Internal structure of spiral arms traced with [C II]: Unraveling the WIM, H\textsc{i}, and molecular emission lanes

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ABSTRACT

Context. The spiral arm tangencies are ideal lines of sight in which to determine the distribution of interstellar gas components in the spiral arms and study the influence of spiral density waves on the interarm gas in the Milky Way. [C\textsc{ii}] emission in the tangencies delineates the warm ionized component and the photon dominated regions and is thus an important probe of spiral arm structure and dynamics.

Arms. We aim to use \([\text{C\textsc{ii}}]\), H\textsc{i}, and \(^{12}\text{CO}\) spectral line maps of the Crux, Norma, and Perseus tangencies to analyze the internal structure of the spiral arms in different gas layers.

Methods. We use \([\text{C\textsc{ii}}]\) – V maps along with those for H\textsc{i} and \(^{12}\text{CO}\) to derive the average spectral line intensity profiles over the longitudinal range of each tangency. Using the \(V_{LSR}\) of the emission features, we locate the \([\text{C\textsc{ii}}]\), H\textsc{i}, and \(^{12}\text{CO}\) emissions along a cross cut of the spiral arm. We use the \([\text{C\textsc{ii}}]\) velocity profile to identify the compressed warm ionized medium (WIM) in the spiral arm.

Results. We present a large scale (\(\sim 15^\circ\)) position-velocity map of the Galactic plane in \([\text{C\textsc{ii}}]\) from \(l = 326^\circ 6\) to \(341^\circ 4\) observed with Herschel HIFI. In the spectral line profiles at the tangencies \([\text{C\textsc{ii}}]\) has two emission peaks, one associated with the compressed WIM and the other the molecular gas PDRs. When represented as a cut across the inner to outer edge of the spiral arm, the \([\text{C\textsc{ii}}]–\text{WIM}\) peak appears closest to the inner edge while \(^{12}\text{CO}\) and \([\text{C\textsc{ii}}]\) associated with molecular gas are at the outermost edge. H\textsc{i} has broader emission with an intermediate peak located nearer to that of \(^{12}\text{CO}\).

Conclusions. The velocity resolved line data of the spiral arm tangencies unravel the internal structure in the arms locating the emission lines within them. We interpret the excess \([\text{C\textsc{ii}}]\) near the tangent velocities as shock compression of the WIM induced by the spiral density waves and as the innermost edge of spiral arms. For the Norma and Perseus arms, we estimate widths of \(\sim 250\) pc in \([\text{C\textsc{ii}}]–\text{WIM}\) and \(\sim 400\) pc in \(^{12}\text{CO}\) and overall spiral arm widths of \(\sim 500\) pc in \([\text{C\textsc{ii}}]\) and \(^{12}\text{CO}\) emissions; in H\textsc{i} the widths are \(\sim 400\) pc and \(\sim 620\) pc for Perseus and Norma, respectively. The electron densities in the WIM are \(\sim 0.5\) cm\(^{-3}\), about an order of magnitude higher than the average for the disk. The enhanced electron density in the WIM is a result of compression of the WIM by the spiral density wave potential.

Key words. ISM: Warm Ionized Medium – Galactic structure – [CII] fine-structure emission

1. Introduction

The large scale structure of spiral arms in the Milky Way has been a subject of great interest for understanding the dynamics of the Galaxy and for interpreting its properties. However, there have been long standing disagreements about the number of arms and their physical parameters. While a majority of published papers favor a four-arm structure others prefer a two-arm structure with a small pitch angle, allowing nearly two turns of the arms within the solar circle. In a series of papers Valdè (2013, 2014\textsuperscript{[1,3]}) attempted a statistical modeling analysis of all assembled recent positional data on the Milky Way’s spiral arms and observed tangencies in a number of tracers such as CO, H\textsc{i}, methanol masers, hot and cold dust, and FIR cooling lines, such as \([\text{C\textsc{ii}}]\). The most recent version of his idealized synthesized Galactic map can be found in Valdè (2014\textsuperscript{a}). Modeling the Galactic spiral structure is based mostly on the data at the spiral arm tangents as observed by different gas tracers and stars. However each of these spiral arm tracers can occupy a separate lane, or layer, across an arm (e.g. Valdè 2014\textsuperscript{c}), resulting in an inconsistency among the various models extracted from observational data.

In this paper we present new \([\text{C\textsc{ii}}]\) spectral line \(l-V\) maps of the Galactic plane covering \(l=326^\circ 6\) to \(341^\circ 4\) and \(l=304^\circ 9\) to \(305^\circ 9\) as obtained by Herschel\textsuperscript{[2]} HIFI On-The-Fly (OTF) mapping. These maps illuminate the structure of different gas components in the spiral arms. Using the \([\text{C\textsc{ii}}]\), H\textsc{i} and \(^{12}\text{CO}\) maps of the Crux, Norma and start of the Perseus tangencies, we derive the intensity profiles of their emissions across these spiral arms and quantify the relative displacement of the compressed warm ionized medium (WIM), atomic, and molecular gas lanes with respect to the inner and outer edges of the arms. Our results reveal an evolutionary transition from the lowest to the highest density states induced by the spiral arm potential. This compressed WIM component traced by \([\text{C\textsc{ii}}]\) is distinct from the ionized gas in H\textsc{ii} regions which traces the spiral arms with characteristics similar to those of molecular gas traced by CO (cf. Valdè 2014\textsuperscript{b}, Downes et al. 1980).

The spiral tangent regions (c.f. Valdè 2008, Benjamin 2009) are ideal laboratories in which to study the interaction of the interstellar gas and spiral density waves in the Milky Way. The tan-

\textsuperscript{1} Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
gents provide a unique viewing geometry with sufficiently long path lengths in relatively narrow velocity ranges to detect the diffuse WIM component traced by [C ii] emission and to study its relationship to the neutral H\textsc{i} and molecular $^{12}$CO gas components within spiral arms and the influence of spiral arm density waves on the interstellar medium (ISM).

COBE FIRAS observed strong [C ii] and [N ii] emission along the Galactic spiral arm tangencies and Steiman-Cameron et al. (2010) fit the COBE results with four well-defined logarithmic spiral arms in the gaseous component of the ISM. However, COBE’s 7° beam and spectrally unresolved lines preclude obtaining detailed information on the scale and properties of the gas within the spiral tangencies, nor can one use the COBE data to separate the emission that arises from the Photon Dominated Regions (PDRs) from that in the WIM. The HIFI Galactic Observations of Terahertz C+ (GOT C+) survey (Langer et al. 2010) of the Milky Way also detects the strongest [C ii] emission near the spiral arm tangential directions (Pineda et al. 2013; Velusamy & Langer 2014). In the velocity resolved HIFI spectra Velusamy et al. (2012) separated the WIM component of the [C ii] emission, in velocity space, from that in the molecular and neutral gas. They suggested that excitation by electrons in the WIM, with a density enhanced by the spiral arm potential, accounts for a low surface brightness [C ii] excess observed at the tangent velocities along the Scutum-Crux spiral tangency. To determine whether a similar spatial and density distribution is a general property of Galactic spiral arms it is important to observe the velocity structure of the [C ii] emission in other spiral arm tangencies and compare it with the corresponding H\textsc{i} and $^{12}$CO emissions.

Here we present a large scale ($\sim 15°$) position-velocity map of the Galactic plane in [C ii] and derive the following characteristics of the spiral arm features: the relative locations of the peak emissions of the WIM, H\textsc{i}, and molecular gas lanes, including the PDRs, and the width of each layer. In addition, we use the [C ii] emission to derive the mean electron density in the WIM. These results confirm our earlier conclusion (Velusamy et al. 2012) that in the velocity profile of [C ii] emission at the Scutum tangency, the WIM and molecular gas components of [C ii] are distinguished kinematically (appearing at well separated velocities around the tangent velocity).

In the analysis presented here we use the fact that [C ii] emission can arise in the three major constituents of the interstellar gas, namely, fully or partially ionized gas (as in the WIM), neutral atomic gas (as in HI clouds) and in H\textsc{ii} molecular gas (as in CO clouds or PDRs) excited, respectively, by electrons, H atoms, and H\textsc{ii} molecules. In the velocity resolved HIFI spectra these components are identified as demonstrated in the GOT C+ results (c.f. Pineda et al. 2013; Langer et al. 2014). Furthermore, Velusamy & Langer (2014) show that in the inner Galaxy $\sim 60\%$ of the [C ii] emission is tracing the H\textsc{ii} molecular gas while at least 30\% of the [C ii] is tracing the WIM and that emission in H\textsc{i} excited by H atoms is not a major contributor. Here, to study spiral arm structure we identify two major [C ii] components, one component stems from the WIM and the other from PDRs. We find that in the spiral arm tangencies the [C ii] spectral line data alone can be used to study the relative locations of the WIM and molecular gas PDR layers.

An outline of our paper is as follows. The observations are discussed in Section 2. In Section 3 we construct the spatial-velocity maps, and compare the distributions of [C ii] with H\textsc{i} and $^{12}$CO and their relation to the spiral arms. In Section 4 we analyze the velocity structure of these gas components at the spiral arm tangencies and use it to infer the relative locations of the different gas “lanes” within the spiral arm. Note that in discussing the internal structure of the spiral arms we refer to the emission layers of the gas tracers as “lanes”, analogous to the terminology used in external spiral galaxies. We also derive the average electron density in the WIM using the [C ii] emission and a radiative transfer model. We summarize our results in Section 5.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Spiral arms in the 4th quadrant are represented in a $V_{LSR}$–longitude ($V–l$) plot, adapted from Vallee (2008): red: Norma–Cygnus; blue: Scutum–Crux; green: Sagittarius–Carina; magenta: Perseus. The rectangular boxes indicate the longitude range in longitude between 326° and 341° which include the Norma and Perseus tangencies. The vertical dashed line represents a line of sight at a given longitude that intercepts multiple spiral arms, thus demonstrating the need for velocity resolved spectral line data to separate them.}
\end{figure}

2. Observations

The longitudinal and velocity coverage of the [C ii] observations, at latitude $b = 0°$ presented here are summarized in Figure 1 along with a schematic of the spiral arm velocity–longitude relationship. All [C ii] spectral line map observations were made with the high spectral resolution HIFI (de Graauw et al. 2010) instrument onboard Herschel (Pilbratt et al. 2010). These observations were taken between October 2011 and February 2012. We used 37 On-The-Fly (OTF) scans for the large scale [C ii] map of the Galactic plane ($b = 0°$) covering a $15°$ range in longitude between 326° and 341° which include the Norma and Perseus tangencies. The observations of the fine-structure transition of C+ ($^2P_{3/2} - ^2P_{1/2}$) at 1900.5369 GHz were made with the HIFI band 7b using the wide band spectrometer (WBS). Each OTF scan was taken along the Galactic longitude at latitude $b = 0°$ and was 24 arcmin long. For the Crux tangency two OTF longitude scan data were used: (i) one 24 arcmin long centered at
l=305.1 and b=0° (note an earlier version of this map was presented in Velusamy & Langer [2014] and it is included here for completeness in the analysis of the tangencies), and, (ii) a shorter 6 arcmin long scan centered at l=305.76 and b=0.15. All HIFI OTF scans were made in the LOAD-CHOP mode using a reference off-source position about 2 degrees away in latitude (at b = 1°9). However in our analysis we do not use off-source data (see below). All the 24 arcmin long OTF scans are sampled every 40 arcsec and the shorter scan every 20 arcsec. The total duration of each OTF scan was typically ~2000 sec which provides only a short integration time on each spectrum (pixel). Thus the rms (0.22 K in T\textsubscript{mb}) in the final maps with an 80'' beam and 2 km s\textsuperscript{-1} wide channels in the OTF spectra is much larger than that in the HIFI spectra observed in the HPOINT mode, for example in the GOT C+ data. The observations for the Crux tangency used longer integrations.

We processed the OTF scan map data following the procedure discussed in Velusamy & Langer [2014]. The [C\textsc{ii}] spectral line data were taken with HIFI Band 7 which utilized Hot Electron Bolometer (HEB) detectors. These HEBs produced strong electrical standing waves with characteristic periods of ~320 MHz that depend on the signal power. The HIPE Level 2 [C\textsc{ii}] spectra show these residual waves. We found that applying the fitHiFiFringe\footnote{http://herschel.esac.esa.int/hcss-doc-12.0/index.jsp?hifi_um:hifium section 10.3.2} task to the Level 2 data produced satisfactory baselines. However, removal of the HEB standing waves has remained a challenge until the recent release of HIPE-12, which includes a new tool hebCorrection\footnote{http://herschel.esac.esa.int/hcss-doc-12.0/index.jsp?hifi_um:hifium section 10.4.5} to remove the standing waves in the raw spectral data by matching the standing wave patterns (appropriate to the power level) in each integration using a database of spectra at different power levels (see Herschel Science Center (HSC) HIPE-12 release document for details). We used this HSC script to apply hebCorrection to create the final pipeline mapping products presented here. Following one of the procedures suggested by Dr. David Teyssier at the HSC, the OTF map data presented here were re-processed by re-doing the pipeline without off source subtraction to produce Level 1 data. The hebCorrection was then applied to this new Level 1 data. The fact that hebCorrection subtracts the matching standing wave patterns from a large database of spectra eliminates the need for off-source subtraction. Thus in our analysis the processed spectral data are free from any off source contamination. While fitting the HEB waves we also used the feature in the hebCorrection script to exclude the IF frequencies with strong [C\textsc{ii}] emissions. Finally, the Level 2 data were produced from the HEB corrected Level 1 data.

From Level 2 data the [C\textsc{ii}] maps were made as “spectral line cubes” using the standard mapping scripts in HIPE. Any residual HEB and optical standing waves in the reprocessed Level 2 data were minimized further by applying fitHiFiFringe to the “gridded” spectral data (we took the additional precaution in fitHiFiFringe of disabling DoAverage in order not to bias the spectral line “window”). The H-- and V--polarization data were processed separately and were combined only after applying fitHiFiFringe to the gridded data. This approach minimizes the standing wave residues in the scan maps by taking into account the standing wave differences between H-- and V--polarization.

All OTF scan map data were reprocessed and analyzed in HIPE 12.1, as described above, to create spectral line data cubes. We then used the processed spectral line data cubes to make longitude–velocity (l–V) maps of the [C\textsc{ii}] emission as a function of the longitude range in each of the 39 OTF observations. For HIFI observations we used the Wide Band Spectrometer (WBS) with a spectral resolution of 1.1 MHz for all the scan maps. The final l–V maps presented here were restored with a velocity resolution of 2 km s\textsuperscript{-1}. At 1.9 THz the angular resolution of the Herschel telescope is 12'' but, the [C\textsc{ii}] OTF observations used 40'' sampling. Such fast scanning results in heavily undersampled scans broadening the effective beam size along the scan direction\footnote{www.astro.ufl.edu/thrumms}. Therefore all [C\textsc{ii}] maps have been restored with effective beam sizes corresponding to twice the sampling interval along the scan direction (~ 80''). Figure 2 shows an example of a l–V map reconstructed using the map data processed in HIPE 12.1 for a single OTF scan map observed at longitude l = 336°. To compare the distribution of atomic and molecular gas with the ionized gas we use the \textsuperscript{12}CO and H\textsc{i} data in the southern Galactic plane surveys available in the public archives. The \textsuperscript{12}CO(1-0) data are taken from the Three-mm Ultimate Mopra Milky Way Survey\footnote{Alves et al. [2014]} (ThrUMMS) observed with the 22m Mopra telescope\footnote{Barnes et al. [2011]}. The H\textsc{i} data are taken from the Southern Galactic Plane Survey (SGP) observed with the Australia Telescope Compact Array\footnote{McCleure-Griffiths et al. [2005]}. Although the Park HIPASS Galactic plane map of the H\textsuperscript{16}6,167, & 168\textup{a} radio recombination lines (RRL) is now available\footnote{Anderson et al. [2009]}, its low velocity resolution (~20 km s\textsuperscript{-1}) precludes using it for the analysis presented here. Furthermore, as the H\textsc{i} regions are associated with star formation and dense molecular gas (e.g. Anderson et al. [2009]) the RRL emission...
The \([\text{C} \text{ii}]\) longitude-velocity \((l-V)\) map covering \(\sim 15^\circ\) in longitude over the range \(l = 326.6^\circ\) to \(341.4^\circ\) at \(b = 0.0^\circ\). The intensities are in main beam antenna temperature \((T_{\text{mb}})\) with values indicated by the color wedge. A square root color stretch is used to bring out the low brightness emission features. The velocity resolution in all maps is 2 km s\(^{-1}\) and the beam size along the longitudinal direction is \(80''\). A sketch of the spiral arms in the 4th quadrant, adopted from Vallée (2008), is overlaid and are indicated in the following colors: red-solid: Norma–Cygnus; white-solid: Scutum–Crux; white-broken: Sagittarius–Carina; red-broken: Perseus. The rectangular boxes indicate the extent of the spiral tangencies as labeled.

3. Results

In this Section we present the \(l-V\) emission maps and analyze the structure of the different gas components. We use a schematic of the expected relationship between velocity \((V_{\text{LSR}})\) and location with respect to Galactic center, to guide the analysis of the gas lane profile across the arm. We show that the emissions reveal an orderly change in gas components across the arms leading from the least dense WIM to the densest molecular clouds.

3.1. longitude–velocity maps

We “stitched” all the individual OTF maps (an example is shown in Figure 2) within the longitude range 326.6 to 341.4 to create a single longitude velocity map which includes the Perseus and Norma tangencies. The \(l-V\) map is shown in Figure 3. An \(l-V\) representation of the spiral arms is overlaid on the \([\text{C} \text{ii}]\) map. Note that strong \([\text{C} \text{ii}]\) emissions are seen in the tangencies (denoted by the boxes in Figure 3) as seen in the GOT C+ data base (Pineda et al. 2013; Velusamy & Langer 2014) and COBE data (Steiman-Cameron et al. 2010). However, the rest of the spiral arm trajectories show poor correspondence with the brightness of \([\text{C} \text{ii}]\) emission likely due to the uncertainties in the model parameters (e.g. pitch angle) used for the spiral arms.

We assembled the \(l-V\) maps that match the \([\text{C} \text{ii}]\) map for the \(^{12}\text{CO}(1-0)\) (Figure 4) and \(\text{H} \text{i}\) (Figure 5) maps using the Mopra ThrUMMS survey and SGPS data. Note that the intensities for ThrUMMS \(^{12}\text{CO}(1-0)\) data are uncorrected for main beam efficiency (Ladd et al. 2005; Barnes et al. 2011).

The \([\text{C} \text{ii}]\) maps in Figure 3 contain, in addition to information about the tangency, a rich data set on \([\text{C} \text{ii}]\) emission in the diffuse gas, the molecular gas, and PDRs; these properties have been analyzed in detail for a sparse galactic sample using the GOT C+ data base (Pineda et al. 2013; Langer et al. 2014; Velusamy & Langer 2014). However, the continuous longitude coverage in the data presented here offers a better opportunity to study the Galactic spiral structure and the internal structure of the arms. In principle it is possible to derive a 2–D spatial–intensity map of this portion of the Galaxy using the kinematic distances for each velocity feature in the maps. However, such a study is subject to the near–far–distance ambiguities inherent in lines of sight inside the solar circle (see discussion in Velusamy & Langer 2014), except along the tangencies. The tangencies offer a unique geometry in which to study kinematics of the interstellar gas without the distance ambiguity. Furthermore the tangential longitudes provide the longest path length along the line of sight through a cross section of the spiral arm thus making it easier to detect weak \([\text{C} \text{ii}]\) emission from the WIM and the molecular gas. In this paper we limit our analysis only to the \([\text{C} \text{ii}]\) emission in tangencies and compare it with...
Fig. 4. The $^{12}$CO(1-0) longitude–velocity (l–V) map covering $\sim 15^\circ$ in longitude over the range $l = 326.6$ to $341.4$ at $b = 0^\circ$. The $^{12}$CO(1-0) data are taken from Mopra ThrUMMS survey (Barnes et al. 2011). See the caption in Figure 3 for the color labels.

Fig. 5. The HI longitude–velocity (l–V) map covering the $\sim 15^\circ$ range in longitude $l = 326.6$ to $341.4$ at $b = 0^\circ$. The HI data are taken from the SGPS survey (McClure-Griffiths et al. 2005). See the caption in Figure 3 for the color labels.
In Figure 6 we show a schematic model of the internal structure of a spiral arm based on the results of Vallée (2014a, b) and Velusamy et al. (2012), using the Norma tangency example. The top panel (a) illustrates how the emission tangency probes the “lanes” seen in different tracers. Vallée’s schematic (see his Figure 5) both H I and [C II] emissions occur displaced from $^{12}$CO towards the inner edge near the side of the Galactic center. In Vallée’s sketch the placement of [C II] with respect to $^{12}$CO is based on the C data (Steiman-Cameron et al. 2010). However in the very resolved HIFI data for the Scutum tangency (Velusamy et al. 2013), the WIM component of [C II] emission occurs near the inner edge while that associated with molecular gas and H I is coincident with $^{12}$CO emission. The boxed region in Fig. 6 represents the area in the tangency over which the emission tracers are computed. The expected velocity profiles at the tangents relative to the other emission layers, are shown schematically in Figure 6(b) and these can be compared with the actual observed velocity profiles for each tracer in the maps in Figures 3 to 5. Thus by analyzing the velocity profiles of different gas types we can examine the location of the respective emission relative to each other within each spiral arm.

In the $l$–$V$ maps the trajectory of each spiral arm radiating velocity ($V_{LSR}$) as a function of Galactic longitude is a shown line. In reality, however, it is expected to be much broader complex. Obviously there is no single unique value of the longitude that can be assigned as a tangency. Furthermore, the longitudes listed in the literature (e.g. Vallée 2014a) are often corrected, to data averaged over a wider range of Galactic latitudes. But the $l$–$V$ maps presented here are all in the Galactic plane ($b = 0^\circ$) observed with narrow beam sizes ($12''$, $33''$, and $150''$ for [C II], $^{12}$CO, and H I, respectively) in latitude. In the maps in Figures 3 to 5 we refer to a range of longitudes for each spiral tangency as indicated by the box sizes.

Using the $l$–$V$ maps in Figures 3 to 5 we average the emissions within a $2^\circ$ and 2.5 longitude range for the Perseus and Norma tangencies, respectively, and in all observed longitudes for the Crux tangency. The resulting averaged spectra are plotted in Figures 7(b) & 8(c). Note that the $^{12}$CO spectra shown have new baselines fitted to the map data in Figure 7. For clarity we limit the velocity range to cover only the tangencies. Furthermore, the intensity scale for each spectrum is adjusted such that the highest value corresponds to its peak brightness listed in Table 1. The tangent velocity is indicated on the spectra in each panel in Figures 7 & 8 in order to provide a reference to the $V_{LSR}$ velocities. The tangent velocities are estimated using the mean longitude and assuming Galactic rotational velocity (220 km s$^{-1}$) at the tangent points (c.f. Levine et al. 2008). We note that the tangent velocity varies from panel to panel corresponding to its longitude range. The [C II] spectra of the tangencies show remarkably distinct differences compared to spectra of H I or $^{12}$CO. [C II], unlike H I or $^{12}$CO, shows a clear emission peak near the tangent velocity, well separated from the H I and $^{12}$CO peaks. To bring out the uniqueness of such differences in the tangencies in Figures 7 and 8 we compare the spectra at tangencies (labeled “On-tangent”) with those at neighboring longitudes (labeled “Off-tangent”). As discussed below, only the spectra at the tangencies show the excess [C II] emission peak at more negative velocities. As illustrated in the schematic in

Fig. 6. (a) Schematic view of the Norma spiral arm tangency. The emissions (distinguished by the color) tracing the spiral arm are shown as a cross cut of the layers from the inner to outer edges (adapted from Figures 2 & 3 in Vallée (2014a)). (b) A sketch indicating the velocity ($V_{LSR}$) structure of the corresponding spectral line intensities near the tangency for each layer. Note that this cartoon is intended to be a schematic and is not to scale. Figure 6 it is possible to delineate individually the emission layers or the lanes, bringing out the internal structure of the spiral arms, for [C II] in both the WIM and the PDRs, as well as that of molecular gas in $^{12}$CO and atomic gas in H I. The characteristics of the observed velocity profiles in each tangency are summarized in Table 1.

3.2.1. Norma tangency

The Norma tangency has been determined as $328^\circ$ for $^{12}$CO (Bronfman et al. 2000) and H I (Finkmaier & Gerhard 1999), $329^\circ$ for 60$\mu$m dust (Bloemen et al. 1990), and $332^\circ$ for 870$\mu$m dust (Beuther et al. 2012). García et al. (2014) assign tangent directions to the Crux (Centaurus), Norma, and 3 kpc expanding arms of 310/0, 330/0, and 338/0, respectively, by fitting a logarithmic spiral arm model to the distribution of Giant Molecular Clouds (GMCs). As discussed above, the detection of [C II] from the WIM is strongest along the tangencies and thus is a good discriminator of the tangent direction of a spiral arm. Thus the emission profiles shown in Figure 4 provide strong evidence that the longitude of the tangent direction is well constrained to $l < 329.5^\circ$. In the On-tangent spectrum the $^{12}$CO emission shows a small peak near the tangent velocity. However, this feature is
Fig. 7. Norma tangency spectra. The [C\textsc{ii}], H\textsc{i}, and \(^{12}\)CO emission spectra are plotted against velocity (V\textsubscript{LSR}). Each panel shows the spectra for the longitude ranges indicated. Note that the intensity scale is normalized to the peak emission within the velocity range. The corresponding 1–\(\sigma\) error bars are indicated on the [C\textsc{ii}] and \(^{12}\)CO spectra. The tangent velocity is marked on each panel by a vertical arrow. Panel (a): Off-tangent. Panel (b): Norma On-tangent. The dashed lines indicate the V\textsubscript{LSR} shift between the [C\textsc{ii}] and \(^{12}\)CO peaks.

Fig. 8. Spectra for the location of the start of the Perseus tangency. Caption same as for Figure 7. Panels (a) & (c): Off-tangent. Panel (b): Perseus On-tangent. The dashed lines indicate the shifted V\textsubscript{LSR} of peak emission of the [C\textsc{ii}] and \(^{12}\)CO peaks.

3.2.2. Start of Perseus tangency

The tangency at the start of the Perseus arm has been determined as 336\(^\circ\) for \(^{12}\)CO (Bronfman et al. 2000), 338\(^\circ\) for the [C\textsc{ii}] & [N\textsc{ii}] FIR lines (Steiman-Cameron et al. 2010), and 338\(^\circ\) for 870\(\mu\)m dust (Beuther et al. 2012). Green et al. (2011) suggest that part of the Perseus arm could harbor some of the methanol masers found toward the tangent direction of the 3 kpc expanding arm. According to the spiral arm model of Russeil (2003) the starting point of the Perseus arm would be found in the region between the Norma and the 3 kpc expanding arms. Though there are some doubts about this longitude being the start of the Perseus arm (c.f. Green et al. 2011), we adopt the longitude range \(l = 336\(^\circ\)–338\(^\circ\)\) as the start of the Perseus arm following the work of Vallée (2014a). The emission profiles in Figure 8 clearly show the detection of a tangent direction in this longitude range, as seen by the strong [C\textsc{ii}–WIM emission compared to the weaker [C\textsc{ii}] emission in the neighboring longitudes on either side.

3.2.3. Crux tangency

Vallée (2014a) lists the Crux tangency as between \(l = 309\(^\circ\)\) and 311\(^\circ\) in different tracers with CO at \(l = 309\(^\circ\)\) (Bronfman et al. 2000) and dust at \(l = 311\(^\circ\)\) (Drimmel 2000; Bloemen et al. 1990; Beuther et al. 2012). However, using the GLIMPSE source counts Benjamin et al. (2005) and Churchwell et al. (2009) place the Crux tangency within a broader longitude range 306\(^\circ\)< \(l < 313\(^\circ\). Furthermore it has been suggested that the Crux tangency provides an ideal testing ground for models of spiral density wave theory (Benjamin 2008), as the \(l = 302\(^\circ\)\) to 313\(^\circ\) direction is known to have several distinct anomalies, including large deviations in the H\textsc{i} velocity field (McClure-Griffiths & Dickey 2007) and a clear magnetic field reversal (Brown et al. 2007). Although we do not have a complete map of this region, it is of sufficient interest that we present a partial map covering \(l = 304\(^\circ\)\) and 305\(^\circ\), which is close to the Crux tangency. This partial \(l-V\) map, which comes from another of our [C\textsc{ii}] Herschel projects, is shown in Figure 9 along with the corresponding \(^{12}\)CO and H\textsc{i} maps. Note that the velocity range for the emission in the \(^{12}\)CO map is much narrower than in the [C\textsc{ii}] map indicative of a broader diffuse emission component in [C\textsc{ii}].

Also referred to as Centaurus as it appears in this constellation.
its similarity to the results for the Scutum tangency strongly favors its interpretation as the WIM. This detection of WIM in the \([\text{C} \text{II}]\) close to the tangent velocity. Nevertheless, the detection of the \([\text{C} \text{II}]\) emission shows a peak in emission while there is little, or no, \(^{12}\text{CO}\) and \(\text{H} \text{i}\) weak, but increasing slowly with velocity. (The low intensity \(^{12}\text{CO}\) peak near the tangent velocity in Figure 7 is relatively less prominent when compared to the dominant \([\text{C} \text{II}]\) emission);

2. The velocity of the \([\text{C} \text{II}]\) peak beyond the tangent velocity corresponds to the radial distance closest to the Galactic center. Therefore it is near the inner edge of the spiral arm, representing the onset of the spiral arm feature;

3. The peak emissions for \(\text{H} \text{i}\) and \(^{12}\text{CO}\) appear at still higher velocities than for the first \([\text{C} \text{II}]\) peak corresponding to distances away from the inner edge;

4. \([\text{C} \text{II}]\) emission shows two peaks: one near or beyond the tangent velocity representing the WIM component traced by \([\text{C} \text{II}]\) and the second corresponding to the molecular gas traced by \([\text{C} \text{II}]\) observed in association with \(^{12}\text{CO}\) arising from the PDRs of the CO clouds; and,

5. The observed velocity profiles are consistent with the schematic shown in Figure 6 for the internal structure of the spiral arm.

The anomalous excess \([\text{C} \text{II}]\) emission in the velocity profiles for all the spiral arm tangencies represents the direct unambiguous detection of the large scale Galactic diffuse ionized gas (WIM) through its 158\(\mu\text{m}\) \([\text{CII}]\) line emission. Our Herschel HIFI detection of the diffuse ionized gas provides detailed spatial and kinematic information on the nature of this gas component in the spiral arms that has not been possible with prior \([\text{C} \text{II}]\) surveys. For example, in contrast to the direct detection of the
We can resolve the anatomical structure of the spiral arms, namely how each gas component is arranged spatially as a function of radialelectron excitation of $C^+$ and not from H atom excitation from diffuse H$_2$ clouds (warm neutral medium or cold neutral medium) for the following reasons, as first noted in our earlier study of the WIM in the Scutum–Crux arm (Velusamy et al. 2012, Velusamy & Langed 2014). In the spectra in Figures 7 & 8 the H$_2$ emission at the lowest velocities (near the left around the tangent velocities) is seen along with [C ii] only for the longitudes of tangent directions which are identified to have [C ii] in the WIM (Figures 4b & 8b). However, in all other longitude directions (Figures 7a, 8a & 8c) strong H$_2$ emission is seen with little or no associated [C ii] emission. If H atom collisional excitation contributed to any of the [C ii] emission we would identify as coming from the WIM, then we should have seen [C ii] associated with the H$_2$ emission for all longitudes in Figures 7 & 8. However, we see none. It is even more unlikely that [C ii] excess in the tangents is associated with CO-dark H$_2$ gas. In the tangent region the velocity profiles beyond the tangent velocities the [C ii] emission starts appearing at lower velocities than $^{12}$CO. In contrast in the Off-tangent regions in the velocity profiles both [C ii] and $^{12}$CO begin to appear simultaneously. Considering the relatively weak $^{12}$CO emission, if at all, we expect only a small fraction the [C ii] excess at the tangent is excited by H$_2$ molecules. Therefore we assume that [C ii] excess is dominated by contribution from excitation by electrons.

The detection of WIM emission from our HIFI OTF survey is surprising because the average electron density in the WIM throughout the disk, $\sim$few×10$^{-2}$ cm$^{-3}$, is too low to result in detectable [C ii] emission at the sensitivity of our HIFI OTF maps. Our explanation for the [C ii] emission detected in our survey is that it originates from denser ionized gas along the inner edge of the spiral arms that has been compressed by the spiral density wave shocks (Figure 6 as previously discussed by Velusamy et al. 2012, for the Scutum–Crux arm. Indeed, as shown below, the electron density is significantly higher in the spiral arm WIM than between the arms. In what follows we derive the physical characteristics of the spiral arm gas lanes and the electron density in the WIM lane.

### 4.1. The internal structure of spiral arms traced by [C ii], H$_1$, and $^{12}$CO

We can resolve the anatomical structure of the spiral arms, namely how each gas component is arranged spatially as a function of distance from its edges, using the velocity profiles in the tangencies. We locate the peak emissions in the layers traced by [C ii]–WIM component, H$_1$ (diffuse atomic clouds), $^{12}$CO (the GMCs), and the [C ii] in molecular gas (PDRs), as indicated in the cartoon in Figure 8 as a function of radial distance from the Galactic center (GC). The radial distances are derived from the observed radial velocities ($V_{LSR}$) assuming a constant Galactic rotational speed of 220 km s$^{-1}$ for radius $> 3$ kpc, at the distance of these spiral arm tangencies. The Galactocentric distances derived from the $V_{LSR}$ are listed in Table 1. The uncertainty in the Galactocentric distances, which depends on the assumed Galactic rotational speed at the tangency, does not affect our results significantly, as we are interested only in the relative displacement between them. It is easy to characterize the emission profiles on the near side to the Galactic Center near the tangent velocities where the emissions are increasing from zero. On the far side of the Galactic Center the emissions become too complex to extract the profile parameters due to confusion by emission from adjacent arms. This confusion is especially prominent on either side of the peak of the [C ii] -WIM component. Therefore, to derive the width of the emission lanes of each tracer, we use only the cleaner profile on the rising portion of spiral feature on the near side to the Galactic Center. We compute the Galactocentric radial distances to the $V_{LSR}$ of peaks and the half intensity points of each emission profile. Using these radial distances we get the distance between the peak and half intensity points in each emission lane. The total width is obtained by simply doubling this value and the results are summarized in Tables 1 and 2.

We derive an approximate lower bound on the width for the spiral arm by assuming [C ii]–WIM traces the inner edge and $^{12}$CO the outer edge, and list them in Table 2. Note that in the anatomy suggested by Vallée (2014a) the hot dust emission traces the inner edge on the near side of the Galactic center with $^{12}$CO tracing the midplane while [C ii] is in between. Using the parameters in Table 1 we sketch the cross cut view of the spiral arm in Figure 11. We plot each lane tracing the [C ii]–WIM, H$_1$, and molecular gas (HCO) by an approximate Gaussian profile. Note we did not plot the lanes for the Crux arm because the available data do not include the major part of this tangency (see Section 3.3). We list the results in Table 2 as a rough estimate for this tangency because of the poor longitude coverage of the tangency. Nevertheless, the largest arm width inferred for Crux seems to be consistent with narrower widths for Perseus and Norma. The Crux spiral tangency is at the largest radial distance ($\sim 7$ kpc) in contrast to $\sim 3.5 – 4.5$ kpc for the other arms studied here.

The cross-cut emission profiles of the internal structures (Figure 11 for Norma and the start of the Perseus spiral arms are quite consistent with each other. The overall sizes are $\sim 480$ pc and $\sim 500$ pc for the Perseus and Norma arms, respectively. To be consistent with Vallée (2014a) we present the location of the emission lanes of [C ii]–WIM and H$_1$ with respect to the location of the $^{12}$CO peak emission. We identify the inner edge of the arm as the location of the half power point in the [C ii] emission profile on the near side of the Galactic Center and on far side from $^{12}$CO. Similarly we identify the outer edge as the location of the half power point in $^{12}$CO emission profile on the far side from the Galactic Center. We calculate the spiral arm sizes as the distance between inner and outer edges as marked in Figure 11. With the exception of the Crux arm (which also has the poor longitude coverage of the tangency in our analysis), the overall sizes are $\sim 480$ pc and $\sim 500$ pc for the Perseus and Norma arms, respectively. The similar width for these arms suggests a width of $\sim 500$ pc is likely to be characteristic of all spiral arms in the Galaxy. Our result is close to that obtained by Vallée (2014a) who estimates a mean width $\sim 600$ pc for the spiral arms using the range of tangent directions observed using hot dust at the inner edge and $^{12}$CO at the outer edge. Our analysis and the values for the widths presented here are likely to be less ambiguous than those of Vallée (2014a), as our data are based on fully sampled longitudinal maps in the galactic plane observed with similar spatial and velocity resolutions. Another difference between our data and those used by Vallée (2014a) is that in his data the tangent directions were observed using maps averaged over a range of latitudes while ours are only in the plane at $b = 0^\circ$.0.
near the extreme low velocities (near the inner edge of the spiral arm) only [C\textsc{ii}] of the spiral feature) while there is little, or no, (Velusamy et al. 2012). Our WIM in the velocity resolved HIFI data for the Scutum tangency results presented here corroborate the previous detection of the Galactic di gives the direct unambiguous identification of the large scale from the inner edge. This anomalous excess [C\textsc{ii}] the velocity profiles is observed only for the spiral arm tangency (Figure 6) the emissions from di different layers in a cross-cut of the profile of the spiral arms. However in reality, as seen in the maps in Figures 3 to 5 the emissions occur over a range of longitudes and it is too complex to assign a single longitude as the tangency. In other words, all tracers have emission within a range of longitudes representing their tangency. Therefore we take a different approach to resolve and delineate the emission layers within each tangency kinematically by studying the velocity structure in each tracer spectrum. As illustrated in the cartoon of the tangency (Figure 5) the emissions from different layers will show separate velocity $V_{LSR}$ due to Galactic rotation.

4.2 [C\textsc{ii}] emission in the compressed WIM along the spiral arm

The spectra in Figures 7 to 10 bring out clearly the exceptional characteristics of the [C\textsc{ii}] emission at the tangencies. Namely, near the extreme low velocities (near the inner edge of the spiral arm) only [C\textsc{ii}] shows an emission peak (representing the onset of the spiral feature) while there is little, or no, $^{12}$CO and the H$^1$ intensity is still increasing with velocity. In contrast, both H$^1$ and $^{12}$CO emission peaks appear at still higher velocities away from the inner edge. This anomalous excess [C\textsc{ii}] emission in the velocity profiles is observed only for the spiral arm tangencies, where the path lengths are largest, and its detection represents the direct unambiguous identification of the large scale Galactic diffuse ionized gas (WIM) by the 158\ang [C\textsc{ii}] line. The results presented here corroborate the previous detection of the WIM in the velocity resolved HIFI data for the Scutum tangency (Velusamy et al. 2012). Our Herschel HIFI detection of the diffuse ionized gas provides detailed spatial and kinematic information on the nature of this gas component in the spiral arms.

It has been suggested that in the WIM any contribution to the [C\textsc{ii}] emission from excitation by H atoms is small and negligible (Velusamy et al. 2012, Velusamy & Langer 2014). For the WNM and WIM conditions ($T_e = 8000$ K; Wolfire et al. 2003) the critical density for excitation of [C\textsc{ii}] by H atoms is $\sim 1300$ cm$^{-3}$, and for electrons $\sim 45$ cm$^{-3}$ (see Goldsmith et al. 2012). Using the H$^1$ intensities integrated over the line width of the [C\textsc{ii}]-WIM component and the path lengths listed in Table 3 we estimate a mean H density $n(H) \sim 0.59$ cm$^{-3}$ and 0.31 cm$^{-3}$ in the Perseus and Norma tangencies respectively. As shown in the case for the Scutum tangency (Velusamy et al. 2012) such low H$^1$ densities cannot account for the [C\textsc{ii}] emission detected at the tangencies. Our interpretation that the [C\textsc{ii}] emissions near the tangent velocity are the result of $C^+$ excitation by the collisions with electrons in the WIM and not with H atoms, is further corroborated by strong evidence seen in the data presented here as discussed above in Section 4.

Although the [C\textsc{ii}] emission from the compressed WIM is observed only at, or near, the tangent longitudes, it is omnipresent all along the spiral arms in all directions. But, unlike the tangent direction, it is not easy to detect this enhancement in the spiral arms layers due to: (i) insufficient path length through the WIM: it is a factor of 4 to 5 smaller when viewed in any other direction than along the tangency, therefore much higher sensitivities are required to detect the weaker emission; (ii) at other longitudes, due to the viewing geometry, the velocities are blended with other components and it is difficult to disentangle the diffuse WIM emission from [C\textsc{ii}] emissions from the molecular gas and PDRs. However it is possible to separate the emissions with spectral line data obtained with higher sensitivity

### Table 1. Observed spiral arm parameters at the Perseus, Norma and Crux tangencies

| Tangency | Perseus | Norma | Crux$^1$ |
|----------|---------|-------|---------|
| longitude $l$ | $336:0 - 338:0$ | $327:0 - 329:5$ | $304:9 - 305:9$ |
| Emissions: $V_{peak}$ (km s$^{-1}$) | | | |
| [C\textsc{ii}]-WIM | -126 | -99.5 | -52 |
| [C\textsc{ii}] (molecular)$^2$ | -113 | -91.5 | -35 |
| $^{12}$CO | -117 | -91 | -32.5 |
| H$^1$ | -118 | -92 | -38 |
| Emissions: Peak brightness $T_{peak}$ (K) | | | |
| [C\textsc{ii}]-WIM | 0.56 | 0.35 | $\sim 0.94$ |
| [C\textsc{ii}](molecular) | 0.58 | 0.35 | 5.0 |
| $^{12}$CO$^3$ | 2.03 | 2.12 | 4.8 |
| H$^1$ | 70 | 118 | 106 |
| Galactocentric distance of emission layers (kpc)$^4$ | | | |
| [C\textsc{ii}]-WIM | 3.45 | 4.57 | 6.59 |
| $^{12}$CO (Mid plane) | 3.60 | 4.76 | 7.20 |
| H$^1$ | 3.58 | 4.74 | 7.01 |

$^1$This longitude range is offset from the true tangency by $\sim 2\degree$. Our data are available only for this longitude range.

$^2$This identification with H$^1$ gas is used just to distinguish it from the compressed WIM. However, in addition to excitation by H$^1$ this component may include some [C\textsc{ii}] excited by atomic H or electrons in the diffuse ionized medium.

$^3$Uncorrected for main beam efficiency.

$^4$From the Galactic center as determined from the $V_{LSR}$ and Galactic rotation velocity.
Using this approach, assuming a fully ionized gas, fractional abundance \(x(e)=n(e)/n_\text{i} = 1\), we calculate \(n(e)\) for all three tangencies and find \(n(e)\) in the range 0.42 to 0.74 cm\(^{-3}\) (see Table 2 for \(T_\text{e} = 8000\) K. For a fully ionized gas this implies a total density \(n(H^+) = n(e)\). These values are strictly a lower limit if the gas is partially ionized, \(x(e) < 1\), but only weakly so. The densities in the WIM at the leading edge of the spiral arms are an order of magnitude higher than the average density in the disk which is dominated by the interarm gas. Our determination of the WIM density from the [C\(\text{n}\)] emission is several times higher than the LOS averaged densities inferred from pulsar dispersion and \(H\alpha\) measurements, \(n(e) \sim 10^{-2} \text{ cm}^{-3}\) \citep{Haffner2009} and we argue that our larger mean value is a result of compression by the WIM–spiral arm interaction.

5. Summary:

We present large scale [C\(\text{n}\)] spectral line maps of the Galactic plane for \(l = 326.6\) to 341.4 and \(l = 304.9\) to 305.9 observed with \textit{Herschel} HIFI using On-The-Fly scans. All maps are shown as longitude-velocity (\(l-V\)) maps at latitude, \(b = 0\), except for \(l = 305.7\) to 305.9 for which \(b = +0.15\). The [C\(\text{n}\)] \(l-V\) maps along with those for H\(\text{i}\) and 12CO, available from southern Galactic plane surveys \citep{Barnes2011, McClure-Griffiths2009}, are used to analyze the internal structure of the spiral arms as traced by these gas layers in the large [C\(\text{n}\)]–WIM and molecular gas PDR layers.

and by making a spaxel by spaxel comparison with CO emission \citep[e.g.][]{Velusamy2014}. Thus, the WIM component may add significantly to the total [C\(\text{n}\)] luminosity in galaxies, while being difficult to detect along the average line of sight.

4.2.1. Electron densities in the spiral arm WIM

The electron density of the WIM is an important parameter for understanding the conditions in the ISM, such as the pressure and ionization rate. To estimate the electron densities required to produce the observed [C\(\text{n}\)] emission in the WIM we follow the approach in \cite{Velusamy2012}. At the low densities of the diffuse medium the excitation is subthermal and the emission is optically thin, therefore the intensity in an ionized gas is given by (see Section 4 in \cite{Velusamy2012})

\[
\langle n(e) \rangle \sim 0.277 T_{\text{e}}^{1/2} \left( I([C\text{n}])/L_{\text{pke}} \right)^{0.5},
\]

which assumes a fully ionized gas, a fractional abundance of C\(^+\) with respect to the total hydrogen density, \(n_\text{i}, X(C^+) \approx 1.4 \times 10^{-4}\), and where \(L_{\text{pke}}\) is the path length in kpc, \(T_\text{e}\) is the kinetic temperature in 10\(^3\) Kelvin, and

\[
I([C\text{n}]) = \int T_{\text{n}}([C\text{n}])dv
\]

is the intensity in K km s\(^{-1}\). The [C\(\text{n}\)] intensities given in Table 2 are integrated over the velocity widths for the [C\(\text{n}\)]–WIM profiles. The path lengths listed in Table 2 are derived using the Galactocentric radial distance and the thickness of the [C\(\text{n}\)] emission layer, as discussed above, assuming approximately circular geometry at the tangencies.

Table 2. Derived Spiral arm structure at the Perseus, Norma and Crux tangencies

| Spiral Arm | Perseus | Norma | Crux |
|------------|---------|-------|------|
| [C\(\text{n}\)]–WIM peak | -190 | -190 | -600 |
| H\(\text{i}\) peak | -20 | -25 | -180 |

| Emission lane width | Perseus | Norma | Crux |
|---------------------|---------|-------|------|
| [C\(\text{n}\)]–WIM | 250 | 270 | 220 |
| 12CO | 400 | 400 | 440 |
| H\(\text{i}\) | 400 | 620 | 640 |
| Full arm width traced by [C\(\text{n}\)] and 12CO | 480 | 500 | 940 |

\(^1\)This longitude range is offset from the true tangency and therefore the parameters listed are only indicative of the trends within the arm structure.

\(^2\)FWHM as estimated using the profile on the rising side (near-side to the Galactic Center)—see text.

\(^3\)Mean path length estimated using the radial distance from the Galactic Center and the width.

4Assuming that the [C\(\text{n}\)] emission here is due to C\(^+\) excitation by electrons and that excitation by H\(\text{atoms}\) is negligible (c.f. \cite{Velusamy2014, Velusamy2013}).

Using this approach, assuming a fully ionized gas, fractional abundance \(x(e)=n(e)/n_\text{i} = 1\), we calculate \(n(e)\) for all three tangencies and find \(n(e)\) in the range 0.42 to 0.74 cm\(^{-3}\) (see Table 2 for \(T_\text{e} = 8000\) K. For a fully ionized gas this implies a total density \(n(H^+) = n(e)\). These values are strictly a lower limit if the gas is partially ionized, \(x(e) < 1\), but only weakly so. The densities in the WIM at the leading edge of the spiral arms are an order of magnitude higher than the average density in the disk which is dominated by the interarm gas. Our determination of the WIM density from the [C\(\text{n}\)] emission is several times higher than the LOS averaged densities inferred from pulsar dispersion and \(H\alpha\) measurements, \(n(e) \sim 10^{-2} \text{ cm}^{-3}\) \citep{Haffner2009} and we argue that our larger mean value is a result of compression by the WIM–spiral arm interaction.

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\]

which assumes a fully ionized gas, a fractional abundance of C\(^+\) with respect to the total hydrogen density, \(n_\text{i}, X(C^+) \approx 1.4 \times 10^{-4}\), and where \(L_{\text{pke}}\) is the path length in kpc, \(T_\text{e}\) is the kinetic temperature in 10\(^3\) Kelvin, and

\[
I([C\text{n}]) = \int T_{\text{n}}([C\text{n}])dv
\]

is the intensity in K km s\(^{-1}\). The [C\(\text{n}\)] intensities given in Table 2 are integrated over the velocity widths for the [C\(\text{n}\)]–WIM profiles. The path lengths listed in Table 2 are derived using the Galactocentric radial distance and the thickness of the [C\(\text{n}\)] emission layer, as discussed above, assuming approximately circular geometry at the tangencies.
the \([\text{C}\text{ii}]\) intensities and a radiative transfer model to determine the electron densities \(W\text{IM}\) traced by \([\text{C}\text{ii}]\). The electron densities in the compressed \(W\text{IM}\) are \(\sim 0.5 \text{ cm}^{-3}\), about an order of magnitude higher than the average for the disk. The enhanced electron density in the \(W\text{IM}\) is a result of compression of the \(W\text{IM}\) by the spiral density wave potential.

5. Finally, we suggest that the \(W\text{IM}\) component traced by \([\text{C}\text{ii}]\) at the spiral arm tangencies exists all along the spiral arms in all directions, but unlike in the tangent direction it is not easy to detect because of insufficient path length of \(C^0\) across the arms, and confusion due to velocities blended with other components. Thus, the \(W\text{IM}\) component along the spiral arms may add significantly to the total \([\text{C}\text{ii}]\) luminosity in galaxies, while being difficult to detect along the average line of sight.

In this paper, we demonstrated the utility of spectrally resolved \textit{Herschel} HIFI OTF scan maps of \([\text{C}\text{ii}]\) emission to unravel the internal structure of spiral arms using the velocity resolved spectral line profiles at the spiral arm tangencies. Our results provide direct observational evidence of the cross section view of the spiral arms in contrast to the synthetic model by Vallée \cite{2014a} using the longitude tangents as traced by different tracers. Combining \([\text{N}\text{ii}]\) with \([\text{C}\text{ii}]\) yields additional constraints \cite[e.g.][]{Langer et al. 2015, Yildiz et al. 2015} and future \([\text{Ni}]\) spectral line maps of the spiral arms are needed to characterize fully the compressed \(W\text{IM}\) detected here, and the Galactic arm–interarm interactions.

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