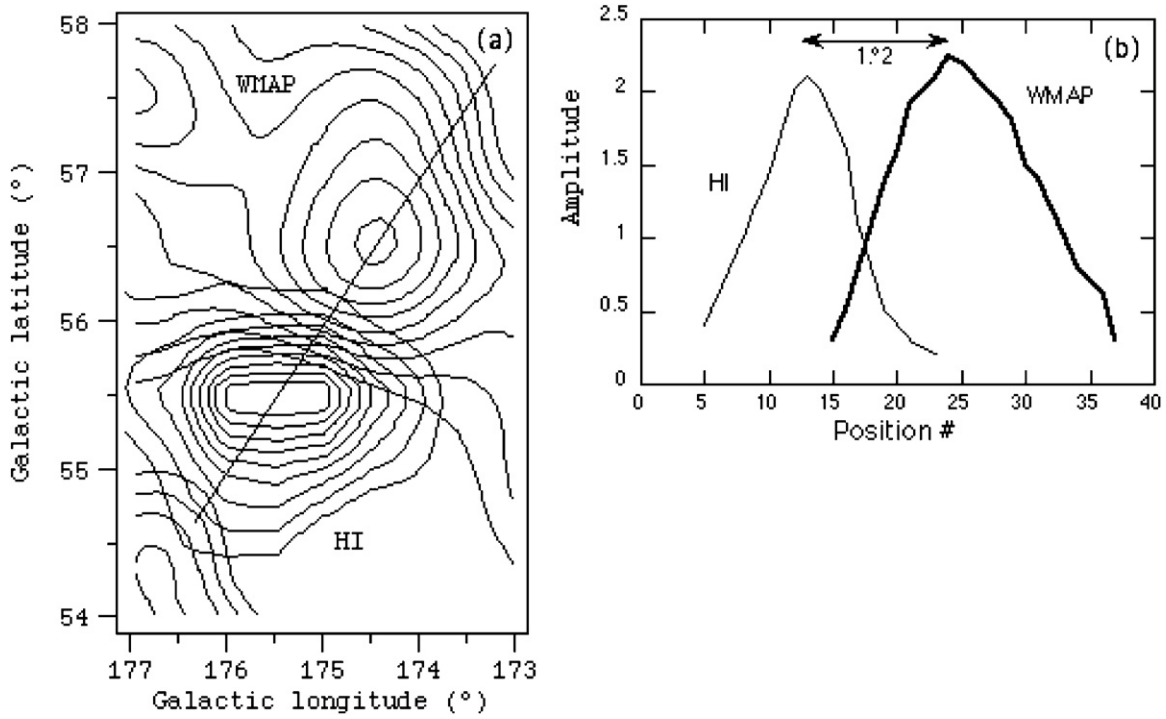


Figure 14. Example of closely abutting pair of features that appear to be unresolved at their interface. (a) The lower set of contours represent the H I brightness at -102 km s^{-1} (2 km s^{-1} bandwidth) around $(l, b) = (175^\circ, 56^\circ)$. The upper set of closed contours represents the ILC data. (b) This is a schematic cross section along an axis joining the relevant H I and ILC peaks plotted in (a). The data were read off at small intervals along the axis marked in (a) and the scale may be judged from the fact that the H I and ILC peaks are located 1.2° apart. At the interface between the two features, the edges are unresolved (see the text) and notice the close agreement in overall morphology of the two forms of radiation.

Table 5
Correlation Coefficients

Source Name	H I Velocity	R in Longitude	R in Latitude
Overlap	-87 km s^{-1}	0.81 unshifted	0.89
(Paper I)	-118 km s^{-1}	0.94 offset by 0.7°	0.87
		0.94	0.94 offset by 0.7°
Source no. 74	$+1 \text{ to } +3 \text{ km s}^{-1}$	0.71 unshifted	0.86
(Figure 14(c))		0.92 offset by 0.5°	
Source no. 79	$-50 \text{ to } 48 \text{ km s}^{-1}$	0.87 unshifted	0.87
(Figure 14(a))		0.94 offset by 0.5°	
In between	$-40 \text{ to } 38 \text{ km s}^{-1}$	0.86	0.72
(Figure 14(b))			
Abutting peaks	-102 km s^{-1}	0.95 offset by	
(Figure 13)		1.1° at an angle	
MI (Figure 5(b))	-110 km s^{-1}	0.84	0.98 resolved
22 km s^{-1} wide component		0.89 offset 1°	Offset 1° in long
MI	$-10 \text{ to } 5 \text{ km s}^{-1}$	0.97 resolved	0.94
(Figure 7(b))		Offset 0.8° in lat	Offset 0.8° in lat

Notes. Due to beamwidth differences, $R = 0.93$ for unresolved features is equivalent to $R = 1.00$; see the text. Structures are unresolved unless otherwise noted.

For low optical depth, the observed brightness temperature as a function of ν is then:

$$T_B(\nu) = \tau_{\text{ff}} T_e. \quad (7)$$

The expected continuum signal expected from free-free emission as defined by Equations (6) and (7) can be calculated from the angular width of the electron enhancements (or cloud) on the sky, θ_o , and the aspect ratio (depth of feature relative to its width) for a given distance as well as the derived linear diameter or width D_o .

For a distance L in pc and expressing the scales in cm, the linear diameter is given by

$$D_o = 5.3 \times 10^{16} \theta_o L \text{ cm}. \quad (8)$$

If the linear depth of the electron cloud in the beam that produces the observed column density is defined as D_l then

$$D_l = 5.3 \times 10^{16} \theta_o A L \text{ cm}. \quad (9)$$

If N_H is the observed H I column density in units of

10^{18} cm^{-2} , then the volume density, n_H , is given by

$$n_H = 19 N_H (\theta_o A L)^{-1} \text{ cm}^{-3}. \quad (10)$$

For a fraction, f , of the H I density in the form of electrons, the electron column density N_e allows the electron volume density, n_e , to be derived in order to determine the emission measure. Here, it is assumed that in general the electron “clouds” are associated with the adjacent H I features of known column density, although the two could be quite unrelated depending on how the electrons are produced.

Using the above we find that

$$n_e = 18.9 f N_H (\theta_o A L)^{-1} \text{ cm}^{-3}. \quad (11)$$

Using Equation (11) and substituting in Equations (6) and (7), the brightness temperature as a function of frequency ν and the observed H I column density is then given by

$$T_B(\nu) = 1.86 \times 10^{17} \nu^{-2} T_e^{-0.5} \ln(4.7 \times 10^{10} T_e/\nu) \times f^2 N_H^2 (\theta_o A L)^{-1} \text{ K}. \quad (12)$$

Equation (12) assumes that the source fills the beam. However, the observed brightness temperature will be diluted in the case of unresolved sources in the ratio of source area divided by the beam area. In evaluating the equation in the next section, this will be considered.

10.2. Evaluating the Equation: Another Coincidence?

In order to evaluate Equation (12) information on distance, angular scale, and temperatures of the electron features (clouds?) is required. In the case of the most striking associations between H I and ILC structures shown in Paper I, it was noted that in many cases H I at multiple velocities appears to be associated with a given ILC peak. Thus, the H I emission in three velocity regimes (high, intermediate-, and low-velocity) is associated. This suggests that all the relevant H I at high latitudes is relatively local, within at most 200 pc of the Sun, if we use the canonical half-width of the galactic disk to be 100 pc and take into account the latitude of the areas under consideration. This point is reinforced by the recent study of Verschuur & Schmelz (2010, in preparation). Furthermore, the fact that H I at distinctly different velocities appears to be interacting in the area where the high-frequency emission is enhanced suggests that the phenomenon of interaction may be involved in triggering the creation of electrons at an interface between the interacting H I features, or where H I features interact with surrounding plasma through which they travel.

Verschuur (1991) has argued that enhancements in H I brightness seen in twisted filamentary features will be produced where the filament geometry twists into and out of the line of sight to cause the total H I column density to increase in certain directions. This defines an aspect ratio of $A > 1$ for structure in filaments. However, there is no a priori reason to reject the possibility that $A < 1$, which would apply in the case of sheet-like structures along the line of sight.

A key parameter required to evaluate Equation (12) is the electron temperature, T_e . Two values will be tested below. One corresponds to that of cold H I, approximately 50 K (e.g., Wakker et al. 1991 and a summary in Kulkarni & Heiles 1988), and 8000 K, corresponding to the temperature of ionized hydrogen.

The amplitude for free-free emission is expected to vary as ν^{-2} according to Equation (12) with the dependence on

ν encompassed by the $\ln$ term small in comparison. Hence between the two extremes of the *WMAP* frequency range of 23 and 94 GHz the amplitude will decrease by a factor of nearly 16. However, the beamwidths are 0°88 and 0°22, respectively, and thus the beam dilution factor goes will increase the observed signal by a factor of 16 across the same frequency range, which effectively counterbalances the variation with frequency produced by free-free emission. Thus, the resulting spectrum produced by unresolved structure in the beam will, to first order, appear flat across this frequency range.

10.3. HFCE Produced by Unresolved Interstellar Electron Features

In order to evaluate the possible magnitude of this signal expected from free-free emission from interstellar electrons, a first-order attempt to apply observable parameters to Equation (12) taking into account beam dilution was undertaken. The H I features most closely associated with ILC structures for MI and MII discussed above have a typical column density of order $1.4 \pm 0.3 \times 10^{20} \text{ cm}^{-2}$ with corresponding positive ILC average amplitude $0.16 \pm 0.03 \text{ mK}$. Clearly, each pair of associated structures may be at a different distance, each may have a different aspect ratio, and each may have a different temperature. However, the purpose of this exercise is to determine whether it is possible, for a reasonable choice of parameters, to expect that HFCE at the level of 0.16 mK could be produced by free-free emission from clumps of interstellar electrons.

Figure 15 plots the expected brightness temperature at both 23 and 94 GHz as a function of total electron column density for a number of models. Their properties were chosen to be illustrative only. (1) Model 1: distance 35 pc, source diameter 6', aspect ratio 1, and $T_e = 8000 \text{ K}$. (2) Model 2: distance 35 pc, source diameter 1', $A = 0.2$, and $T_e = 50 \text{ K}$. (3) Model 3: distance 100 pc, source diameter 6', $A = 1$, and $T_e = 8000 \text{ K}$. (4) Model 4: distance 100 pc, source diameter 1', $A = 0.2$, and $T_e = 50 \text{ K}$. An aspect ratio of < 1 implies a flattened structure along the line of sight. In all four plots, the horizontal arrows at the center show the range of electron column density that would produce the observed amplitude of 0.16 mK and the vertical arrow shows the limits of the brightness temperature expected at 23 and 94 GHz at the best-fit electron density. The striking fact that emerges from these examples is that the signals produced by free-free emission from unresolved electron structure in the beams at these two frequencies are closely similar and that they are relatively insensitive to the electron temperature. Also, the spectrum would appear nearly flat over the frequency range 23–94 GHz. The electron column densities required to produce the HFCE are of order 20% of the associated H I features for the MI and MII data.

Table 6 summarizes some of the specific parameter values related to these models. The chosen values entered into Equation (12) are listed in the first four rows and the value for N_e the electron column density in the source structure required to produce the desired HFCE amplitude of 0.16 mK at 23 GHz is shown in the fifth row. The next four rows list the derived parameters for each model that are associated with the 0.16 mK signals at 23 GHz. The derived electron volume densities in the source for these models range from 170 to 1400 cm^{-3} . These imply emission measures of order $1.6\text{--}12 \times 10^3 \text{ cm}^{-6} \text{ pc}$. This may be compared to typical values derived from the Wisconsin H-alpha Mapper (WHAM; Haffner et al. 2003). Allowing for beam dilution within the WHAM beam of 1° and converting to Rayleighs, this would produce an observed emission measure of

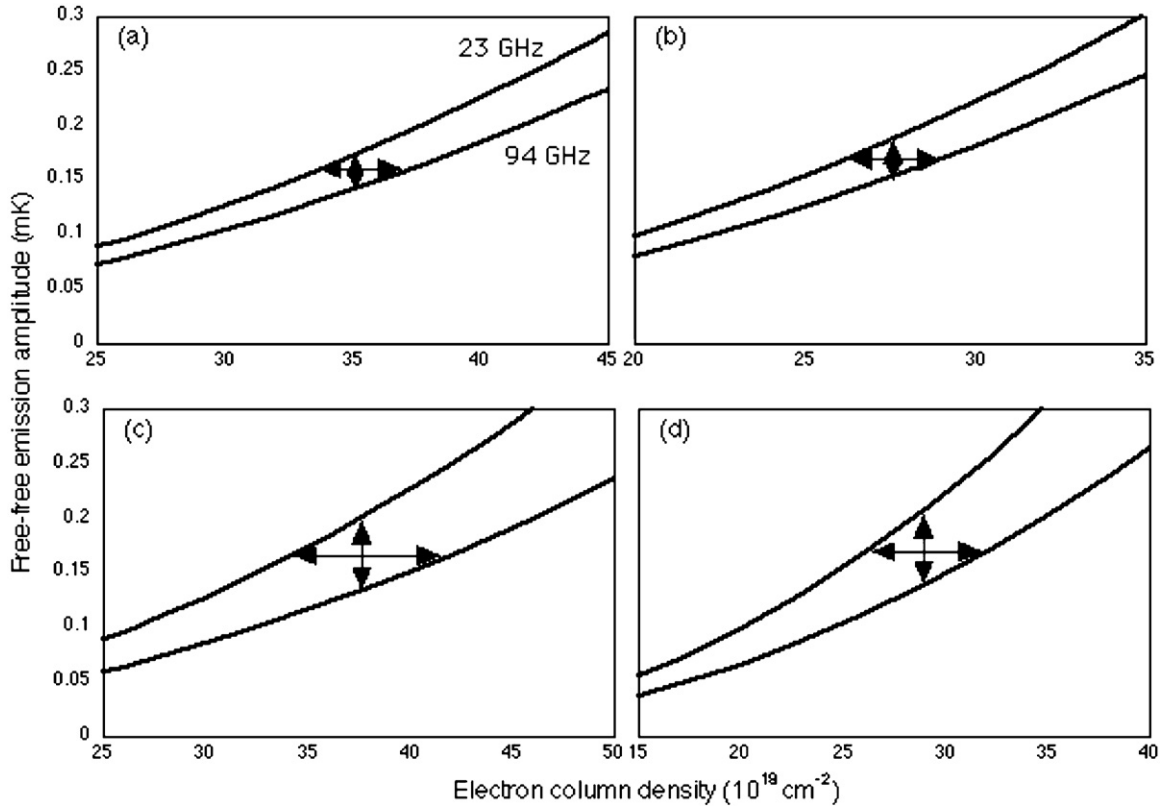


Figure 15. Plots of the expected amplitude of free–free emission that would be observed at the two extremes of the *WMAP* frequency band from electron concentrations in interstellar space as a function of the column density of the electrons in units of 10^{18} cm^{-2} . (a) Model 1: distance 35 pc for electron temperature 8000 K in a feature $6'$ in diameter and aspect ratio = 1. The horizontal line indicates the average value of the observed (positive) signal in the *ILC* data. (b) Model 3: distance 100 pc for an electron temperature of 8000 K for a feature $6'$ in diameter and aspect ratio = 0.2. (c) Model 2: distance 35 pc, electron temperature 50 K in a feature $1'$ in diameter, and aspect ratio = 1. (d) Model 4: distance 100 pc, electron temperature 50 K in a feature $1'$ in diameter, and aspect ratio = 0.2. See the text.

order $20 R$, far greater than anything observed at high galactic latitudes, where the typical $\text{H}\alpha$ levels are in the range $0.2\text{--}0.4 R$. Thus, if the *WMAP* structure is produced by free–free emission from unresolved electron density enhancements at the edges of H I features the electron temperatures cannot be of order 8000 K since the corresponding $\text{H}\alpha$ emission is not observed. Instead we should consider features where the electron temperatures may be as cold as the H I itself, perhaps as low as 50 K, in which case no $\text{H}\alpha$ emission is expected. In that case some mechanism must be invoked to keep the electrons separated from the positive ions to prevent rapid recombination. In Section 12, we will consider what observations would be needed to test this hypothesis. The final two rows illustrate the range of electron column densities that are required to produce a signal of 0.16 mK at 23 and 94 GHz. The values are very close, as can be seen in Figure 15.

11. ON THE NATURE OF THE POSSIBLE SMALL-SCALE STRUCTURES

A great deal of data relating to the small-scale structure of interstellar structure exist in the literature. For example, aperture synthesis observations of neutral hydrogen emission and absorption structure (e.g., Braun & Kanekar 2005; Diamond et al. 1989) reveal very small angular diameter structure to be common. Also, optical observations of absorption profiles produced by NaI in front of a distant stars or globular clusters (e.g., Meyer & Lauroesch 1999) show that the absorbing interstellar medium has structure on scales less than 10,000 AU across (<0.05 pc). The average angular diameter of the H I

Table 6
Model Parameters

Parameter	Model 1	Model 2	Model 3	Model 4
Chosen parameters:				
Electron temperature (K)	8000	50	8000	50
Angular width ($'$)	6	1	6	1
Aspect ratio	1	1	0.2	0.2
Distance (pc)	35	35	100	100
For N_e (10^{18} cm^{-2}) the	34	34	26	25
derived parameters are:				
T_B at 23 GHz (mK)	0.16	0.16	0.16	0.16
T_B at 94 GHz mK	0.13	0.11	0.13	0.10
Volume density (cm^{-3})	184	1,100	250	1,400
Average n_e in l.o.s. (cm^{-3})	0.32	0.32	0.09	0.08
For $T_B(\nu) = 0.16$ mK,				
the required N_e values are:				
At 23 GHz (10^{18} cm^{-2})	34	34	26	25
At 94 GHz (10^{18} cm^{-2})	37	42	28	31

features found in the above study appears to be of order 1° but it is known from high-resolution studies of high-velocity H I, for example, by Schwarz & Oort (1981), Wakker (1991), and Wakker & Schwarz (1991), that interstellar structures can have angular dimensions as small as $1'$ in extent within larger complexes. A comprehensive discussion with many literature references for such “microstructure” in the diffuse interstellar medium has been presented by Hartquist et al. (2003) and in Section 12 we will return to relate their discussion to our model.

In Section 10.3, it is hypothesized that unresolved concentrations of electrons in interstellar space could give rise to

continuum emission at a level observed by *WMAP* summarized in Figure 15 and Table 6. This raises the question as to whether independent evidence exists that might confirm the hypothesis. The discovery by Fiedler et al. (1987) of extreme scattering events, or ESEs, indicates that small-scale concentration of electrons does exist. They estimated that electron clouds with densities of order 1000 cm^{-3} and a linear scale of order 0.5 AU lie along the lines of sight to several high-latitude quasars. The precise mechanism by which the ESEs are produced remains enigmatic, as discussed by Walker & Wardle (1998), and from our point of view these features appear to be very much smaller than required to produce the necessary continuum emission observed by *WMAP*.

The likely existence of the necessary small-scale structure produced as a result of MHD turbulence in the interstellar medium has been discussed in a series of theoretical papers, for example, by Kowal et al. (2007). It is not immediately apparent how to relate the properties predicted by such turbulent models with the data discussed here but that could provide a fruitful avenue for future research.

A recent direct measurement of the electron density along a path length at a high galactic latitude is found in Howk et al. (2003) who derived a column density of between 1.3 and $7.9 \times 10^{-19} \text{ cm}^{-3}$ for a 10 kpc path toward the star vZ1128 at $b = 78^\circ 7'$. In part they used WHAM data. The values derived in Section 10.3 and summarized in Table 6 and Figure 15 lie within this range. However, to reconcile these two facts implies that the bulk of the electron column density found by Howk et al. (2003) is confined to very small diameter, high-density clumps along the line of sight.

To add to the circumstantial evidence in favor of deciding that we are dealing with more than just odd coincidences is the fact that the properties of the structures hypothesized to account for the HFCE as summarized in Figure 15 and Table 6 are that the implied volume densities of electrons in such features ($200\text{--}1400 \text{ cm}^{-3}$) are in the range of the microstructures discussed by Hartquist et al. (2003) said to be of order 100 AU in extent (equivalent to $5 \times 10^{-4} \text{ pc}$). However, this is much smaller than the values pertaining to our model estimates, 0.03 pc at 35 pc distant and 0.01 pc at 100 pc. Since the Hartquist et al. (2003) discussion concerns neutral hydrogen structure, the question then becomes whether electron structures with the sizes and densities implied above also exist in the diffuse interstellar medium. Falle & Hartquist (2002) have argued that in a cold plasma a variety of slow waves can introduce large density perturbations under suitable conditions and in this regard we note that the diffuse interstellar medium is a cold plasma. The issue then becomes one of recognizing whether the H I microstructures, when they become ionized, will produce regional enhancements of electron density of the same order as is required to produce the HFCE according to Equation (12). Clearly, similarities between the parameters implied by models such as summarized in Table 6 and the discussions of Hartquist et al. (2003) and Falle & Hartquist (2002) deserve further consideration.

All of these relationships can individually be described as being due to chance coincidences, which would imply that they have no physical significance. Taken together, however, they raise tantalizing questions.

12. DISCUSSION

This paper has presented what appear to be several intriguing coincidences.

1. Small-scale structure observed by *WMAP* as summarized in the *ILC* map appears to be associated with similar structure found in the distribution of interstellar H emission when mapped in a small velocity band of order 3 km s^{-1} wide and separated by 2 km s^{-1} in center velocity.
2. The angular separation between members of associated pairs is usually of order $0^\circ 8'$.
3. In several cases examined closely the associations appear even more dramatic when the H I column densities in specific line width families are mapped.
4. The angular structure of the two types of features is closely similar showing a cross-correlation coefficient of order unity when allowance is made for beamwidths and small offsets in angle.
5. In the majority of cases where an association has been noted, H I at more than one velocity may be involved.
6. Free-free emission from interstellar electrons clumped in unresolved structures could produce signals of the same intensity as the HFCE observed by *WMAP*.

Given the pervasive existence of complex H I structure in the galactic foreground and the equally pervasive nature of the small-scale structure observed by *WMAP*, it is important to determine whether confusion can be created in the *WMAP* data by previously unrecognized foreground signals associated with interstellar structure. The *WMAP* team (e.g., Hinshaw et al. 2007) went to great lengths to remove contributions from well-understood sources of galactic radio frequency radiation, such as are observed from the galactic disk, the spurs of radio continuum emission, and previously mapped interstellar dust. There was no a priori reason for them to expect that HFCE could be produced through processes occurring in otherwise “normal” and relatively dust-free interstellar space. At the high galactic latitudes to which we have confined our study, very little if any cirrus dust is associated with the H I structures in question, although evidence for weak dust emission in H I complex M has recently been reported by Peek et al. (2009).

The overall pattern found in the associations found to date is that small angular offsets exist between paired structures. This is not unexpected, given that there is no a priori reason to expect that the two types of matter (neutral hydrogen and, for example, clouds of enhanced electron density that may give rise to the HFCE observed by *WMAP*), will coexist in identical volumes of space. More likely is the situation in which the HFCE could be generated at the interfaces between interacting H I features, or at the interface between such features moving with respect to surrounding interstellar plasma. This would produce a form of limb brightening observed along the region of the interface. Depending on the orientation of the axis describing the relative motions of the interacting gas masses with respect to the line of sight, the associations between H I and HFCE structure may appear coincident in position or will more generally appear slightly offset in angle projected on the sky.

If the reader is willing to consider that the above sections do not merely list a string of odd coincidences, it may also be necessary to recognize the role of magnetic fields in concentrating electrons through a pinch mechanism or to examine how electrons enhancements could be produced in the first place. For example, the poorly understood process discussed by Peratt & Verschuur (2000) may be involved in which a plasma phenomenon can trigger ionization when neutral material streams into a plasma. Also the role of weak dust emission found toward H I complex M by Peek et al. (2009) may need to be considered and such dust, in turn, will have a bearing on any discussion of

the cooling and recombination of electrons, no matter how they are produced. It is also intriguing to recognize that the volume density of electrons implied by the above models is of the order found in planetary nebulae but that the derived diameters found for these models are of order of 1%–10% of the diameters of such nebulae. This would imply the existence of a category of structures smaller than the canonical planetary nebulae.

Whether or not unresolved structures in interstellar electron distribution accounts for the HFCE can be tested by using very different primary beamwidths at the same frequencies used by *WMAP*. Note that the Boomerang experiments (Jones et al. 2006) observed the small-scale structure at frequencies of 145, 245, and 345 GHz with effective beamwidth from 11'5–9'1. If there exist structures in the electron distribution of order of an arcminute in extent the Boomerang data might cast additional light on this model. However, when the Boomerang beamwidths and frequencies are entered in Equation (12) the curves in Figure 15 are merely shifted to slightly higher electron column densities by only a factor of 1.3 to obtain the same average signal of 0.16 mK. Given signal-to-noise limitations, this may not be sufficient to test the validity of the model suggested here.

Based on the derived values of the average electron density along the line of sight, the models involving the source distances of order 35–100 pc share a common property. Using Equation (12), it turns out that more distant features with the same internal total electron column density produce much weaker signals in a given beamwidth. For example, for Models 3 and 4 at distances of 500 or 1000 pc, the expected brightness of the HFCE will be of order 0.03 and 0.01 mK, respectively, at both 23 and 94 GHz and would be below the present threshold of detection. Thus, even in the galactic disk foreground sources consisting of patches of enhanced electron density will dominate the structure observed by *WMAP*.

A large-scale comparison meant to detect direct point-to-point correlations between *ILC* and galactic H I structures found in the narrow velocity bands shows no clear effect (Section 3), but then there is no obvious evidence that a point-to-point relationship is common in the data. It is true that foreground galactic H I features exhibit angular scales similar to those observed by *WMAP* as epitomized in the *ILC* map and, of course, it is well known that the galactic H I emission covers all of the sky. Therefore, near coincidences with H I features will be expected for structure in the *ILC* map. Thus, the challenge is one again to seek independent evidence that could either corroborate or negate the claims made above.

In two instances, the relationship to excess soft X-ray structure reinforces the argument that in interstellar space there may indeed exist physical processes capable of producing not only some of the HFCE observed by *WMAP* but also excess, albeit weak, soft X-ray emission. In one case, MI, the result of Gaussian analysis showed that it is H I in a specific line width regime that is most closely associated with the *ILC* structure.

It should be stressed that the above discussion of close associations has been confined to structures found in an area of sky where the *WMAP* data required very small if any corrections for possible contributions from dust or synchrotron radiation as can be seen in the analysis of Hinshaw et al. (2007), in particular their Figure 5. If one is prepared to consider that what has been found above is not due to chance associations, it will clearly be worthwhile to compare the H I data with the structures seen in the individual, unsmoothed data obtained by *WMAP* at its five-frequency bands, in particular at 94 GHz, the highest resolution data set available.

What has been shown above is that any attempts to confirm or negate the significance of the apparent associations between H I and *ILC* structures cannot be accomplished by simply comparing the *ILC* data with total H I column densities or even the distribution found by integrating over a 10 km s^{−1} velocity range as was done in Paper I, or by Land & Slosar (2007). Instead, a search for closely offset associations needs to make use of H I area maps integrated over, say, 3 km s^{−1} and examining them at 2 km s^{−1} intervals as was done here. (Note that H I at 100 K will produce a line width of 2.2 km s^{−1}, which sets a practical limit to the resolution required.) Furthermore, such maps must be studied over the entire velocity range over which H I is found in any given area of sky, a range can be as large as 300 km s^{−1}, in order to determine at what velocity the association of a given *ILC* peak with an H I structure appears. After all, if, for example, the HFCE is produced where two H I features interact then the velocity at which an association is found will depend on the physical conditions of the H I in a given direction. These interactions will not occur at a specific velocity over the whole sky.

The physics of interstellar structure, in particular of H I, is clearly complex and a full understanding of such structure as it pertains to creating patches of enhanced electron densities may require invoking the role of plasma and/or magnetohydrodynamic phenomena as was done by Falle & Hartquist (2002) and Hartquist et al. (2003). Perhaps this should also consider magnetic reconnection and/or plasma instabilities in field-aligned H I filaments in order to derive a comprehensive description of the processes that underly the production of HFCE in the direction of diffuse interstellar H I features. It is even possible that a relatively little known plasma phenomenon known as Marklund convection (Marklund 1979), if it is operating in interstellar space, could account for separation of electrons from their parent ions in H I features. A full discussion of the many implications of the above discussions is way beyond the scope of this paper.

If galactic foreground emission is responsible for at least some of the small-scale structure in the high-frequency continuum radiation observed by *WMAP* (and by implication *COBE*), it is then very interesting and perhaps a remarkable coincidence that the acoustic spectrum said to describe the existence of sound waves in the early universe should be found to describe the HFCE data obtained by *WMAP*.

In Section 11, it was concluded that the WHAM survey data appear to rule out the possibility that dense concentrations of electrons usually associated with a warm ionized medium could be present to produce the observed continuum emission observed by *WMAP*. Instead the observational restraints provided by the WHAM survey lead to the conclusion that the free-free emission that gives rise to a continuum signal as derived from Equation (12) involves cold electrons at temperatures below which a significant fraction would be ionized to produce H α emission. The most obvious test of the claims made in this paper then comes back to observing the H I and HFCE at higher resolutions to determine if apparent associations between H I and HFCE persist. The immediate step toward such a comparison will be to examine continuum data obtained by the Planck spacecraft and H I structures observed with the 100 m Byrd Green Bank Telescope (GBT), both of which have beamwidths of order 9'. However, even before then, those who have ready access to the highest resolution raw *WMAP* could determine if the observations at 94 GHz contain structure that can be related to H I data obtained with the GBT.

13. CONCLUSIONS

Apparent associations between small-scale galactic H I features and structure in the *WMAP* *ILC* data have been presented above and in Paper I. The cross-correlation between paired features is extremely high while a general point-to-point relationship expected for directly associated features is not found. It appears that the high-frequency continuum structure observed by *WMAP* may be produced by free-free emission from unresolved clumps of interstellar electrons. The typical offsets between the two forms of emission suggest that the continuum radiation originates at the interface between H I features that are either interacting with one another or with surrounding plasma through which they are moving. In general, the line of sight will intersect such features at some angle that would favor our observing an offset between the two types of radiation, although direct positional agreement has been noted in several cases. The possibility that these phenomena may be due to more than chance coincidence is reinforced by the fact that the amplitude of high-frequency continuum radiation is at a level expected for free emission from electrons.

In summary, the data considered so far suggest several alternative explanations for the apparent near associations between small-scale and highly correlated structures in the distribution of H I and the HFCE observed by *WMAP*. (1) The most obvious one is that the association is all due to chance: This includes 108 close associations reported here and in Paper I, and another 100 or so noted in a cursory examination of limited areas of the southern skies. However, the “chance association” conclusion is based on the unstated assumption that we know enough about interstellar processes that we can be sure that it is impossible for a previously unrecognized mechanism to produce HFCE in volumes of space where H I features are interacting with their surroundings, or with one another. (2) Some of the associations are due to chance and some may be real. This quickly poses the same dilemma as in (1). As soon as a few examples are shown to be clearly related to galactic phenomena, such as appears to be the case for MI and MII and the examples given in Paper I, then the challenge is again to determine what physical mechanisms may be responsible for these associations so as to estimate what fraction of the *ILC* peaks may still be assigned a non-galactic origin. (3) The associations are significant. If one favors this interpretation, then new aspects of interstellar gas dynamics and physics may be revealed and if the above analysis is any indication then a full discussion will require a great deal more work than can be encompassed in the brief summary presented here.

In order to understand the physical nature of the apparent associations, the properties of the relevant H I features must be determined by making use of higher angular and velocity resolution data. Thus, some of the key associations discussed above should be studied using H I data obtained with the GBT with a 9' beam and compared to structure in the HFCE to be observed by the Planck spacecraft with a similar beamwidth.

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