AN OUTER ARM IN THE SECOND GALACTIC QUADRANT: STRUCTURE

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ABSTRACT

The lack of arm tracers, especially remote tracers, is one of the most difficult problems preventing us from studying the structure of the Milky Way. Fortunately, with its high-sensitivity CO survey, the Milky Way Imaging Scroll Painting (MWISP) project offers such an opportunity. Since completing about one-third of its mission, an area of \( l = [100, 150] \degree \), \( b = [-3, 5] \degree \) has nearly been covered. The Outer arm of the Milky Way first clearly revealed its shape in the second galactic quadrant in the form of molecular gas—this is the first time that the Outer arm has been reported in such a large-scale mapping of molecular gas. Using the 115 GHz \(^{12}\)CO(1–0) data of MWISP at the LSR velocity \( \approx [-100, -60] \) km s\(^{-1}\) and in the area mentioned above, we have detected 481 molecular clouds in total, and among them 332 (about 69\%) are newly detected and 457 probably belong to the Outer arm. The total mass of the detected Outer arm clouds is \( \sim 3.1 \times 10^6 M_\odot \). Assuming that the spiral arm is a logarithmic spiral, the pitch angle is fitted as \( \sim 13^\circ \). Besides combining both the CO data from MWISP and the 21 cm H i data from the Canadian Galactic Plane Survey (CGPS), the gas distribution, warp, and thickness of the Outer arm are also studied.

Key words: catalogs – Galaxy: structure – ISM: clouds – ISM: molecules

Supporting material: machine-readable table

1. INTRODUCTION

It is well-known that our galaxy has a spiral structure, but (Oort et al. 1958; Bok 1959) a detailed understanding of the Milky Way is still lacking. Since Georgelin & Georgelin (1976) presented a large-scale spiral pattern with H\(\text{\textsc{ii}}\) regions, nearly 100 Milky Way models have been proposed (Steiman-Cameron 2010). However, most models share the same large structure in spite of differing details (e.g., Russell et al. 2007; Vallée 2008; Hou & Han 2014).

The fact that there exists a spiral arm beyond the Perseus arm has been generally recognized for a long time. Since Moffat & Vogt (1975) noticed that several young star clusters were located far beyond the position of the Perseus arm, more work has been done to confirm the existence of this external arm. Henderson et al. (1982) first systematically studied the distribution of H\(\text{\textsc{i}}\) in the outer galaxy beyond the solar circle, which is a vast frontier of our galaxy. Heyer et al. (1998) described the molecular image of the outer galaxy with the Five College Radio Astronomy Observatory (FCRAO) CO survey results, providing evidence for the presence of molecular clouds in this outer area. Negueruela & Marco (2003) traced the external arm using OB stars and concluded that the Cam OB3 association lies on it. On the basis of a maser source (associated with high-mass star-forming region, HMSFR) distances, Reid et al. (2014) first delineated several spiral arms, including the Outer arm, using the trigonometric parallax method. In addition, detailed parallax results and analyses of the Outer arm are also presented by Hachisuka et al. (2015).

However, accurate maser source positions cannot outline the distributions of interstellar gases. The FCRAO CO survey only traced the high-mass molecular clouds because of its poor sensitivity. Fortunately, the Milky Way Imaging Scroll Painting (MWISP) project\(^4\) provides a chance to study the molecular gases with no-bias high sensitive \(^{12}\)CO(1–0), \(^{13}\)CO (1–0), and \(^{18}\)O(1–0) observations. Due to such high-sensitivity observations, a new spiral arm (hereafter the New arm) beyond the Outer arm has been discovered by Sun et al. (2015). Combining the \(^{12}\)CO(1–0) observations of MWISP and atomic hydrogen data from the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003), we presented the results of the Outer arm: the arm located between the Perseus arm and the New arm. The results derived from \(^{13}\)CO(1–0) and \(^{18}\)O (1–0) data and further analyses will be published in future works.

Please note that the Outer arm does not have a particular name yet. Some authors have labeled it the “Cygnus arm,” or the “Perseus +I arm,” or the “Norma—Cygnus arm” (Vallée 2008). Otherwise, the name “Outer arm” is also widely used (e.g., Dame et al. 2001; Reid et al. 2014). Considering the fact that the name “Cygnus” has been described as the location near the Sun in some early papers, here we choose the name “Outer arm” to avoid confusion.

In Section 2 we introduce our CO observation conditions and archival data of atomic hydrogen. In Section 3 we describe how we pick out the Outer arm clouds and briefly study their properties. In Section 4 we study the properties of the Outer arm, including the pitch angle, the gas distribution, the thickness, and the warp. A10 summary is given in Section 5.

2. OBSERVATIONS AND ARCHIVAL DATA

2.1. CO Observations

The \(^{12}\)CO (1–0), \(^{13}\)CO(1–0), and \(^{18}\)O(1–0) lines were observed simultaneously using the Purple Mountain Observatory Delingha 13.7 m telescope from 2011 September to 2015 March as one of the scientific demonstration regions for the MWISP project, which is the first no-bias high-sensitivity CO
survey with such a large-scale aiming at $l = [-10, 250]^{\circ}$, $b = [-5, 5]^{\circ}$. With the on-the-fly (OTF) observing mode, MWISP now has completed about one-third of its plan, and an area of $l = [100, 150]^{\circ}$, $b = [-3, 5]^{\circ}$ has mostly been covered—the total area was 288 square degrees. A superconductor-insulator-superconductor (SIS) superconducting receiver with a nine-beam array was used as the front end (Shan et al. 2012). A Fast Fourier Transform (FFT) spectrometer with a total bandwidth of 1000 MHz and 16,384 channels was used as the back end. For the 115 GHz $^{12}$CO (1 − 0) observations, the main beam width was about 52″, the main beam efficiency ($\eta_{\text{MB}}$) was 0.46, and the typical rms noise level was $\sim$0.5 K, corresponding to a channel width of 0.16 km s$^{-1}$. (~0.2 K per 0.8 km s$^{-1}$ channel, which is 3 times better than the FCRAO OGS sensitivity.) All the data were corrected by $T_{\text{MB}} = T_{\text{A}}/\eta_{\text{MB}}$. The data were sampled every 30″. All the data were reduced using the GILDAS/CLASS package.

### 2.2. Archival Data of Atomic Hydrogen

The 21 cm line data were retrieved from the CGPS. We downloaded data of $l = [63, 155]^{\circ}$, $b = [-3, 5]^{\circ}$ from the Canadian Astronomy Data Centre. The velocity coverage of the data is in the range of $-153$ to 40 km s$^{-1}$, with a channel separation of 0.82 km s$^{-1}$. The survey has a spatial resolution of 58″, which is comparable to our CO observations.

### 3. ANALYSIS OF CLOUDS

We have detected 481 clouds in total; 332 (about 69%) clouds are newly detected, 457 clouds are identified in the Outer arm, and 24 are identified in the New arm. Among the Outer arm clouds, 7 are reported by Brand & Wouterloot (1994; hereafter BW94), 75 are reported by Heyer et al. (2001; hereafter HCS01 clouds), 125 are reported by Brunt et al. (2003; hereafter BKP03). And all 24 of the New arm clouds are newly detected. (These 24 New arm clouds do not overlap with the clouds detected by Sun et al. 2015.) The parameters of all 481 clouds are summarized in Table 1.

#### 3.1. Cloud Identification

Because of the differential rotation of the Milky Way, most LSR velocities that are consistent with circular Galactic rotation are negative in the second quadrant. Starting from $V_{\text{LSR}} \sim 0$ km s$^{-1}$, increasingly negative velocities successively trace the Local arm, the Perseus arm, the Outer arm, and the New arm. In order to find all of the Outer arm clouds, we need to know the Outer arm LSR velocity range at every galactic longitude. As mentioned above, the Outer arm LSR velocity is located between the Perseus arm and the New arm, which provides us with a clue for picking out the clouds. First, using the HI data from the CGPS, we plotted the longitude-velocity map of HI, integrated over all latitudes (from $-3^{\circ}$ to $5^{\circ}$). Second, we projected the spatial (x, y) curves of the Outer arm, the Perseus arm (both fitted by Reid et al. 2014, and hereafter the Reid Outer spiral and the Reid Perseus spiral), and the New arm (fitted by Sun et al. 2015, and hereafter the Sun New spiral) on that HI longitude-velocity map. (In other words, we converted the dashed curves shown in Figure 3 into the ones shown in Figure 5. And the converting method is presented in detail in Section 4.3.) And then we marked all the HCS01 clouds on that map. Combining the HI map, the positions of the longitude-velocity curves, and HCS01 clouds, we can estimate the velocity range of the Outer arm as a function of galactic longitude. Third, we compiled an automatic procedure to list all the positions with emissions greater than 2.5σ of the data cube at that velocity range (where $\sigma$ is the typical rms noise and $\sim$0.5 K). Last, we checked both the list and data cube and identified the clouds via the naked eye. It is necessary to emphasize that we did not separate the isolated clouds or cloud complexes into small pieces of molecular clumps. In other words, some of the clouds have multiple spectral or spatial peaks.

Finally, we have detected 481 clouds in total. But not all of them belong to the Outer arm. Of these clouds, 24 may be located in the New arm, since the velocity gap between the 24

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Table 1

| Name               | $V_{\text{LSR}}$ (km s$^{-1}$) | $T_{\text{peak}}$ (K) | $\Delta V$ (km s$^{-1}$) | $I_{\text{CO}}$ (K km s$^{-1}$) | Area (arcmin$^2$) | $d$ (kpc) | $R$ (kpc) | Size (10$^3$ M$_\odot$) | Mass (10$^3$ M$_\odot$) | Z Scale (kpc) | Note |
|--------------------|-------------------------------|------------------------|--------------------------|-----------------------------|------------------|-------------|-----------|------------------------|--------------------------|-----------------|------|
| MWISP G101.400+03.967 | −86.0                         | 2.3                    | 1.6                      | 3.9                         | 15.4             | 8.2         | 12.8      | 10.4                   | 1.3                      | 0.6             |      |
| MWISP G101.508+04.092 | −90.5                         | 3.2                    | 1.1                      | 3.6                         | 3.0              | 8.6         | 13.6      | 8.4                    | 0.2                      | 0.6             |      |
| MWISP G101.633+02.867 | −82.6                         | 3.6                    | 1.6                      | 6.2                         | 10.0             | 7.8         | 12.6      | 11.1                   | 2.0                      | 0.4             |      |
| MWISP G101.683+02.917 | −81.7                         | 4.4                    | 1.3                      | 5.9                         | 21.7             | 7.7         | 12.4      | 11.6                   | 2.5                      | 0.4             |      |
| MWISP G101.700+03.833 | −89.9                         | 7.9                    | 1.4                      | 11.5                        | 25.8             | 8.6         | 13.1      | 14.2                   | 7.4                      | 0.6             |      |
| MWISP G101.708+02.867 | −84.3                         | 4.9                    | 1.2                      | 6.3                         | 18.4             | 8.0         | 12.6      | 11.1                   | 2.5                      | 0.4             |      |
| MWISP G101.767+02.808 | −82.6                         | 16.5                   | 2.9                      | 51.0                        | 43.3             | 7.8         | 12.5      | 16.7                   | 45.8                     | 0.4             |      |
| MWISP G101.800+02.958 | −81.4                         | 2.5                    | 0.7                      | 2.0                         | 4.8              | 7.7         | 12.4      | 5.2                    | 0.2                      | 0.4             |      |
| MWISP G101.808+03.817 | −88.0                         | 2.2                    | 1.6                      | 3.9                         | 18.5             | 8.3         | 12.9      | 11.5                   | 1.7                      | 0.6             |      |
| MWISP G101.850+02.908 | −81.7                         | 7.7                    | 2.0                      | 16.1                        | 40.4             | 7.7         | 12.4      | 15.9                   | 13.1                     | 0.4             |      |

Note. Column (1): source named by the MWISP project and the $T_{\text{peak}}$ position in Galactic Coordinates. Columns (2)−(5): results of a Gaussian fit to the spectra. Column (6): equivalent diameters of the molecular clouds corrected by the beam size of the telescope. Column (10): cloud mass calculated by $M = 1.8 \times 10^{3} \text{cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Dame et al. 2001). Column (11): scale height (∼$\text{Dsin(b)}$). Column (12): BW94: sources detected by Brand & Wouterloot (1994); HCS01: sources detected by Heyer et al. (2001); BKP03: sources detected by Brunt et al. (2003); new Arm: clouds that are supposed to belong to the new spiral arm detected by Sun et al. (2015).
clouds and the other ones is relatively large in the zoomed-in longitude-velocity map.

However, it is necessary to point out that the Outer arm clouds that we found do not absolutely belong to that arm. From $l \approx 100^\circ$ to $120^\circ$, there exists an arm-blending region. The LSR velocities of HI gas of the Perseus arm and the Outer arm are mixed together (see Figures 5 and 6). Also, the LSR velocity gap of CO between the two arms is not obvious. Since our cloud identification criterion is based on the LSR velocity, it is difficult to pick out Outer arm clouds in that region. We may omit some clouds with an LSR velocity $\geq 70$ km s$^{-1}$, or falsely pick the clouds that may be located at the inter-arm area.

### 3.2. Cloud Parameters

Heliocentric distance is one of the most important values for studying both the cloud properties and the spiral structure. Generally there are three methods for measuring the distance: trigonometric parallax, photometry, and the kinematic method. And the accuracy of the trigonometric parallax and photometry methods is better than that for the kinematic method. (see Xu et al. 2006) However, there is only one source with a parallax distance and a luminosity distance in the Outer arm region: the one associated with MWISP G135.267+02.800—its parallax distance is 6.0 kpc (Reid et al. 2014) and its luminosity distance is also 6.0 kpc (Hou & Han 2014). So the kinematic method is the only choice for us.

We chose to use the kinematic distances on the basis of the galactic parameters of Model A5 of Reid et al. (2014) ($\Theta_0 = 240$ km s$^{-1}$, $R_0 = 8.34$ kpc, $\frac{d\Omega}{dr} = -0.2$ km s$^{-1}$ kpc$^{-1}$, $U_0 = 10.7$ km s$^{-1}$, $V_0 = 15.6$ km s$^{-1}$, $W_0 = 8.9$ km s$^{-1}$, $U_d = 2.9$ km s$^{-1}$, $V_d = -1.6$ km s$^{-1}$, hereafter Reid model) and the FORTRAN source code provided by Reid et al. (2009). Note that all of the cloud distances we finally used are kinematic distances, including MWISP G135.267+02.800.

The Reid model is much better than the IAU model (namely $\Theta_0 = 220$ km s$^{-1}$, $R_0 = 8.5$ kpc). Take the cloud MWISP G135.267+02.800 as an example. Its parallax and luminosity distances both are 6.0 kpc and the Reid kinematic distance (using Reid model) is 6.7 kpc, whereas the IAU kinematic distance (using IAU model) is 8.6 kpc. A detailed comparison can be seen in Section 4 of Reid et al. (2009)

However, one should also keep in mind that there still exist biases from the assumption of circular motion inherent in this kinematic distance model. In the second galactic quadrant the kinematic distance may be a little larger than the real distance, just as seen in the example of MWISP G135.267+02.800 or the left panel of Figure 3. A detailed discussion about the biases is presented in Section 4.2.

Knowing the distance $d$ and latitude $b$, we calculated the scale height $Z$ by $Z = d \sin(b)$. And using $b$, $Z$, $d$ and longitude $l$, we calculated the galactocentric radius $R$ with $R^2 = d^2 \cos^2(b) + R_0^2 - 2R_0d \cos(b)\cos(l) + Z^2$.

The cloud solid angle $A$ is defined by the $3\sigma$ limits. The cloud diameter $D$ is obtained after the beam deconvolution: $D = d\sqrt{\frac{2A}{\theta_{\text{MB}}^2}}$ (Ladd et al. 1994), where $\theta_{\text{MB}}$ is the main beam width. Adopting the CO-to-H$_2$ X factor $1.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Dame et al. 2001), cloud mass is calculated from $M = 2 \mu m_h X \int T_R dV$, where $\mu = 1.36$ (Hildebrand 1983) is the mean atomic weight per H atom in the ISM, $m_h$ is the H atomic mass, and $\int T_R dV$ is the integrated intensity of the $T_{\text{peak}}$ spectrum. However, the mass is probably underestimated since the X factor adopted is measured in the solar neighborhood, and a recent study has suggested an increase of $X$ in the outer Galaxy. (Abdo et al. 2010).

### 3.3. Comparison with HCS01

Heyer et al. (2001) have used the CO data of the FCRAO Outer Galaxy Survey to identify molecular clouds. To make a comparison, we plotted the distributions of line width, size, and mass for the HCS01 Outer arm clouds and ours. We have two reasons for not comparing the clouds with BW94 and BKP03: (i) the number of BW94 clouds is too few and (ii) the BKP03 clouds are generated by the same data but from a different method than the HCS01 clouds, and their method tends to find small-size molecular clumps, which is not consistent with our cloud identification criterion. Figure 1 shows the results. One may notice that there are 102 HCS01 clouds in Figure 1, but only 75 clouds are labeled in Table 1. The reason is the different cloud identification methods: HCS01 includes both small, isolated clouds and clumps within larger cloud complexes, but our catalog only includes isolated clouds and cloud complexes. So the clouds are not exactly matched one-to-one.

Since the cloud heliocentric distances of HCS01 are derived from the IAU model, the sizes and masses are correspondingly...
biased. In order make our comparison using the same criterion, we revised the distances of the Reid model and the sizes and masses are correspondingly revised.

However, the comparison result is against expectations. The signal-to-noise ratio of our data is higher than that of HCS01. Consequently, HCS01 should have contained more luminous (and therefore more massive) clouds. But the distribution shows that the fractions of small sizes and low masses of HCS01 are higher than those of ours. Two main reasons may have caused this. (i) HCS01 includes smaller clumps within larger cloud complexes, but we did not detach clumps from cloud complexes. (ii) Because of our higher signal-to-noise ratio, we can detect a larger angle area for the same cloud, which results in larger sizes and masses.

4. PROPERTIES OF OUTER ARM

4.1. Pitch Angle

Spiral arms of external galaxies are usually approximated by logarithmic spirals. This is a simple but reasonable assumption and is also applicable to our Milky Way galaxy. That the pitch angle of one spiral is constant is one of the properties of a logarithmic spiral. Usually, the spiral arms of one galaxy are roughly fitted by logarithmic spirals with the same pitch (e.g., Vallée 2008), or more accurately, different spiral arms are fitted by different pitches (e.g., Russell 2003). And sometimes even one spiral arm is fitted by varying the pitch angle (e.g., the Sagittarius arm in Taylor & Cordes 1993). In fact, Honig & Reid (2015) recently showed that in some external galaxies, the pitch angle in the same spiral arm varies, and the variance is as large as the that among different arms within the same galaxy. So a more accurate assumption may be that the pitch angle of one segment of the arm within one galaxy is constant.

Now we assume that the segment form \( l = 100^\circ \) to \( l = 150^\circ \) of the Outer arm spiral is a logarithmic spiral, and using the same equation as Reid et al. (2009, 2014), we fitted the spiral of those 457 Outer arm clouds using

\[
\ln \left( \frac{R}{R_{\text{ref}}} \right) = -(\beta - \beta_{\text{ref}}) \tan(\psi),
\]

where \( \psi \) is the spiral pitch angle, \( \beta \) is the galactocentric azimuth (namely the Source-GC-Sun angle), and \( R_{\text{ref}} \) and \( \beta_{\text{ref}} \) are the reference radius and reference azimuth, respectively. The fitting algorithm is a minimizing chi-square error statistic, and the chi-square error statistic is computed as

\[
\chi^2(k, b) = \sum_{i=1}^{N} W_i (y_i - b - kx_i)^2.
\]

where \( k = -\tan(\psi), b = \beta_{\text{ref}} \tan(\psi) + \ln(R_{\text{ref}}), x_i \) and \( y_i \) are \( \beta \) and \( \ln(R) \) of each cloud, respectively, and \( W_i \) is the weight. The weight is defined as \( W = \log_{10} \left( \frac{M}{M_{\odot}} \right) \).

Figure 2 shows the fitting result. The pitch angle is \( \sim 13^\circ 1 \), the \( R_{\text{ref}} \) is \( \sim 13.6 \) kpc, the \( \beta_{\text{ref}} \) is \( \sim 26^\circ 9 \), and the \( \chi^2 \) is \( \sim 4.1 \). Our fitting pitch angle is close to the result of Reid et al. (2014; pitch = 13°8), and is consistent with the results of Vallée (2015), who summarized large numbers of recent studies about Milky Way pitch angle and yielded a mean global value of 13°1.

Figure 2. Fitting result of the Outer arm pitch angle. R is the Galactocentric radius in units of kpc, \( \beta \) is Galactocentric longitude. Circles indicate molecular clouds of the Outer arm, and their sizes indicate different masses. The fitting line is weighted by mass.

4.2. Plan View

Since Georgelin & Georgelin (1976) presented the famous Milky Way plane view, numerous models have been suggested (see Figure 2 in Steiman-Cameron 2010). Our knowledge about the Milky Way structure has advanced since then a little, so at least the existence of Outer arm is now undoubted, though it was absent in the Georgelin model. In contrast, the lack of arm tracers, especially the remote tracers, still prevent us from knowing more about our galaxy. Thanks to the high-sensitivity CO survey of MWISP, so many molecular clouds of the Outer arm have been detected, and this is the first time that we have detected such large numbers of remote molecular clouds, which contributes a lot to studying the Milky Way structure.

The left panel of Figure 3 shows the plane view of the Milky Way. The red thick curve indicates the Outer arm spiral fitted by us (hereafter our Outer spiral). Since the Outer arm pitch angle fitted by us is similar to the one fitted by Reid et al. (2014), and their parallax distance of the Outer arm is more precise, we moved our Outer spiral to be parallel to the position of the Reid Outer spiral. Accordingly, the Outer arm clouds are parallelly moved by the same distance. The detailed moving process is as follows. First, using the \( R_{\text{ref}} \) and \( \beta_{\text{ref}} \) fitted by Reid et al. (2014), with the pitch angle fitted by us, we plotted a new spiral curve as the parallel moved curve. Second, we calculated the distance between the new curve and the old curve at every cloud galactic longitude. Third, the new cloud heliocentric distance was calculated as the “old cloud heliocentric distance minus the distance obtained in the second step.” This moving process decreased the cloud heliocentric distances but did not change their longitudes. The right panel of Figure 3 is the result after the move.

We mentioned these distance biases in Section 3.2. One may wonder why the kinematic distances obtained from the model that Reid et al. (2014) provided are greater than the distances that they measured. In fact, the biases are mainly caused by errors. Limited parallax data and the parallax measuring errors lead to larger errors of the galactic model. The Reid model narrows the gap between the kinematic distance and the parallax distance but cannot perfectly match them. (And actually, the cloud distances that we moved are roughly below the parallax distance errors. Just see the error bars of the Outer arm HMSFRs in Figure 3.) Besides, the Reid model is a global
model and it is fitted by maser sources that distribute in almost three galactic quadrants (see Figure 1 of Reid et al. 2014). But different regions of the Milky Way may have their own peculiar motions. So in different regions the kinematic distances calculated from their model may be a little biased. As a result of these reasons, in the second galactic quadrant (or more exactly in the Outer arm region of the second galactic quadrant) the kinematic distances are a little larger than the parallax distances, just as we see in the left panel of Figure 3.

Figure 4 shows the whole view of the Milky Way. We extended our translational (namely the parallel moved) spiral to the inner galaxy. The Reid Outer spiral is also plotted. Additionally, for comparison we plotted two recent fitting results for this arm, of which the arm tracers or fitting methods are different. The cyan dashed curve is one of the fitting results from Hou & Han (2014; “arm-5” in the third column of Table 4 in their paper). Their arm tracers are H II regions, and their fitting model is the polynomial-logarithmic spiral arm model. The magenta pecked curve is the fitting result from Bobylev & Bajkova (2014). Their arm tracers are 3 HMSFRs and 12 very young star clusters, and their fitting model is the logarithmic spiral. The fact that our translational spiral is located closer to the other three spirals may suggest that the translational locations of the clouds are relatively better. However, this suggestion is not adequate enough to make us revise the distances and other parameters such as mass in Table 1. The original parameters derived in Section 3.2 are retained.

Figure 3. (Left panel) Locations of molecular clouds and HMSFRs in the plane view of the Milky Way. The red and blue circles respectively mark the molecular clouds of the Outer arm and New arm, which are summarized in Table 1. The blue triangles mark the molecular clouds of the New arm that were detected by Sun et al. (2015). Different sizes of circles and triangles indicate different masses. The red and green squares respectively mark the HMSFRs (Reid et al. 2014) of the Outer and Perseus arms. Distance error bars of HMSFRs are indicated. The red diamonds indicate the locations of the Outer arm HMSFRs calculated by kinematic method. The green, red, and blue dashed curves respectively indicate the Reid Perseus spiral, the Reid Outer spiral, and the Sun New spiral. The red thick curve indicates our Outer spiral. The gray dotted curves indicate galactocentric radii = 10, 12, 14, 16 kpc. The gray dotted lines indicate galactic longitudes = 60°, 75°, 90°, 105°, 120°, 135°, 150°. The gray crosses and the words beside them indicate the locations and the corresponding LSR velocities. (Right panel) Translational result of the Outer arm clouds and our Outer spiral. For a better comparison, we have not moved or changed any symbols except the red circles and the red thick curve, and the sizes of the red circles remain the same although their masses are changed because of the revised distances.

Figure 4. An artist’s conception of the Milky Way (R. Hurt: NASA/JPL-Caltech/SSC). The red circles indicate the parallel moved Outer arm clouds with mass > 10⁸ M☉. The white squares indicate the Outer arm HMSFRs and the distance error bars are also plotted. The red thick curve indicates the extended translational position of our Outer spiral, and the red thick dashed curve indicates the original position of our Outer spiral. The white dotted curve indicates the Reid Outer spiral. The cyan dashed curve and magenta pecked curve indicate the Outer arm fitting results of Hou & Han (2014) and Bobylev & Bajkova (2014), respectively.
Figure 5. Longitude–velocity diagram of H\textsc{i} from the CGPS, integrated over all latitudes (from $-3^\circ$ to $5^\circ$). The red and blue circles respectively mark the molecular clouds of the Outer arm and the New arm, which are summarized in Table 1. The blue triangles mark the molecular clouds of the New arm detected by Sun et al. (2015). Different sizes of circles and triangles indicate different masses. The red and green squares respectively mark the HMSFRs of the Outer and Perseus arms. The green, red, and blue dashed curves respectively indicate the projections of the Reid Perseus spiral, the Reid Outer spiral, and the Sun New spiral. The red thick curve indicates the projection of the Outer arm spiral fitted by us. The pink ribbon indicates the integrated velocity window of Figure 7.

Figure 6. Velocity–latitude montage of H\textsc{i} from the CGPS, integrated every $5^\circ$ of galactic longitude. The Outer arm is embraced in the two dotted red lines in each figure except the figures of the arm-blending region. The meanings of other symbols are consistent with Figure 5. Note that the low-mass clouds ($<10^3 \, M_\odot$) are not plotted, and the symbol size does NOT indicate mass.
\textbf{4.3. }\textit{l–V, V–b and l–b Map}

Figure 5 shows the \textit{l–V} map of H\textsc{i} emission. All the clouds (including the New arm clouds) and HMSFRs are marked on it. Also, the projections of the Reid Outer spiral, the Reid Perseus spiral, the Sun New spiral, and our Outer spiral are plotted. In order to project those spiral curves on the \textit{l–V} map, or in other words, to convert the dashed curves shown in Figure 3 into the ones shown in Figure 5, we compiled a C program on the basis of the FORTRAN code provided by Reid et al. (2009). Their program can calculate the revised heliocentric kinematic distances when inputting the cloud positions and the LSR velocities, just as mentioned in Section 3.2. Our program is the inverse—the inputs are cloud position (galactic longitude and latitude) and galactocentric radius, and the output is the LSR velocity. Knowing the expression of the arm curves (namely through Equation (1)), we can obtain an array of galactocentric radii at every galactic longitude. And then, using the Reid model, the cooresponding LSR velocities can be calculated by our C program. Using the arrays of longitudes and velocities, we then can plot the \textit{l–V} curves of the arms.

Figure 6 shows the \textit{V–b} montage of H\textsc{i} emission. The high-mass Outer arm clouds (>10^3 \textit{M}_\odot), the New arm clouds, and the HMSFRs are marked on it. As mentioned in Section 3.1, from longitude \textit{l} \approx 100^\circ to 120^\circ, there exists an arm-blending region. This phenomenon can be clearly seen from those two figures and may mainly be caused for the following three reasons. (i) Streaming motions near spiral arms have long been predicted by density wave theory and have been observed in other galaxies. (e.g., Figure 4 in Visser 1980, Figure 5 in Aalto et al. 1999) This can probably happen at this region in our galaxy. (ii) Spiral shock may lead to the condition that one LSR velocity could share two different distances. (e.g., Foster & MacWilliams 2006) (iii) The expansion motion of the H\textsc{i} super-bubble near \textit{l} = 123^\circ, \textit{b} = −6^\circ associated with the Perseus arm may also lead to velocity mixing. (Sato et al. 2007) Whatever reason mainly causes the mixing LSR velocities, this at least suggests that in this region the gas motion is very peculiar.

Figure 7 shows the velocity-integrated intensity of H\textsc{i} emission. All the clouds and HMSFRs of the Outer arm are marked on it. Since the velocity ranges of the Outer arm are different at different longitudes, we need to define an \textit{l–V} function as the integrated velocity window. We have adopted two polynomial fitting curves as the outline of integrated range instead of the spiral \textit{l–V} projection. This is because the Outer arm velocity ranges are irregular and the polynomial fitting curve is more appropriate for defining the various ranges. The inset of Figure 7 shows the mass of molecular gas as a function of galactic longitude. The bin is 1 galactic longitude degree. The total mass of all the Outer arm clouds is \approx 3.1 \times 10^6 \textit{M}_\odot. More details about gas distributions are presented in Section 4.4.

Those three figures present a 3D view of the arm. The H\textsc{i} and H$_2$ gases are roughly matched. The warp is obvious.

\textbf{4.4. }\textbf{Gas Distribution}

The gas distribution of the Milky Way is a frequently discussed topic. (e.g., Gordon & Burton 1976; Sodroski et al. 1987; Nakanishi & Sofue 2003 and their serial papers; Duarte-Cabral et al. 2015). Whereas, most works often discuss its global distribution (e.g., Burton et al. 1975), only a few have focused on the individual arm (e.g., Grabelsky et al. 1987). Now we present our results of the Outer arm gas distribution.

Figure 8 shows the Outer arm H\textsc{i} surface density distribution (or column density distribution) along the galactic longitude. Assuming that the 21 cm line is optically thin, the H\textsc{i} surface density is calculated from \(\Sigma_{\text{H}_1} = 1.82 \times 10^{18} m_{\text{H}1} \int T_b (d) V\), and the column density is calculated by the conversion factor of \(1 \textit{M}_\odot \text{pc}^{-2} = 1.25 \times 10^{20} \text{cm}^{-2}\), where \(m_{\text{H}1}\) is the H atom mass, and \(\int T_b d V\) is the integrated intensity. The velocity-integrated range is the pink ribbon shown in Figure 5. Clearly, the H\textsc{i} surface density abruptly descends at \textit{l} \approx 100^\circ, and ascends a little at \textit{l} \approx 120^\circ. The arm-blending region may account for the
sharp drop in \( l = [100, 120]^{\circ} \), but cannot explain the low surface density region of \( l = [120, 155]^{\circ} \). This may suggest that in one spiral arm the gas quantity can largely change. One possible reason may be that: some of the apparent variation in \( H_I \) surface density could arise from colder, optically thick \( H_I \) gas, which is known to be widespread in the outer Galaxy, perhaps overlapping with some of the molecular clouds. (see Knee & Brunt 2001, Strasser et al. 2007, and Gibson 2010).

Using the \( H_I \) surface density and kinematic distance, the \( H \) mass is obtained from the following process. First, since we know the \( H_I \) surface density at every pixel of the \( H_I \) integrated surface density region of \( d < 23 \), \( b = [-3, 5]^{\circ} \), we then can calculate the mean surface density at every square degree. (This step is somewhat like smoothing the integrated map into a one square degree per pixel map.) Second, using the Reid model we calculate the kinematic distance of every square degree, and the mean LSR velocity of the integrated window (namely the pink ribbon of Figure 5) at every galactic longitude is used as the LSR velocity of its corresponding square degree. Third, using the kinematic distance and the surface density we can calculate the \( H_I \) mass in every square degree by \( M_{H_I} = \Sigma_{H_I} d_{HI} \), where \( \Sigma_{H_I} \) and \( d_{HI} \), respectively indicate the surface density and kinematic distance at the corresponding square degree. Figure 9 shows the \( H_I \) and \( H_2 \) mass distribution along the galactic longitude. (Note that \( H_2 \) is different from molecular gas; the latter includes helium.) The bins of \( H_I \) and \( H_2 \) are both 1 galactic longitude degree. The total mass of \( H_I \) in \( l = [63, 155]^{\circ} \), \( b = [-3, 5]^{\circ} \) of the Outer arm is \( \sim 1.4 \times 10^8 M_\odot \). And the total mass of \( H_2 \) in \( l = [100, 150]^{\circ} \), \( b = [-3, 5]^{\circ} \) is \( \sim 2.3 \times 10^8 M_\odot \). Since the observation is not fully covered in \( b \), the mass must be higher. The mean mass ratio of \( H_2 \) to \( H_I \) in \( l = [100, 150]^{\circ} \), \( b = [-3, 5]^{\circ} \) is about 0.1. Figure 10 shows the \( H_I \) and \( H_2 \) mass distributions along the \( Z \) scale in the region of \( l = [100, 150]^{\circ} \), \( b = [-3, 5]^{\circ} \). About 50% of the gas mass is included in \( Z = [0.2, 0.4] \) kpc.

Interestingly, there seems to be a trend in the \( Z \) scale distribution (Figure 10): as the total gas mass becomes large, the \( H_2 \) to \( H_I \) ratio becomes higher. For example, in Figure 10, at \( Z = 0.3 \) kpc, the total gas mass is the largest, and accordingly the \( H_2 \) to \( H_I \) ratio is the highest. On the other hand, at \( Z = 0.1 \) kpc, the gas mass descends and so does the ratio. Also, this trend is visible in the longitude distribution (Figure 9). One possible explanation may be that although the \( H_2 \) distribution is not as diffuse as \( H_I \), once it exists, it contributes a lot to the total mass.

It is necessary to emphasize that we are reporting only the mass of \( H_2 \) traced by detected CO emission. Significant additional \( H_2 \) which CO cannot detect (or say the “CO-dark” \( H_2 \), e.g., Grenier et al. 2005) may also be present. Most of the sight lines plotted in Figure 8 exceed the minimum column density for self-shielding \( H_2 \) (a few times \( 10^{20} \) cm\(^{-2} \); see Snow & McCall 2006 and Sheffer et al. 2008). This is for individual clouds rather than integrated sight lines, but it still seems likely that \( H_2 \) could exist in many sightlines where the total \( H_I \) column is high enough.
that of of H$_2$ (about 7 times thicker, which is not obvious in Figure 7).

The increasing trend of spiral arm thickness with galactocentric radius has been widely observed and accepted. (e.g., Wouterloot et al. 1990; Kalberla & Kerp 2009). Here we detected a similar trend. Assuming a mean distance of 2 kpc, the H\textsc{i} thickness of the Perseus arm is about 200 pc, corresponding to $5\degree$. And as mentioned above, the Outer arm thickness is about 550 pc. Meanwhile, the thickness of the New arm is 400–600 pc (Sun et al. 2015). Obviously the Outer arm is much thicker than the Perseus arm, but is nearly as thick as the New arm. Maybe this provides a little evidence to a trend newly discovered by Honig & Reid (2015) that in the outermost parts of the galaxies some arms become narrow.

5. SUMMARY

Combining 115 GHz $^{12}$CO(1$\rightarrow$0) data ($l = [100, 150]\degree$, $b = [-3, 5]\degree$) of MWISP and 21 cm H\textsc{i} data ($l = [65, 115]\degree$, $b = [-3, 5]\degree$) of CGPS, we present the properties of the Outer arm in the second galactic quadrant of the Milky Way.

(1) Using CO(1$\rightarrow$0), we have detected 481 molecular clouds in total, of which 332 (about 69\%) are newly detected, 457 clouds are identified in the Outer arm, and 24 are identified in the New arm. The parameters of all 481 clouds are summarized in Table 1.

(2) Assuming that the spiral arm is logarithmic spiral, the pitch angle of the Outer arm is fitted by minimizing the chi-square error statistic algorithm, and the result is $\sim 13\degree$.

(3) The total masses of molecular gas and H$_2$ from $l = 100\degree$ to $150\degree$ in the Outer arm are about $3.1 \times 10^9 M_\odot$ and $2.3 \times 10^9 M_\odot$, respectively. And the total mass of H\textsc{i} gas from $l = 63\degree$ to $155\degree$ is about $1.4 \times 10^9 M_\odot$. Since the observation is not fully covered in $b$, the mass must be higher. The mean mass ratio of H$_2$ to H\textsc{i} in $l = [100, 150]\degree$, $b = [-3, 5]\degree$ is about 0.1.

(4) The warp of the Outer arm is obvious. The mean Outer arm thicknesses of H\textsc{i} and H$_2$ are about 550 and 80 pc, respectively, while the scale height of both gases is $\approx 0.3$ kpc.

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REFERENCES

Aalto, S., Hüttemeister, S., Scoville, N. Z., & Thaddeus, P. 1999, ApJ, 522, 165
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 710, 133
Bobylev, V. V., & Bajkova, A. T. 2014, MNRAS, 437, 1549
Bok, B. J. 1959, Obs, 79, 58
Brand, J., & Wouterloot, J. G. A. 1994, A&AS, 103, 503
Brunt, C. M., Kerton, C. R., & Pomerleau, C. 2003, ApJS, 144, 47
Burke, B. F. 1957, AJ, 62, 90
Butler, W. B., Gordon, M. A., Bania, T. M., & Lockman, F. J. 1975, ApJ, 202, 30
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
