The spiral structure in the Solar neighborhood

L.G. Hou

1 National Astronomical Observatories, CAS, Jia-20 Datun Road, Chaoyang District, Beijing 100101, PR China
2 CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences

Correspondence*: L.G. Hou
lghou@nao.cas.cn

ABSTRACT

The spiral structure in the Solar neighborhood is an important issue in astronomy. In the past few years, there is significant progress in observation. The distances for a large number of good spiral tracers, i.e. giant molecular clouds, high-mass star-formation region masers, H II regions, O-type stars and young open clusters, have been accurately estimated, making it possible to depict the detailed properties of nearby spiral arms. In this work, we first give an overview about the research status for the Galaxy’s spiral structure based on different types of tracers. Then the objects with distance uncertainties better than 15% and <0.5 kpc are collected and combined together to depict the spiral structure in the Solar neighborhood. Five segments related with the Perseus, Local, Sagittarius-Carina, Scutum-Centaurus and Norma Arms are traced. With the large dataset, the parameters of the nearby arm segments are fitted and updated. Besides the dominant spiral arms, some substructures probably related to arm spurs or feathers are also noticed and discussed.

Keywords: H II regions – Galaxy: structure – stars: early-type – stars: massive – masers

1 INTRODUCTION

As observers deeply embedded in the Galactic disk, mapping the spiral structure of the Milky Way and understanding its formation and evolution have long been difficult issues in astronomy. Superpositions of multiple structures along the same observed line of sight have to be solved to trace the distribution of matters in our Galaxy. Additionally, the widespread dust in the interstellar medium causes extinction, making the situation more complex. However, because we live in the Milky Way, the positions and kinematics for a large number of objects could be measured with high accuracy, making the Milky Way as the only galaxy in the universe that we can investigate in detail.

Spiral structure is one of the fundamental characteristics of the Milky Way. It has considerable influences on some other research fields, such as the kinematics of nearby stars (e.g. Williams et al., 2013; Hunt et al., 2019; Trick et al., 2021), the Galactic electron-density distribution (Taylor & Cordes, 1993; Yao et al., 2017; Han et al., 2021), the Galactic dust distribution and extinction map (Drimmel & Spergel, 2001; Hottier et al., 2020), and the large-scale magnetic field of the Milky Way (e.g. Han, 2017). There have been quite a few reviews about the global properties of Galaxy’s spiral structure. Foster & Cooper (2010), Xu et al. (2018b) and Shen & Zheng (2020) reviewed previous efforts. Although, disagreements remain in some details, a general consensus that a global spiral pattern exists in the Galactic disk has been achieved.
In this work, we focus on the Solar neighborhood, where the spiral structure can be better understood, because the distances of a large number of nearby objects can be measured accurately. Significant progress has been made in the past few years by taking advantage of the astrometry measurements in radio to optical bands, which enables us to reliably delineate the nearby spiral structure in unprecedented detail.

Morgan et al. (1952, 1953) first delineated three arm segments in the Solar neighborhood with a sample of aggregates of high-luminosity O-A stars in the 1950s. The three segments are now known to be related to the Sagittarius-Carina, Local and Perseus Arms. At that time, these structures were also studied by using different methods (e.g. Thackeray, 1956; Bok, 1964; Bok et al., 1970; Georgelin & Georgelin, 1971), such as, mapping the distribution of HII regions (Courtes et al., 1970), analyzing multiple structures shown in the H1 21 cm line surveys (van de Hulst et al., 1954) or implied in the observational data of other interstellar absorption lines toward background stars (Münch, 1953). In the 1970s, Georgelin & Georgelin (1976) proposed the famous model of the Galaxy’s spiral structure consisting of four major spiral arm segments. The Sun was placed in the inter-arm region between the Perseus Arm and the Sagittarius Arm. Then, the picture of Galaxy’s spiral structure was extended by taking advantage of more observational data of different types of spiral tracers e.g., HII regions (e.g. Downes et al., 1980; Caswell & Haynes, 1987; Russell, 2003; Paladini et al., 2004), molecular clouds (e.g. Cohen et al., 1980, 1985; Hou et al., 2009, Lépine et al., 2011), neutral atomic gas (Simonsen, 1972; Burton, 1973; Levine et al., 2006; Koo et al., 2017), high-mass star-formation region (HMSFR) masers (e.g. Xu et al., 2006; Reid et al., 2009), OB stars (e.g. Miller, 1972; Stothers & Frogel, 1974; de Zeeuw et al., 1999; Wright, 2020), open clusters (e.g. Becker, 1964; Becker & Fenkart, 1970; Janes et al., 1988; Dias & Lépine, 2005) and cepheids (e.g. Fernie, 1968; Majaess et al., 2009). These great efforts enhanced our understanding of the global properties of Galaxy’s spiral structure. For the spiral structure in the Solar neighborhood, Xu et al. (2013) first found that many HMSFR masers with accurate VLBI parallax measurements (Xu et al., 2006) are situated in the Local Arm, indicating that the Local Arm is probably a major arm segment, rather than an inter-arm spur or a branch as has been suggested for a long time. The existence of the Local Arm also challenges the formation mechanism of Galaxy’s spiral structure (Xu et al., 2016), since it would be difficult to explain its existence according to the standard density-wave theory (Yuan, 1969; Shu, 2016), owing to the narrow space between the Sagittarius Arm and Perseus Arm.

In the past few years, there have been significant progress in observations by taking advantage of the VLBI observations in radio band (Reid et al., 2019; VERA Collaboration et al., 2020) and Gaia astrometry measurements in optical band (Gaia Collaboration et al., 2016). Accurate parallaxes and proper motions have been obtained for a large number of HMSFR masers (e.g. Reid et al., 2019). HII regions (e.g. Hou et al., 2021), O-type stars (e.g. Xu et al., 2021), young open clusters (OCs, e.g. Dias et al., 2021) and evolved stars (e.g. Khoperskov et al., 2020). Additionally, many giant molecular clouds (GMCs) have had accurately determined distances based on the multi-wavelength survey data from optical to infrared bands or the astrometric data of foreground/background stars (Yan et al., 2019, Chen et al., 2020). By combining the available data of different types of tracers together, it is now possible to reliably map the detailed spiral structure within about 5 kpc of the Sun.

In this work, we first give an overview about the observational status for each type of spiral tracer, the available dataset of these objects with accurate distances are collected. Then, we combine them together to give a detailed description of the spiral structure in the Solar neighborhood. Conclusions and discussions follow in the last section.
AN OVERVIEW OF SPIRAL TRACERS

Young objects (HMSFR masers, H II regions, massive OB stars and young open clusters etc.) and GMCs are known as good tracers for the Galaxy’s spiral structure (hereafter gas arms). In addition, the spiral structure is imprinted by the distribution of old and evolved stars (hereafter stellar arms). The gas arms and stellar arms in a galaxy are not necessarily coincident with each other. Discovering a large number of spiral tracers widely spread through the Galactic disk, and measuring their distances as accurately as possible are the key to settle the disputes on the spiral structure of our Milky Way Galaxy. In the following, the observational status about GMCs, HMSFR masers, H II regions, OB stars, young OCs and evolved stars are discussed, respectively.

2.1 Giant molecular clouds

Giant molecular clouds are the vast assemblies of molecular gas with masses from \( \sim 10^3 M_\odot \) to \( \sim 10^7 M_\odot \) (e.g. Murray, 2011). They are believed to primarily form in spiral arms (Dobbs & Baba, 2014) and are the nurseries of most young stars in a galaxy. In the Milky Way, GMCs have long been known as good tracers of spiral arms (e.g., Myers et al., 1986; Grabelsky et al., 1988; Hou & Han, 2014). From the wealthy dataset of Galactic CO surveys (see Heyer & Dame, 2015, for a review), a large number of isolated molecular clouds have been identified by different methods (e.g. García et al., 2014; Rice et al., 2016; Miville-Deschênes et al., 2017; Yan et al., 2020a; Duarte-Cabral et al., 2021). For the majority of them, only kinematic distances are known, which depend on the adopted Galaxy rotation curve, the solution of the kinematic distance ambiguity, and deviation from the hypothetic circular rotation. For instance, Duarte-Cabral et al. (2021) compiled a large catalogue of 10,663 molecular clouds in the inner Galaxy. They estimated the kinematic distances for 10,300 clouds after solving the distance ambiguities through different methods. In addition to determining the distances of molecular clouds and then mapping their distribution in the Galactic disk, the other two methods have been used to reveal the Galaxy spiral structure with CO surveys: (1) Deconvolution of the survey data cube (e.g. Pohl, Englmaier, & Bissantz, 2008; Nakanishi & Sofue, 2016); (2) Modelling the observed longitude-velocity (\( l−v \)) maps of CO (e.g. Bissantz, Englmaier, & Gerhard, 2003; Rodriguez-Fernandez & Combes, 2008; Baba, Saitoh, & Wada, 2010; Pettitt et al., 2014, 2015; Li et al., 2021). A detailed review about these two methods can be found in Xu et al. (2018b). As discussed in Xu et al. (2018b), although there have been many efforts, the spiral structure traced by molecular gas is still unclear, primarily due to the large uncertainties of distances. There have been noticeable progress in the past few years, as accurate distances were estimated for a large number of molecular clouds.

With the CO data of the Milky Way Imaging Scroll Painting survey1, the Gaia DR2 parallax and G-band extinction (Gaia Collaboration et al., 2018), Yan et al. (2019) proposed a background-eliminated extinction-parallax method to estimate the distances of molecular clouds. The distance uncertainties of 11 clouds are \( \lesssim 10\% \). With the same method, Yan et al. (2020a) determined the distances for 28 local molecular clouds \( (d < 1.5 \text{kpc}, \text{here} d \text{is the distance to the Sun}) \) in the first Galactic quadrant. The distances for 76 molecular clouds were measured in the second Galactic quadrant by Yan et al. (2020b). Based on a sample of over 32 million stars with colour excesses and Gaia distances, Chen et al. (2019b) constructed new three-dimensional dust reddening maps of the Milky Way. With the maps and the sample of stars, Chen et al. (2020) identified 567 dust/molecular clouds, and estimated their distances by using a dust model fitting algorithm. The typical distance uncertainty is less than 5\%. These clouds are within \( \sim 3 \text{kpc} \) of the Sun. Based on the near-infrared photometry data from the Two Micron All Sky Survey and the Vista Variables in the Via Lactea Survey, Chen et al. (2019a) tracked the extinction of red clump stars.

—

1 http://www.radioast.nsdc.cn/mwisp.php
versus distance profiles of the sightlines towards a sample of molecular clouds from Rice et al. (2016). Distances of 169 GMCs in the fourth Galactic quadrant were obtained.

We collected the data of GMCs from above references. 475 GMCs with masses \(> 10^4 M_\odot\) were obtained. To reliably depict the local spiral structure, only the GMCs with distance uncertainties better than 15\% were adopted. For the distant clouds, we also required that their distance uncertainties are \(< 0.5\) kpc. In total, 427 GMCs with masses from \(10^4 M_\odot\) to \(2.45 \times 10^6 M_\odot\) were left. Their projected distributions on the Galactic disk are shown in Fig. 1a. According to the trigonometric parallax data of HMSFR masers (see Sect. 2.2), Reid et al. (2019) obtained an updated model of Galaxy’s spiral arms, which is plotted in Fig. 1b to make a comparison with the GMC distribution. It is shown that most of these GMCs are distributed within about 3 kpc of the Sun, in the Perseus, Local and Sagittarius-Carina Arms. Some distant GMCs in the fourth Galactic quadrant are probably associated with the Centaurus Arm and the Norma Arm. Along spiral arms, the distribution of GMCs presents some substructures, especially in the regions within about 2 kpc of the Sun. The accuracies of distances ensure that they are probably true features, but their nature (arm spurs or feathers) and properties have not been well studied.

2.2 High-mass star-forming region masers

The early stage of massive star formation is accompanied by the maser emission from molecular species such as OH, CH\(_3\)OH and H\(_2\)O (Fish, 2007). The maser spots are compact and bright, hence are optimal targets for radio interferometric observations. The trigonometric annual parallax measurement with Very Long Baseline Interferometry (VLBI) is the most accurate method for deriving the distances of astronomical objects. In 2006, a pioneer research on measuring the trigonometric parallax of molecular masers was made by Xu et al. (2006), who found a distance of W3(OH) in the Perseus Arm to be 1.95±0.04 kpc. This work opened a new era to accurately reveal the Galaxy’s spiral structure through VLBI measurements. Since then, nearly 200 HMSFRs have had measured trigonometric parallaxes (typical accuracy is about ±0.02 mas) and proper motions, primarily by the Bar And Spiral Structure Legacy (BeSSeL) Survey using the VLBA (Reid et al., 2019) and the Japanese VLBI Exploration of Radio Astrometry (VERA) project (VERA Collaboration et al., 2020). Some sources were observed by the European VLBI Network and the Australian Long Baseline Array (e.g. Rygl et al., 2010; Krishnan et al., 2017). Based on the data of 199 HMSFRs, parameters of spiral arms in about one third of the Galactic disk were updated by Reid et al. (2019), which is adopted in Fig. 1b to make a comparison with the data distribution.

To depict the local spiral arms with high confidence, only the HMSFRs (Reid et al., 2019; VERA Collaboration et al., 2020) with uncertainties of trigonometric distances better than 15\% were kept as for GMCs. For the distant sources, we also required that their distance uncertainties are \(< 0.5\) kpc. Then, 111 HMSFRs remain. Their distribution is given in Fig. 1b. These HMSFRs are located in six arm segments, i.e. the Outer, Perseus, Local, Sagittarius, Scutum and Norma Arms. Some of the HMSFRs are probably related with spur-like structures in the inter-arm regions (Reid et al., 2019). A prominent one is the spur branching the Sagittarius Arm and the Local Arm near \(l \sim 50^\circ\) (see Fig. 1b), which is firstly identified by Xu et al. (2016).

As shown in Fig. 1b, the HMSFRs with parallax measurements are distributed in the regions covering about one-third of the entire Galactic disk. There is a lack of observational data for many Galaxy areas, especially in the longitude range of \(\sim 240^\circ – 360^\circ\). Other spiral tracers (e.g. GMCs, H\(_\II\) regions, massive OB stars, and young OCs) could be good complementary data, which can help us to better depict the properties of spiral arms in the Solar neighborhood.
Figure 1. Distributions of (a) GMCs, (b) HMSFR masers, (c) H II regions, (d) O-type stars and (e) young OCs in the Solar neighborhood. All of the plotted objects have distance uncertainties better than 15% and <0.5 kpc as determined by trigonometric or photometric method. The symbol sizes of GMCs are proportional to their masses. For HMSFR masers, H II regions and O-type stars, an equal size of the dots is adopted. The symbol sizes of young OCs are proportional to the number of cluster member stars. The position uncertainty for each data point is shown by an underlying gray line segment. The thick gray curved lines indicate the best fitted spiral arm model given by [Reid et al. 2019], the dotted lines denote the arm widths enclosing 90% of the HMSFR masers. The black dashed lines indicate the four spurs or spur-like structures proposed in literature (see Sect. 3.3). In each plot: the segments of spiral arms are labelled; the Sun is at (0.0, 8.15) kpc [Reid et al. 2019], while the Galactic center is at (0.0, 0.0) kpc; the Galactic long bar is indicated by a shaded ellipse [Wegg, Gerhard, & Portail, 2015].
2.3 H\textsc{ii} regions

H\textsc{ii} regions are the regions of ionized gas surrounding recently formed O- or early B-type stars or star clusters. They have been widely detected in the Galactic disk, from the Galactic center (GC) region (Shahzamanian et al., 2019) to the far outer Galaxy (Galactocentric distances >16 kpc, Anderson et al., 2015). As indicators of early evolutionary stage of massive stars, H\textsc{ii} regions have long been known as one of the primary tracers of spiral arms, and helped us to construct the commonly used picture of Galaxy’s spiral structure (e.g., Georgelin & Georgelin, 1976; Caswell & Haynes, 1987; Russeil, 2003; Hou et al., 2009; Hou & Han, 2014). However, for the majority of known H\textsc{ii} regions, only kinematic distances are available, which sometimes have large uncertainties. It is currently the major obstacle for using H\textsc{ii} regions to accurately delineate the spiral arms. There are about 400 H\textsc{ii} regions with measured spectra-photometric (Russeil, 2003; Moisés et al., 2011; Foster & Brunt, 2015) or trigonometric distances (e.g., Xu et al., 2006; Honma et al., 2012). They are distributed within about 5 kpc of the Sun (Hou & Han, 2014). The sample size and the accuracies of distances have yet to be improved.

In a recent work (Hou et al. 2021), we carried out a cross-match between the WISE H\textsc{ii} regions (Anderson et al., 2014) and the known O- or early B-type stars (Chen et al., 2019a; Xu et al., 2021). The ionizing stars of 315 H\textsc{ii} regions were identified. The trigonometric parallaxes for these OB stars from the Gaia Early Data Release 3 (Gaia EDR3, Gaia Collaboration et al., 2020) were used to estimate the distances of H\textsc{ii} regions. In combination with the H\textsc{ii} regions with known spectra-photometric/trigonometric distances, we obtain a sample of 448 H\textsc{ii} regions with accurately determined distances, i.e. distance uncertainties are better than 15% and less than 0.5 kpc. Their distribution in the Galactic disk resembles GMCs and HMSFR masers as presented in Fig. 1c.

These H\textsc{ii} regions are scattered primarily in the Perseus, Local, Sagittarius-Carina and Scutum-Centaurus Arms. The data distribution in the Local Arm and Centaurus Arm deviate from the modelled spiral arms given by Reid et al. (2019) in the 3rd and 4th Galactic quadrants, where the HMSFRs with trigonometric measurements are largely absent. Hence, the extension of the Local Arm and the position of the Centaurus Arm given by Reid et al. (2019) need to be updated. In these arm segments, we also noticed that the H\textsc{ii} regions are not uniformly distributed, but present some substructures. The Sagittarius-Carina Arm is not continuous in the direction of $l \sim 315^\circ - 340^\circ$. Similar property is found for the Perseus Arm in the longitude range of $\sim 150^\circ - 160^\circ$. These properties are consistent with the features illustrated by GMCs (Fig. 1a). Although the number of H\textsc{ii} regions with accurate distances have been increased largely, there is still a lack of accurate distances for many Galactic H\textsc{ii} regions. From Gaia EDR3 or their future data release, it is expected to identify more ionising stars and determine the distances of H\textsc{ii} regions as accurately as possible.

2.4 OB stars

The massive and bright O- and early B-type (OB) stars are born in dense molecular clouds. Many of them are not randomly distributed, but concentrated in loose groups, named as “aggregates” (Morgan et al., 1953) or OB associations (de Zeeuw et al., 1999; Wright, 2020). In the early 1950s, substantial progress on tracing the arm segments in the Solar neighborhood was first made by Morgan et al. (1952, 1953). Three segments of spiral arms (i.e., the Sagittarius, Local and Perseus Arms) appeared in the distribution of their twenty-seven aggregates of O-A stars and additional eight distant stars. After that, some follow-up studies identified more OB stars or OB associations, and determined their spectra-photometric distances (e.g., Walborn, 1971; Miller, 1972; Stothers & Frogel, 1974; Reed & Reed, 2000). However, the picture of Morgan did not expand significantly. With the Hipparcos catalog, de Zeeuw et al. (1999) estimated the trigonometric distances for some OB associations within $\sim 1$ kpc from the Sun, primarily in the Local Arm.
At present, the known OB associations are limited within about \( \sim 2 \) kpc from the Sun (Wright, 2020). To extend the nearby arm segments traced by OB stars or OB associations, higher accuracies of astrometry measurements than the Hipparcos (typical parallax error \( \sim 1 \) mas, de Zeeuw et al., 1999) are needed.

The Gaia satellite (Gaia Collaboration et al., 2016), launched in 2013, will ultimately achieve parallax accuracy comparable to that of VLBI for approximately \( 10^9 \) stars. Many OB stars with accurate distances can be derived from Gaia. By taking advantage of the Gaia data release 2, Xu et al. (2018a) depicted the spiral structure within \( \sim 3 \) kpc of the Sun. About 2,800 O-B2 stars with formal parallax uncertainties better than 10\% were extracted from the Catalog of Galactic OB stars (Reed, 2003). The spiral structure demonstrated by the Gaia OB stars agrees well with that illustrated by the VLBI HMSFR masers. These OB stars also extend the arm segments traced by HMSFR masers into the fourth Galactic quadrant. Chen et al. (2019a) identified 6,858 candidates of O- and early B-type stars. Together with the known spectroscopically confirmed O-B2 stars from literature, a sample of 14,880 OB stars/candidates with Gaia DR2 parallax uncertainties better than 20\% was obtained, and used to delineate the arm segments in the Solar neighborhood. Recently, Gaia published its Early Data Release 3, the parallax accuracies have been improved significantly, to be 0.02–0.07 mas for \( G < 17 \). In a recent work, Xu et al. (2021) compiled the largest sample of spectroscopically confirmed O-B2 stars (Skiff, 2014) available to date with astrometric measurements of Gaia EDR3, including 14,414 O-B2 stars. 9,750 of them have parallax uncertainties better than 10\%. With this sample, the spiral structure within \( \sim 5 \) kpc of the Sun are delineated in detail.

In this work, the sample consisting of about 1,090 O-type stars given by Xu et al. (2021) is adopted. Their distribution in the Galactic disk is shown in Fig. 1d. As discussed in Xu et al. (2021), the distribution of O-type stars in spiral arms are clumped. The Sagittarius-Carina Arm traced by O-type stars seems to be not continuous in the direction of \( l \sim 315^\circ - 340^\circ \). A gap of O-type stars in the range of \( l \sim 150^\circ - 160^\circ \) in the Perseus Arm is also noticed. These properties are consistent with the results shown by using GMCs and H\( \text{II} \) regions.

### 2.5 Young open clusters

An open cluster is a group of stars that formed in a giant molecular cloud. In comparison to individual stars, it is possible to estimate more accurate values of distance, proper motions and radial velocity for an OC, as it has many member stars. In our Galaxy, star formation occurs mainly in spiral arms. Hence, the majority of young OCs are believed to be borned in spiral arms, and too young to migrate far from their birth locations. It is accepted that young OCs (e.g. \(< 20 \) Myr) can be used as good tracers for the nearby spiral arm segments. In comparison, older OCs have more scattered distribution.

Becker (1963, 1964) first used 156 OCs to study the spiral structure in the Solar neighborhood. They suggested that the distribution of those clusters with earliest spectral type between O and B2 follows three spiral arm segments. In comparison, the distribution of the clusters with earliest spectral type between B3 and F does not present arm-like structures and seems to be random. The picture was extended by Becker & Fenkart (1970) and Fenkart & Binggeli (1979). Meanwhile, a different point of view raised by Janes & Adler (1982) and Lynes (1982) with a large sample of about 400 open clusters. They suggested that the observed nonuniform distribution of OCs is affected by the interstellar obscuration, and dominated by the locations of dust clouds rather than by the spiral structure. Janes et al. (1988) mentioned that the young clusters define three complexes, but their association to a spiral structure is not obvious. After that, the number of Galactic open clusters gradually increased (e.g., see Mermilliod, 1995; Dias et al., 2002; Kharchenko et al., 2013; Schmeja et al., 2014; Scholz et al., 2015). Meanwhile, the spiral structure of the Milky Way was better uncovered by multi-wavelength observations (e.g., Georgelin & Georgelin, 1976; Caswell & Haynes, 1987; Dame, Hartmann, & Thaddeus, 2001; Russell, 2012).
especially in radio band, where the dust obscuration has negligible influence on the results. There has been a general consensus that the nonuniform distribution of nearby OCs is related to spiral arms (e.g., Dias & Lépine, 2005; Carraro et al., 2005; Moitinho, 2006; Vazquez, 2008; Moitinho, 2010; Camargo et al., 2013; Bobylev & Bajkova, 2014; Dias et al., 2019).

Before the data release of Gaia, there have been more than 3,000 known OCs (e.g., see, Dias et al., 2002; Kharchenko et al., 2013; Dias et al., 2014; Schmeja et al., 2014; Scholz et al., 2015). Many of them have determined mean proper motions and membership probabilities (Sampedro et al., 2017; Dias, Monteiro, & Assafin, 2018). Since the publication of Gaia DR2 (Gaia Collaboration et al., 2018), on the one hand, the parameters of known OCs have been updated (Cantat-Gaudin et al., 2018; Soubiran et al., 2018; Bossini et al., 2019; Monteiro & Dias, 2019; Cantat-Gaudin & Anders, 2020; Cantat-Gaudin et al., 2020; Tarricq et al., 2021; Dias et al., 2021). On the other hand, a large number of new OCs and candidates have been identified (e.g., see Castro-Ginard et al., 2018; Cantat-Gaudin et al., 2019; Castro-Ginard et al., 2020; Ferreira et al., 2020; He et al., 2020; Hunt & Reffert, 2021; Ferreira et al., 2021). With OCs, the nearby spiral arms were studied by Cantat-Gaudin et al. (2018, 2019), Cantat-Gaudin et al. (2020), Tarricq et al. (2021), and Ferreira et al. (2021) in the past few years. Especially, Monteiro et al. (2021) studied the spiral arms traced by young OCs with the updated OC catalogue of Dias et al. (2021), and determined the spiral pattern rotation speed of the Galaxy, the corotation radius and the statistic properties of OC parameters. Poggio et al. (2021) studied the spiral structure in the Solar neighborhood with samples of young upper main sequence stars, classical Cepheids and open clusters. The open clusters used by Poggio et al. (2021) is from Cantat-Gaudin et al. (2020). Hao et al. (2020) compiled a catalogue of more than 3,700 OCs from the references above, and recalculated the parameters (parallaxes, mean proper motions, radial velocities) based on the latest Gaia EDR3 (Gaia Collaboration et al., 2020). The ages of these OCs were either collected from references or estimated by their analysis.

In this work, we adopted the OC sample provided by Hao et al. (2021), in which the OC parameters are based on the latest Gaia EDR3. There are 627 young OCs (ages < 20 Myr) in their catalogue. The distribution of young OCs in the Galactic disk is shown in Fig. 1e. The distribution of young OCs resembles that of GMCs, HMSFR masers, H II regions and O-type stars. When weighted the OCs with their number of member stars, one can notice that the OCs with more member stars are more inclined to be located in spiral arms.

2.6 Evolved stars

As the velocity dispersion of gas is smaller than that of the old stars, the gas response to any perturbations in the stellar disk is highly amplified (Dobbs & Baba, 2014), making the gas arms easier to identify than the stellar arms traced by old and evolved stars. For our Milky Way, unlike the gas arms well depicted by GMCs, HMSFR masers, H II regions, young OB stars or young OCs, the spiral arms traced by old stars are still not clear. The properties of stellar arms are important to better constrain the formation and evolution of gas arms.

It is commonly suggested that the spiral structure traced by old stars is dominated by two major spiral arms (the Scutum-Centaurus Arm and Perseus Arm) based on analyzing the arm tangencies (Churchwell et al., 2009). In observations, spiral arm tangencies are indicated by the local maxima in the integrated number count of old stars or in the integrated emission in the near-infrared and/or far-infrared bands against the Galactic longitude, and have only been clearly identified for the Scutum-Centaurus Arm (Drimmel, 2000; Drimmel & Spergel, 2001; Churchwell et al., 2009). Clear indications
of tangencies corresponding to the stellar Sagittarius-Carina Arm and Norma Arm have not been found from observational data. As the Sun is located inside the Perseus Arm, the observed line of sight do not penetrate its tangency. The method of analyzing tangency points cannot be applied to this arm. However, the Perseus Arm is also suggested to be a major stellar arm based on symmetry. Indeed, many grand-design spiral galaxies with two well defined spiral arms are observed in the universe (e.g. Willett et al., 2013). In comparison, arm tangencies for the gaseous Sagittarius-Carina Arm, Scutum-Centaurus Arm and Norma Arm could be identified from the wealthy survey data of radio recombination lines, H II regions, CO lines, dense molecular clumps and H I 21-cm line etc. (see Hou & Han, 2015).

By taking advantage of the data quality and large sky coverage of Gaia, it is possible to map the nearby spiral structure traced by evolved stars. Miyachi et al. (2019) studied the surface density distribution of stars aged \( \sim 1 \) Gyr, and identified a marginal arm-like overdensity in the longitude range of \( 90^\circ \leq l \leq 190^\circ \). The overdensity of stars is close to the Local Arm defined by HMSFRs. By analyzing the Gaia DR2 data, Kounkel & Covey (2019) identified a number of clusters, associations, and moving groups

---

**Figure 2.** Distributions of the combined dataset of GMCs (yellow circles), HMSFR masers (blue dots), H II regions (red dots), O-type stars (green dots) and young OCs (yellow dots) are overlaid on a new concept map of the Milky Way, which is credited by: Xing-Wu Zheng & Mark Reid BeSSeL/NJU/CFA based on the spiral arm model of Reid et al. (2019).
distributed within \(\sim 1\) kpc of the Sun, many of them appear to be filamentary or string-like. The youngest strings (\(< 100\) Myr) are orthogonal to the Local Arm. The older ones are suggested to be the remnants of several other arm-like structures which cannot be traced by dust and gas any more. With a new method of analyzing the six-dimensional phase-space data of Gaia DR2 sources, Khoperskov et al. (2020) identified six prominent stellar density structures in the guiding coordinate space, corresponding to a physical spatial coverage of about 5 kpc from the Sun. Four of these structures were suggested to correspond to the Scutum-Centaurus, Sagittarius, Local, and Perseus Arms, while the remaining two may be associated with the main resonances of the Milky Way bar and the outer Lindblad resonance beyond the Solar circle. While Hunt et al. (2020) presented a different point of view. They suggested that the stellar density structures identified by Khoperskov et al. (2020) are known kinematic moving groups, rather than coherent structure in physical space such as spiral arms. In addition, it has also been shown that very different bar and spiral arm models can be tuned to explain the observed features of Gaia data (e.g. Hunt et al., 2019; Monari et al., 2019; Eilers et al., 2020; Khoperskov et al., 2020; Chiba et al., 2021; Trick et al., 2021), making the situation more difficult to handle.

In the past few years, progress in mapping the stellar arms in the Solar neighborhood have been made, but there are no conclusive observational results. As the properties of nearby stellar arms are not clear, we do not incorporate them into our analysis/discussions in the following. But we emphasise that determination of the properties of stellar arms in our Galaxy definitely deserves more attention.

## 3 PROPERTIES OF SPIRAL STRUCTURE IN THE SOLAR NEIGHBORHOOD

In order to better reveal the properties of spiral structure in the Solar neighborhood, we combine the data of good tracers of gas arms, i.e. GMCs, H\(\text{II}\) regions, O-type stars and young OCs. It is probably the most wide spread dataset of spiral tracers with accurate distances available to date. Especially, the data distributions of different types of tracers are complementary to each other in the sky coverage. As shown in Fig. 1 and Fig. 2, although some substructures seem to exist in spiral arms or inter-arm regions, the distributions of these objects are in general follow the dominant spiral arms identified by previous works (e.g. Georgelin & Georgelin, 1976; Russel, 2003; Hou & Han, 2014; Reid et al., 2019). Five segments of spiral arms are delineated by the combined dataset. They are related to the Perseus, Local, Sagittarius-Carina, Scutum-Centaurus and Norma Arms from outer Galaxy to the GC direction. Additionally, there are about 30 sources possibly scattered in the Outer Arm defined by HMSFR masers. However, the aggregation of sources is not obvious. We will not discuss the Outer Arm in this work.

### 3.1 Fitting model to tracer distributions

From the combined dataset of spiral tracers (Fig. 1 and Fig. 2), some noticeable features are the deviations of tracer distributions from the modelled spiral arms given by Reid et al. (2019) in the 3rd and 4th Galactic quadrants, where the HMSFRs with trigonometric measurements are largely absent. For instance, many O-type stars and young OCs in the longitude range of \(l \sim 210^\circ \sim 260^\circ\) deviate from the modelled Perseus Arm towards the GC direction. Similar feature is found for the Local Arm in the longitude range of \(l \sim 260^\circ \sim 280^\circ\). In the 4th quadrant, many GMCs, H\(\text{II}\) regions and O-type stars near \(l \sim 300^\circ \sim 350^\circ\) deviate slightly from the modelled Centaurus Arm of Reid et al. (2019) towards the anti-GC direction. Hence, with the combined dataset, it would be helpful to update the parameters of spiral arms in the Solar neighborhood.

---

\(^2\) The “guiding coordinate space” is defined as (please see Khoperskov et al., 2020 for a detail): \(X_g = -R_g \sin(\psi), Y_g = -R_g \cos(\psi)\), here, \(R_g = L_z / V_{LSR}\) is the guiding radius, \(L_z = R \times V_\phi\) is the instantaneous angular momentum of the star, \(R\) is the Galactocentric distance, \(\psi\) is the azimuthal angle around the Galactic center clockwise from the direction towards the Sun, \(V_\phi\) is the azimuthal velocity in the Galactic plane.
Figure 3. Upper: Distributions of the combined dataset of GMCs, HMSFR masers, HII regions, O-type stars and young OCs in the Galactic disk. For all the plotted sources, their distance uncertainties are better than 15% and smaller than 0.5 kpc. The positional uncertainty for each data point is shown by an underlying gray line segment. The curved solid lines indicate the best fitted spiral arm model given by this work (Table 1). The shaded areas around spiral arms denote the fitted arm widths. The four dashed lines are the spurs or spur-like structures proposed in literature. Lower: similar to the upper panel, but a “density” distribution is calculated according to the distribution of the sources.
Figure 4. Best fitted spiral arm model given by this work (Table 1) are overlaid on the $l-v$ diagram of 12CO (1−0) of Dame, Hartmann, & Thaddeus (2001). The spiral arm segments are indicated by different colors. To convert the position of spiral arms into the $l-v$ diagram, the fitted “universal” form of Galaxy rotation curve given by Reid et al. (2019) was adopted. The distance of the Sun to the GC, $R_0$, is taken as 8.15 kpc. The circular orbital speed at the Sun $\Theta_0$ is 236 km s$^{-1}$ (Reid et al., 2019).

The spiral arms observed in spiral galaxies (e.g. Seigar & James, 1998; Yu et al., 2018) and that predicted by the density-wave theory (e.g. Lin & Shu, 1964; Shu, 2016) are approximately in the form of logarithmic, which is characterized by a constant pitch angle. A simple and pure logarithmic form of spiral arm was commonly adopted in previous works about the Galaxy’s spiral structure (e.g. Russell, 2003; Hou et al., 2009; Vallée, 2008; Reid et al., 2009). On the other hand, it is found that the spiral arms in galaxies do not follow logarithmic spirals perfectly, but seem to be kinked in nature (e.g. Kennicutt, 1981; Kendall, Kennicutt, & Clarke, 2011; Honig & Reid, 2015; Díaz-García et al., 2019, also see the Whirlpool Galaxy M 51). The observed spiral arms can be better described by segments of logarithmic form with different pitch angles. In theories, tidal interactions can result in noticeable kinks along spiral arms in a galaxy (Dobbs & Baba, 2014). In simulation, D’Onghia, Vogelsberger, & Hernquist (2013) found that the perturbers can produce segments, and these segments are joined at kinks to form spiral arm. For our Milky Way Galaxy, signs of kinked spiral arms were also noticed (e.g. Taylor & Cordes, 1993; Hou & Han, 2014), as some of the spiral arms cannot be well fitted by pure logarithmic spirals (e.g. the Sagittarius-Carina Arm). With pure logarithmic spirals, it is also difficult to reproduce the observed $l-v$ maps of CO and HI for the outer Milky Way (e.g. Pettitt et al., 2014). Following Reid et al. (2019), in this work we adopt a form of kinked logarithmic spiral to fit an arm, which do not necessarily have a constant pitch angle.

We allow one or two “kinks” in an arm, which means that two or more segments with different pitch angles are used to describe a single spiral arm. For the $i$th spiral arm, the form is described as:

$$\ln(R/R_{i,kink}) = -(\beta - \beta_{i,kink}) \tan \psi_i,$$

(1)

here, $R$ is the Galactocentric radius at a Galactocentric azimuth angle $\beta$. Following Reid et al. (2019), $\beta$ is defined as 0° toward the Sun and increases in the direction of Galactic rotation. $R_{i,kink}$ and $\beta_{i,kink}$ are the corresponding values of $R$ and $\beta$ at the “kink” position for the $i$th arm. $\psi_i$ is the pitch angle, which may have an abrupt change at the “kink” position. To be consistent with Reid et al. (2019) and compare the results with their models, a Markov chain Monte Carlo (MCMC) approach is adopted in this work to estimate the arm parameters. The best-fitted arm parameters are listed in Table 1 and the model is shown...
in Fig. 3. We also compare it with the observed $l - v$ diagram of CO (Dame, Hartmann, & Thaddeus, 2001) as given in Fig. 4. In the fitting with the combined dataset, an equal weight is adopted, although the sky coverage and sample size for different types of tracers are not the same. Different treatments of weighting parameters were tested, e.g., scaling according to the sample size of different types of tracers, but the differences of the fitted arm positions were found to be small.

In comparison with the best-fitted model of Reid et al. (2019), the extension of the Perseus Arm obtained in this work spirals slightly inward in the third Galactic quadrant. In this work, the Local Arm is best fit with two segments having different pitch angles, and spirals inward to the inner Galaxy regions in the third to fourth Galactic quadrants to match the observational data. The Centaurus Arm in the fourth quadrant is also fit with two segments in this work. Their positions are slightly different from those of Reid et al. (2019) near $l \sim 300^\circ - 350^\circ$ but match the distributions of the collected GMCs, H II regions, O-type stars and young OCs. For the Sagittarius-Carina Arm and the Norma Arm, our fitted arm positions are in general consistent with that of Reid et al. (2019).

To evaluate that how well do the different types of tracers fit the spiral arms, we calculate the percentages of tracers falling into our best fitted spiral arms. The arm widths given in Table 1 were adopted to denote the spiral arm regions. In the Norma Arm, the known HMSFR masers, H II regions, O-type stars and young OCs are still rare. This arm was not used in the calculation. Additionally, the Outer Arm was also omitted. The percentages of tracers falling into spiral arms are estimated to be 44%, 53%, 58%, 65% and 53% for the GMCs, HMSFR masers, H II regions, O-type stars and young OCs, respectively. It seems that the GMCs are less confined to the spiral arms than the other types of tracers. In comparison, if the objects are randomly distributed in the Solar neighborhood, about 33% of them are expected to be in the spiral arms.

### 3.2 Spiral arms in the Solar neighborhood

By taking advantage of the combined dataset of different types of tracers, segments of spiral arms in the Solar neighborhood have been delineated and fitted. Now we discuss their properties in detail.

**Perseus Arm:** The Perseus Arm is a dominant arm in our Galaxy as indicated by high-mass star-formation activity (HMSFR masers, H II regions, O-type stars), young OCs, molecular gas and H I gas (e.g. Morgan et al., 1953; Caswell & Haynes, 1987; Russell, 2003; Hou & Han, 2014; Reid et al., 2019). Additionally, the Perseus Arm has been suggested as one of the two dominant stellar arms of the Milky Way (Drimmel, 2000; Drimmel & Spergel, 2001; Churchwell et al., 2009). As shown in Fig. 3, different types of spiral tracers (GMCs, HMSFR masers, H II regions, O-type stars and young OCs) are mixed together. Their distributions are in general consistent with each other. The depicted Perseus Arm is as long as $\sim 12$ kpc, starts near $(X,Y) = (4.5, 8)$ kpc, and extends to the third Galactic quadrant near $(X,Y) = (-6, 9)$ kpc. In this arm, the spiral tracers are not evenly distributed but tend to cluster. There are two obvious aggregation areas of sources, one is in the longitude range of $l \sim 100^\circ - 150^\circ$, the other is in $l \sim 170^\circ - 190^\circ$, indicating the active star-formation areas in the Perseus Arm. Outside these two regions, some sites of GMCs or star-formation are scattered, and interspersed with regions showing low star-formation activity and/or low number density of GMCs. Outside the segment shown in Fig. 3, the extension of the Perseus Arm to the first or fourth Galactic quadrant could be explored in the $l - v$ diagram of CO and H I survey data, but have not been accurately depicted (Xu et al., 2018b; Reid et al., 2019) has suggested that the Perseus Arm may be not a dominant arm as measured by high-mass star-formation activity over most of its length. More spiral tracers with accurate distances are needed in order to reliably trace this arm to distant Galaxy regions.
**Local Arm:** The Local Arm was thought to be a “spur” or secondary spiral feature for a long time (e.g. Georgelin & Georgelin, 1976; Amaral & Lepine, 1997; Russell, 2003), until the density of HMSFRs in the Local Arm was found to be comparable to that of the Sagittarius Arm and Perseus Arm (Xu et al., 2013, 2016). The Local Arm traced by HMSFR masers stretches for >6 kpc, which is larger and more prominent than previously thought. Hence, it is suggested to be a dominant arm segment. As shown in Fig. 3, there are a large number of spiral tracers (GMCs, HMSFR masers, HII regions, O-type stars and young OCs) located in this arm, which present complex substructures. There are several areas where sources are accumulated. One is near (X,Y) = (1.5, 7.7) kpc in the first Galactic quadrant, another is near (X,Y) = (−2, 8.2) kpc in the fourth quadrant. A filament-like structure appears in the region from (X,Y) = (2, 7.5) kpc to (X,Y) = (0.8, 9) kpc, and spirals outward toward the anti-GC direction with respect to the fitted arm center. Interestingly, a substructure near $l \sim 100^\circ - 150^\circ$ and with $d \sim 0.6$ kpc is indicated by many GMCs, but without associated HMSFR masers, HII regions, O-type stars or young OCs, at least shown by the collected dataset. For the majority of sources in this arm, their distance uncertainties are less than 10%, hence, these substructures are believed to be true features. In general, the depicted Local Arm could be as long as $\sim 9$ kpc, starts near (X,Y) = (4.5, 6) kpc, and extends to the third and even fourth quadrant near (X,Y) = (−3, 8) kpc. Outside the delineated segment, the extension of the Local Arm is still not clear. The Local Arm seems to gradually spiral inward in the fourth Galactic quadrant, becoming very close to the Carina Arm. **It is indicating that the Local Arm is possibly an arm branch locating between the Perseus Arm and the Sagittarius-Carina Arm.** More observational data are needed to uncover its nature.

**Sagittarius-Carina Arm:** This arm can be clearly traced by GMCs (Grabelsky et al., 1988) and massive star-formation regions (Russell, 2003; Urquhart et al., 2014; Hou & Han, 2014). There are a large number of sources in this arm. The Sagittarius-Carina Arm in Fig. 3 starts near (X,Y) = (4.5, 4) kpc, extends to the fourth quadrant near (X,Y) = (−7, 5) kpc, as long as $\sim 19$ kpc. It is found that this arm cannot be well fitted by a single pitch angle model, especially in the longitude range of $20^\circ - 40^\circ$ (e.g. Taylor & Cordes, 1993; Russell, 2003; Hou & Han, 2014; Reid et al., 2019). Three major aggregation areas of sources are noticed. One is near $l \sim 30^\circ$, showing an elongated structure, which is probably a true feature as it is not only traced by HMSFR masers, but also by HII regions, O-type stars or young OCs. The other two areas are near $l \sim 340^\circ - 360^\circ$ and close to the tangent region of the Carina Arm ($l \sim 280^\circ - 290^\circ$). The distribution of sources in this arm is well consistent with the model given by Reid et al. (2019). Outside the long segment traced in Fig. 3, the extension of the Sagittarius-Carina Arm could be well delineated by the distribution of GMCs or HII regions with kinematic distances, or indicated by the features shown in the $l - v$ diagrams of CO and H1.

**Scutum-Centaurus Arm:** Similar to the Sagittarius-Carina Arm, the Scutum-Centaurus Arm has also been traced by many GMCs and massive star-formation regions. In addition, it is also suggested to be one of the two dominant stellar spiral arms of the Milky Way, as the Centaurus Arm tangent was clearly shown by the evolved stars surveyed by Spitzer (Drimmel, 2000; Drimmel & Spergel, 2001; Churchwell et al., 2005). The collected GMCs, HII regions, O-type stars and young OCs enrich the sample of spiral tracers in this arm, especially in the fourth Galactic quadrant. As shown in Fig. 3 the spiral tracers in this arm seem to be more evenly distributed than that of the Perseus Arm, Local Arm and Sagittarius-Carina Arm. The traced segment of the Scutum-Centaurus Arm starts near (X,Y) = (2.5, 4) kpc, and extends to the fourth Galactic quadrant near (X,Y) = (−5, 4.5) kpc, as long as $\sim 8$ kpc.
Table 1. Parameters of the best-fitted model of spiral arms (see Eq. 1) with the combined dataset of GMCs, HMSFR masers, H\textsc{ii} regions, O-type stars and young OCs. For the $i$th spiral arm, $\beta$ Range in column (2) gives the range of the arm segment as shown in Fig. 3. $\beta$ is the Galactocentric azimuth angle, which is defined as $0^\circ$ toward the Sun and increases in the Galactic rotation direction. $\beta_{kink}$ and $R_{kink}$ in column (3) and (4) are the corresponding values of $\beta$ and $R$ at the “kink” position, here $R$ is the Galactocentric radius. The pitch angle is $\psi_<$ for $\beta < \beta_{kink}$, and $\psi_>$ for $\beta > \beta_{kink}$. The fitted arm width is listed in column (7).

| Arm                  | $\beta$ Range (deg) | $\beta_{kink}$ (deg) | $R_{kink}$ (kpc) | $\psi_<$ (deg) | $\psi_>$ (deg) | Width (kpc) |
|---------------------|---------------------|----------------------|------------------|----------------|----------------|-------------|
| Perseus             | $-28 \rightarrow 28$ | 32.7                 | 9.57             | 3.9            | 19.9           | 0.26        |
| Local               | $-22 \rightarrow 39$ | $-2.0$               | 8.46             | 4.4            | 12.6           | 0.23        |
| Sagittarius-Carina 1| $-57 \rightarrow 17.5$ | $-22.8$             | 7.92             | 11.9           | 22.2           | 0.33        |
| Sagittarius-Carina 2| $17.5 \rightarrow 48$ | 17.5                 | 5.95             | 21.3           | 0.2            | 0.25        |
| Scutum-Centaurus    | $-50 \rightarrow 41$ | $-26.3$              | 6.47             | $-0.5$         | 16.5           | 0.25        |
| Norma               | $-38 \rightarrow 18$ | 18.0                 | 4.5              | 1.3            | 19.0           | 0.07        |

**Norma Arm:** This arm is distant ($\gtrsim 4$ kpc) from the Sun, and most likely starts near the near end of the Galactic bar. Previously, the Normal Arm has not been clearly traced by GMCs or massive star-formation regions. Mainly because the majority of spiral tracers possibly associated with this arm only have kinematic distances. With the collected dataset, it seems that only a segment of the Norma Arm can be roughly traced by GMCs in the fourth Galactic quadrant. The number of HMSFR masers, H\textsc{ii} regions, O-type stars or young OCs related to this arm is still very limited.

### 3.3 Substructures in the spiral arms or inter-arm regions

Besides the extended structure of major spiral arms which probably wrap fully around the Milky Way, substructures named as branches, spurs and features are often observed in spiral galaxies (Elmegreen, 1980; Dobbs & Bonnell, 2006). As discussed in La Vigne, Vogel, & Ostriker (2006) and Dobbs & Baba (2014), there are no formal definitions of these different types of substructures in observations and/or numerical simulations. Different definitions have been adopted (Chakrabarti, Laughlin, & Shu, 2003; Dobbs & Bonnell, 2006). The initial definitions based on observations are as follows: (1) arm branches are in general the structures locating between two major spiral arms, and/or where one arm bifurcates into two, branches may extend from one arm to another (Elmegreen, 1980; La Vigne, Vogel, & Ostriker, 2006; Dobbs & Baba, 2014). (2) Spurs are shorter features than branches, and indicated by strings of star formation sites in the inter-arm regions. They jut out from spiral arms into the inter-arm regions at larger pitch angles than the arm itself (Weaver, 1970; Elmegreen, 1980). Two or more spurs are commonly found to be close or parallel to one another. (3) Feathers are also short features, but indicated by thin dust lanes or extinction features that cut across spiral arms and have large pitch angles. Outside the luminous arms, these extinction features become mostly undetectable (Lynds, 1970). Arm branches, spurs and features are typically extend away from the trailing side of spiral arms (e.g. M 51, Dobbs & Baba, 2014).

As shown in Fig. 3, the objects in spiral arms are not uniformly distributed, resulting in the patchy and/or bifurcate appearance of spiral arms. Additionally, about 40% of the collected sources distribute in the inter-arm regions, also present some structural features. These substructures may be related to arm branches, spurs and/or feathers as found in some nearby face-on spiral galaxies (e.g. M 51, M 101,
Our knowledge about these substructures in our Galaxy is very limited.

In our Galaxy, several spurs and/or spur-like structures have been classified from observations. In the direction of $l \sim 90^\circ - 210^\circ$, a structural feature named as Orion spur (e.g. Fig.1 of Humphreys, 1970; Schmidt-Kaler, 1975; Kolesnik & Vedenicheva, 1979) or Cepheus spur (Pantaleoni González et al., 2021) was discussed. This feature is suggested to be located between the Local Arm and the Perseus Arm, which may even extend to the first Galactic quadrant (Aasi et al., 2016). However, the name of Orion spur was also used to indicate the Local Arm in some literature (Amaral & Lepine, 1997; Carraro, 2014; Eker et al., 2014), which brings up a question: if the Orion spur discussed in the early days (e.g. Humphreys, 1970) exists or not? It will be helpful to reinvestigate this question with modern observational data. Recently, Xu et al. (2016) identified a spur near the direction of $l \sim 50^\circ$ traced by five HMSFRs with VLBI parallax measurements, bridging the Local Arm to the Sagittarius Arm and having a pitch angle of $\sim 18^\circ$ ($\sim 13^\circ$ given by a recent analysis of Reid et al., 2019). The existence of this spur is also supported by the CO features shown in the $l - v$ diagram. By analyzing the distribution and peculiar motions of HMSFR G352.630–1.067 and five O-type stars, a possible spur-like structure is proposed by Chen et al. (2019), which extends outward from the Sagittarius Arm. Reid et al. (2019) mentioned that the Norma Arm in the first Galactic quadrant displays a spur-like structure, which starts at $(X, Y) = (3, 2)$ kpc near the end of the Galactic bar and extends to about $(X, Y) = (2, 5)$ kpc at Galactic azimuth angle of $\sim 18^\circ$. This structure has a large pitch angle of $\sim 20^\circ$. In addition, a spur-like structure bridging the Scutum Arm and the Sagittarius Arm is also mentioned in Reid et al. (2019), which is indicated by the distribution and proper motions of six HMSFRs and has a large pitch angle of $\sim 20^\circ$. These proposed spurs or spur-like structures are plotted in Fig. 1 and Fig. 3. It seems that some GMCs, H II regions, O-type stars and young OCs are coincident with these structures in positions.

Except the Orion spur mentioned in some early literature, the known spurs or spur-like structures identified in the past few years are nearly all based on the astrometric data of HMSFR masers. In comparison to HMSFR masers, the GMCs, H II regions and especially O-type stars and young OCs with accurate distances have covered a much wider Galactic range. Hence, it is expected that more substructures could be identified. To identify the substructures in the inter-arm regions or spiral arms, radial velocities and/or proper motions for the sources would be helpful, which are still not available for many of them. Additionally, the properties of these substructures will help us to better understand the formation mechanisms of Galaxy’s spiral structure. As the formation of these features is different for different spiral arm models (Dobbs & Baba, 2014).

3.4 Formation mechanisms of Galaxy’s spiral structure

Besides accurately mapping the spiral structure, understanding its formation mechanism is another difficult issue. Different mechanisms have been proposed, e.g., the quasi-stationary density wave theory (Lin & Shu, 1964, 1966), localized instabilities, perturbations, or noise-induced kinematic spirals (Sellwood & Carlberg, 1984), dynamically tidal interactions (Toomre & Toomre, 1972), or a combination of some of them (Dobbs & Baba, 2014). Although many efforts have been dedicated to elaborate plausible hypotheses concerning the origin of the dominant spiral arms of the Galaxy, it is still not conclusive for now. One way is to analyse the kinematic properties of stars in the vicinity of the Sun (e.g. Williams et al., 2013; Faure et al., 2014; Liu et al., 2017; Kawata et al., 2018). However, it has been shown that very different bar and spiral arm models can be tuned to look like the local Gaia data (Hunt et al., 2019), or convincingly explain all observed features at once (e.g. Monari et al., 2019; Eilers et al., 2020; Khoperskov et al., 2020; Chiba et al., 2021; Trick et al., 2021). The other method is comparing the
relative positions of gas arms and stellar arms (e.g. Roberts, 1969; Shu, 2016; Dobbs & Pringle, 2010; Dobbs & Baba, 2014; Hou & Han, 2015; Monguió et al., 2015; He et al., 2021), which can be used to verify the predictions of different theories. Observational evidence for the spatial offsets between the gas arms and stellar arms have been noticed for the tangent regions (e.g. Hou & Han, 2015). However, for other regions in the Galactic disk, it is not clear whether the systematic spatial offsets or age pattern exist or not (Monguió et al., 2015; Vallée, 2018; He et al., 2021). More tests based on observations are needed.

In addition, the properties of the Local Arm make the situation more complex. Its existence induces some challenge to the density wave theory applied to our Galaxy (Xu et al., 2013, 2016). Before 2017, no specific mechanism for the origin of the Local Arm has been proposed. Lépine et al. (2017) first interpreted the Local Arm as an outcome of the spiral corotation resonance, which traps arm tracers and the Sun inside it (also see Michtchenko et al., 2018). Their modelled corotation zone looks consistent with the banana-like structure of the Local Arm shown by the distributions of GMCs, H II regions, O-type stars and young OCs in Fig. 3. In the context of other mechanisms, e.g. localized instabilities, perturbations, or noise-induced kinematic spirals, the properties of the Local Arm may be easily interpreted. The Milky Way has been suggested to be quite different from a pure grand design spiral, but probably resemble a multi-armed galaxy M 101, due to the existence of the Local Arm and the many possible spurs noticed from observational data (Xu et al., 2018b). Typically, the localized instabilities are associated with flocculent or multi-armed galaxies (Dobbs & Baba, 2014).

4 CONCLUSIONS AND DISCUSSIONS

In this work, the spiral structure in the Solar neighborhood are discussed based on the largest dataset available to date, which consists of different types of good spiral tracers. They are GMCs, HMSFR masers, H II regions, O-type stars and young OCs. All the collected data have accurate distances with uncertainties <15% and <0.5 kpc. With the dataset, we update the parameters of spiral arm segments in the Solar neighborhood, and discuss their properties. The spiral structure traced by GMCs, HMSFR masers, H II regions, O-type stars and young OCs are in general consistent with each other. Five segments of dominant spiral arms in the Solar neighborhood are depicted, they are the Perseus, Local, Sagittarius-Carina, Scutum-Centaurus and Norma Arms. However, the extensions of these arm segments to distant Galaxy regions have not been reliably traced. In the spiral arms and inter-arm regions, the distributions of spiral tracers present complex substructures, which are probably true features as the distance uncertainties of the tracers are small. At least five spurs or spur-like features have been identified in the literature by taking advantage of the astrometric data of HMSFR masers, but more substructures remain to be uncovered with the updated dataset of different types of good spiral tracers. In comparison to the gas arms traced by GMCs and star-formation activity, the properties of stellar arms indicated by evolved stars are still inconclusive.

There is significant progress in understanding the Galaxy’s spiral structure in the past few years, which is heavily dependent on the developments of astrometric observations by the VLBI in radio band and the Gaia satellite in optical band. The VLBI observations have the advantage to measure the spiral tracers in distant Galaxy regions with high accuracies (as high as 0.006 mas, typically about ±0.2 mas, Reid et al., 2019), and almost not affected by dust extinction. BeSSeL is planned to extend to the southern sky (Reid et al., 2019), which will provide parallax and proper motion measurements for many HMSFRs in the third and fourth Galactic quadrants, where the data of such kind of measurements are largely absent at present. In the near future, the SKA is expected to open a new era for the trigonometric measurements of a large number of HMSFRs and hence for the investigations on the Galaxy’s global spiral structure. On the other hand, the Gaia EDR3 has been released in the end of 2020, the parallax uncertainties have
beaten significantly improved to be 0.02 – 0.03 mas for $G$ band magnitude less than 15, and 0.07 mas for $G = 17$. The full Gaia DR3 is expected in 2022. Gaia is still committing itself to improve the accuracies of parallaxes and proper motions for a large number of stars. Although the stars measured by Gaia suffered from the dust extinction, so that distant objects cannot be measured, the Gaia data have the advantage to reveal the detailed structures/substructures and kinematic properties in the Solar neighborhood, at least for the regions within about 5 kpc of the Sun. In the Solar neighborhood, the segments of dominant spiral arms have been well traced as discussed in the main text. However, the properties of substructures in the spiral arms or inter-arm regions, and the properties of stellar arms traced by evolved stars are still far from conclusive, which may be deserving of more attention.

ACKNOWLEDGMENTS

The author thanks the anonymous referees for constructive comments and suggestions that significantly improved this work, and Prof. Y. Xu for helpful suggestions. The author also would like to thank Dr. C. J. Hao for kindly providing the data of young OCs, and Dr. X. Y. Gao for carefully reading the manuscript. This work is supported by the National Key R&D Program of China (NO. 2017YFA0402701) and the National Natural Science Foundation (NNSF) of China No. 11988101, 11933011, 11833009. L.G.H thanks the support from the Youth Innovation Promotion Association CAS. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

REFERENCES

Aasi J., Abbott B. P., Abbott R., Abbott T. D., Abernathy M. R., Acernese F., Ackley K., et al., 2016, PhRvD, 93, 042006
Amaral, L. H. & Lepine, J. R. D. 1997, MNRAS, 286, 885
Anderson, L. D., Armentrout, W. P., Johnstone, B. M., et al. 2015, ApJS, 221, 26
Anderson, L. D., Bania, T. M., Balser, D. S., et al. 2014, ApJS, 212, 1
Baba J., Saitoh T. R., Wada K., 2010, PASJ, 62, 1413
Becker, W. 1963, ZA, 57, 117
Becker, W. 1964, in The Galaxy and the Magellanic Clouds, ed. F. J. Kerr, Vol. 20, 16
Becker, W. & Fenkart, R. B. 1970, in The Spiral Structure of our Galaxy, ed. W. Becker & G. I. Kontopoulos, Vol. 38, 205
Bissantz N., Englmaier P., Gerhard O., 2003, MNRAS, 340, 949.
Bobylev, V. V., & Bajkova, A. T. 2014, MNRAS, 437, 1549
Bok, B. J. 1964, in The Galaxy and the Magellanic Clouds, ed. F. J. Kerr, Vol. 20, 147
Bok, B. J., Hine, A. A., & Miller, E. W. 1970, in The Spiral Structure of our Galaxy, ed. W. Becker & G. I. Kontopoulos, Vol. 38, 246
Bossini D., Vallenari A., Bragaglia A., Cantat-Gaudin T., Sordo R., Balaguer-Núñez L., Jordi C., et al., 2019, A&A, 623, A108
Burton, W. B. 1973, PASP, 85, 679
Camargo, D., Bica, E., & Bonatto, C. 2013, MNRAS, 432, 3349
Cantat-Gaudin T., Jordi C., Vallenari A., Bragaglia A., Balaguer-Núñez L., Soubiran C., Bossini D., et al., 2018, A&A, 618, A93

This is a provisional file, not the final typeset article
Hou L.G.

Nearby spiral structure

Cantat-Gaudin T., Krone-Martins A., Sedaghat N., Farahi A., de Souza R. S., Skalidis R., Malz A. I., et al., 2019, A&A, 624, A126
Cantat-Gaudin T., Anders F., 2020, A&A, 633, A99
Cantat-Gaudin T., Anders F., Castro-Ginard A., Jordi C., Romero-Gómez M., Soubiran C., Casamiquela L., et al., 2020, A&A, 640, A1
Carraro G., 2014, IAUS, 298, 7.
Carraro G., Vázquez R. A., Moitinho A., Baume G., 2005, ApJL, 630, L153
Caswell, J. L. & Haynes, R. F. 1987, A&A, 171, 261
Castro-Ginard A., Jordi C., Luri X., Julbe F., Morvan M., Balaguer-Núñez L., Cantat-Gaudin T., 2018, A&A, 618, A59
Castro-Ginard A., Jordi C., Luri X., Cantat-Gaudin T., Balaguer-Núñez L., 2019, A&A, 627, A35
Castro-Ginard A., Jordi C., Luri X., Álvarez Cid-Fuentes J., Casamiquela L., Anders F., Cantat-Gaudin T., et al., 2020, A&A, 635, A45
Chakrabarti S., Laughlin G., Shu F. H., 2003, ApJ, 596, 220.
Chen, B. Q., Huang, Y., Hou, L. G., et al. 2019a, MNRAS, 487, 1400
Chen, B. Q., Huang, Y., Yuan, H. B., et al. 2019b, MNRAS, 483, 4277
Chen, B. Q., Li, G. X., Yuan, H. B., et al. 2020, MNRAS, 493, 351
Chen, X., Li, J.-J., Zhang, B., et al. 2019, ApJ, 871, 198
Chiba, R., Friske, J. K. S., & Schönrich, R. 2021, MNRAS, 500, 4710
Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, PASP, 121, 213
Cohen, R. S., Cong, H., Dame, T. M., & Thaddeus, P. 1980, ApJL, 239, L53
Cohen, R. S., Grabelsky, D. A., May, J., et al. 1985, ApJL, 290, L15
Courtès, G., Georgelin, Y. P., Georgelin, Y. M., & Monnet, G. 1970, in The Spiral Structure of our Galaxy, ed. W. Becker & G. I. Kontopoulos, Vol. 38, 209
Dame T. M., Hartmann D., Thaddeus P., 2001, ApJ, 547, 792
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354
Dias W. S., Alessi B. S., Moitinho A., Lépine J. R. D., 2002, A&A, 389, 871
Dias, W. S. & Lépine, J. R. D. 2005, ApJ, 629, 825
Dias, W. S., & Lépine, J. R. D. 2005, A&A, 629, 825
Dias W. S., Monteiro H., Caetano T. C., Lépine J. R. D., Assafin M., Oliveira A. F., 2014, A&A, 564, A79
Dias W. S., Monteiro H., Assafin M., 2018, MNRAS, 478, 5184
Dias W. S., Monteiro H., Lépine J. R. D., Barros D. A., 2019, MNRAS, 486, 5726
Dias W. S., Monteiro H., Moitinho A., Lépine J. R. D., Carraro G., Paunzen E., Alessi B., et al., 2021, MNRAS.tmp
Díaz-García S., Salo H., Knapen J. H., Herrera-Endoqui M., 2019, A&A, 631, A94
D’Onghia E., Vogelsberger M., Hernquist L., 2013, ApJ, 766, 34.
Dobbs C. L., Bonnell I. A., 2006, MNRAS, 367, 873.
Dobbs, C. & Baba, J. 2014, PASA, 31, e035
Dobbs, C. L. & Pringle, J. E. 2010, MNRAS, 409, 396
Downes, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, A&A, 40, 379
Drimmel, R. 2000, A&A, 358, L13
Drimmel, R. & Spergel, D. N. 2001, ApJ, 556, 181
Duarte-Cabral A., Colombo D., Urquhart J. S., Ginsburg A., Russeil D., Schuller F., Anderson L. D., et al., 2021, MNRAS, 500, 3027.
Eilers, A.-C., Hogg, D. W., Rix, H.-W., et al. 2020, ApJ, 900, 186
Nearby spiral structure

Eker Z., Bilir S., Soydugan F., Gökçe E. Y., Soydugan E., Tüysüz M., Şenyüz T., et al., 2014, PASA, 31, e024
Elmegreen D. M., 1980, ApJ, 242, 528.
Faure, C., Siebert, A., & Famaey, B. 2014, MNRAS, 440, 2564
Fenkart, R. P. & Binggeli, B. 1979, A&AS, 35, 271
Fernie, J. D. 1968, AJ, 73, 995
Ferreira F. A., Corradi W. J. B., Maia F. F. S., Angelo M. S., Santos J. F. C., 2020, MNRAS, 496, 2021
Ferreira F. A., Corradi W. J. B., Maia F. F. S., Angelo M. S., Santos J. F. C., 2021, MNRAS, 502, L90
Fish, V. L. 2007, Astrophysical Masers and their Environments, 242, 71.
Foster T., Cooper B., 2010, ASPC, 438, 16
Foster, T. & Brunt, C. M. 2015, AJ, 150, 147
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2020, arXiv e-prints, arXiv:2012.01533
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gaia Collaboration, Brown A. G. A., Vallenari A., Prusti T., de Bruijne J. H. J., Babusiaux C., Biermann M., 2020, arXiv, arXiv:2012.01533
García, P., Bronfman, L., Nyman, L.-Å., Dame, T. M., & Luna, A. 2014, ApJS, 212, 2
Georgelin, Y. M. & Georgelin, Y. P. 1976, A&A, 49, 57
Georgelin, Y. P. & Georgelin, Y. M. 1971, A&A, 12, 482
Grabelsky, D. A., Cohen, R. S., Bronfman, L., & Thaddeus, P. 1988, ApJ, 331, 181
Hachisuka, K., Brunthaler, A., Menten, K. M., et al. 2006, ApJ, 645, 337
Han, J. L. 2017, ARA&A, 55, 111
Hao C., Xu Y., Wu Z., He Z., Bian S., 2020, PASP, 132, 034502
He Z.-H., Xu Y., Hao C.-J., Wu Z.-Y., Li J.-J., 2020, arXiv, arXiv:2010.14870
He, Z.-H., Xu, Y., & Hou, L.-G. 2021, Research in Astronomy and Astrophysics, 21, 009
Heyer, M. & Dame, T. M. 2015, ARA&A, 53, 583
Honig Z. N., Reid M. J. 2015, ApJ, 800, 53.
Honma, M., Nagayama, T., Ando, K., et al. 2012, PASJ, 64, 136
Hottier, C., Babusiaux, C., & Arenou, F. 2020, A&A, 641, A79
Hou, L. G. & Han, J. L. 2014, A&A, 569, A125
Hou, L. G. & Han, J. L. 2015, MNRAS, 454, 626
Hou, L. G., Han, J. L., & Shi, W. B. 2009, A&A, 499, 473
Humphreys R. M., 1970, AJ, 75, 602.
Hunt, J. A. S., Bub, M. W., Bovy, J., et al. 2019, MNRAS, 490, 1026
Hunt, J. A. S., Johnston, K. V., Pettitt, A. R., et al. 2020, MNRAS, 497, 818
Hunt E. L., Reffert S., 2021, A&A, 646, A104
Janes K., Adler D., 1982, ApJS, 49, 425.
Janes, K. A., Tilley, C., & Lynga, G. 1988, AJ, 95, 771
Kawata, D., Baba, J., Ciucă, I., et al. 2018, MNRAS, 479, L108
Kendall S., Kennicutt R. C., Clarke C., 2011, MNRAS, 414, 538
Kennicutt R. C., 1981, AJ, 86, 1847
Kharchenko N. V., Piskunov A. E., Schilbach E., Röser S., Scholz R.-D., 2013, A&A, 558, A53
Khoperskov, S., Gerhard, O., Di Matteo, P., et al. 2020, A&A, 634, L8
Kolesnik, L. N. & Vedenicheva, I. P. 1979, A&A, 76, 124
Koo, B.-C., Park, G., Kim, W.-T., et al. 2017, PASP, 129, 094102
Hou L.G.

Nearby spiral structure

Kounkel, M. & Covey, K. 2019, AJ, 158, 122
Krishnan, V., Ellingsen, S. P., Reid, M. J., et al. 2017, MNRAS, 465, 1095
La Vigne M. A., Vogel S. N., Ostriker E. C., 2006, ApJ, 650, 818
Lépine, J. R. D., Michtchenko, T. A., Barros, D. A., & Vieira, R. S. S. 2017, ApJ, 843, 48
Lépine, J. R. D., Roman-Lopes, A., Abraham, Z., Junqueira, T. C., & Mishurov, Y. N. 2011, MNRAS, 414, 1607
Levine, E. S., Blitz, L., & Heiles, C. 2006, Science, 312, 1773
Li Z., Shen J., Gerhard O., Clarke J. P., 2021, arXiv, arXiv:2103.10342
Lin, C. C. & Shu, F. H. 1964, ApJ, 140, 646
Lin, C. C. & Shu, F. H. 1966, Proceedings of the National Academy of Science, 55, 229
Liu, C., Wang, Y.-G., Shen, J., et al. 2017, ApJL, 835, L18
Liu L., Pang X., 2019, ApJS, 245, 32
Lynds B. T., 1970, IAUS, 38, 26
Lynga G., 1982, A&A, 109, 213
Majaess, D. J., Turner, D. G., & Lane, D. J. 2009, MNRAS, 398, 263
Mermilliod J.-C., 1995, ASSL, 127.
Michtchenko, T. A., Lépine, J. R. D., Barros, D. A., & Vieira, R. S. S. 2018, A&A, 615, A10
Miller, E. W. 1972, AJ, 77, 216
Miville-Deschênes, M.-A., Murray, N., & Lee, E. J. 2017, ApJ, 834, 57
Miyachi, Y., Sakai, N., Kawata, D., et al. 2019, ApJ, 882, 48
Moisés, A. P., Damineli, A., Figuerêdo, E., et al. 2011, MNRAS, 411, 705
Moitinho, A., Vázquez, R. A., Carraro, G., et al. 2006, MNRAS, 368, L77
Moitinho, A. 2010, in Star Clusters: Basic Galactic Building Blocks Throughout Time and Space, eds. R. de Grijs, & J. R. D. Lépine, IAU Symp., 266, 106
Monari, G., Famaey, B., Siebert, A., Wegg, C., & Gerhard, O. 2019, A&A, 626, A41
Monguíó, M., Grosbol, P., & Figueras, F. 2015, A&A, 577, A142
Monteiro H., Dias W. S., 2019, MNRAS, 487, 2385
Monteiro H., Barros D. A., Dias W. S., Lépine J. R. D., 2021, arXiv, arXiv:2104.00134
Morgan, W. W., Sharpless, S., & Osterbrock, D. 1952, AJ, 57, 3
Morgan, W. W., Whitford, A. E., & Code, A. D. 1953, ApJ, 118, 318
Münch, G. 1953, PASP, 65, 179
Murray, N. 2011, ApJ, 729, 133
Myers, P. C., Dame, T. M., Thaddeus, P., et al. 1986, ApJ, 301, 398
Nakanishi H., Sofue Y., 2016, PASJ, 68, 5.
Paladini, R., Davies, R. D., & De Zotti, G. 2004, MNRAS, 347, 237
Pantaleoni González M., Maíz Apellániz J., Barbá R. H., Reed B. C., 2021, MNRAS.tmp
Pettitt A. R., Dobbs C. L., Acreman D. M., Price D. J., 2014, MNRAS, 444, 919
Pettitt A. R., Dobbs C. L., Acreman D. M., Bate M. R., 2015, MNRAS, 449, 3911
Pohl M., Englmaier P., Bissantz N., 2008, ApJ, 677, 283
Poggio E., Drimmel R., Cantat-Gaudin T., Ramos P., Ripepi V., Zari E., Andrae R., et al., 2021, arXiv, arXiv:2103.01970
Reed, B. C. 2003, AJ, 125, 2531
Reed, B. C. & Reed, L. G. 2000, PASP, 112, 409
Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2019, ApJ, 885, 131
Reid, M. J., Menten, K. M., Zheng, X. W., et al. 2009, ApJ, 700, 137
Hou L.G.

Nearby spiral structure

Rice, T. S., Goodman, A. A., Bergin, E. A., Beaumont, C., & Dame, T. M. 2016, ApJ, 822, 52
Roberts, W. W. 1969, ApJ, 158, 123
Rodriguez-Fernandez N. J., Combes F., 2008, A&A, 489, 115
Russle, D. 2003, A&A, 397, 133
Rygl, K. L. J., Brunthaler, A., Reid, M. J., et al. 2010, A&A, 511, A2
Sampedro L., Dias W. S., Alfarco E. J., Monteiro H., Molino A., 2017, MNRAS, 470, 3937.
Schmidt-Kaler, T. 1975, Vistas in Astronomy, 19, 69
Schmeja S., Kharchenko N. V., Piskunov A. E., Röser S., Schilbach E., Froebrich D., Scholz R.-D., 2014, A&A, 568, A51
Scholz R.-D., Kharchenko N. V., Piskunov A. E., Röser S., Schilbach E., 2015, A&A, 581, A39
Seigar M. S., James P. A., 1998, MNRAS, 299, 685
Sellwood, J. A. & Carlberg, R. G. 1984, ApJ, 282, 61
Shahzamanian, B., Schödel, R., Nogueras-Lara, F., et al. 2019, A&A, 632, A116
Shen, J. & Zheng, X.-W. 2020, Research in Astronomy and Astrophysics, 20, 159
Shu, F. H. 2016, ARA&A, 54, 667
Shull, J. M. & Danforth, C. W. 2019, ApJ, 882, 180
Sim G., Lee S. H., Ann H. B., Kim S., 2019, JKAS, 52, 145
Simonson, S. C., I. 1970, A&A, 9, 163
Skiff, B. A. 2014, VizieR Online Data Catalog, B/mk
Soubiran C., Cantat-Gaudin T., Romero-Gómez M., Casamiquela L., Jordi C., Vallenari A., Antoja T., et al., 2018, A&A, 619, A155
Stothers, R. & Frogel, J. A. 1974, AJ, 79, 456
Tarricq Y., Soubiran C., Casamiquela L., Cantat-Gaudin T., Chemin L., Anders F., Antoja T., et al., 2021, A&A, 647, A19
Taylor, J. H. & Cordes, J. M. 1993, ApJ, 411, 674
Thackeray, A. D. 1956, Nature, 178, 1458
Toomre, A. & Toomre, J. 1972, ApJ, 178, 623
Trick, W. H., Fragkoudi, F., Hunt, J. A. S., Mackereth, J. T., & White, S. D. M. 2021, MNRAS, 500, 2645
Urquhart, J. S., Figura, C. C., Moore, T. J. T., et al. 2014, MNRAS, 437, 1791
Vallée J. P., 2008, AJ, 135, 1301.
Vallée, J. P. 2018, ApJ, 863, 52
van de Hulst, H. C., Muller, C. A., & Oort, J. H. 1954, Bull. Astron. Inst. Netherlands, 12, 117
Vázquez, R. A., May, J., Carraro, G., et al. 2008, ApJ, 672, 930
VERA Collaboration, Hirota, T., Nagayama, T., et al. 2020, PASJ, 72, 50
Walborn, N. R. 1971, ApJS, 23, 257
Weaver H. F., 1970, IAUS, 39, 22
Wegg C., Gerhard O., Portail M., 2015, MNRAS, 450, 4050
Willett K. W., Lintott C. J., Bamford S. P., Masters K. L., Simmons B. D., Casteels K. R. V., Edmondson E. M., et al., 2013, MNRAS, 435, 2835
Williams, M. E. K., Steinmetz, M., Binney, J., et al. 2013, MNRAS, 436, 101
Wright, N. J. 2020, New A Rev., 90, 101549
Xu, Y., Bian, S. B., Reid, M. J., et al. 2018a, A&A, 616, L15
Xu, Y., Hou, L. G., Bian, S. B., et al. 2021, A&A, 645, L8
Xu, Y., Hou, L.-G., & Wu, Y.-W. 2018b, Research in Astronomy and Astrophysics, 18, 146
Xu, Y., Li, J. J., Reid, M. J., et al. 2013, ApJ, 769, 15

This is a provisional file, not the final typeset article 22
Xu, Y., Reid, M., Dame, T., et al. 2016, Science Advances, 2, e1600878
Xu, Y., Reid, M. J., Zheng, X. W., & Menten, K. M. 2006, Science, 311, 54
Yan, Q.-Z., Yang, J., Su, Y., Sun, Y., & Wang, C. 2020a, ApJ, 898, 80
Yan, Q.-Z., Yang, J., Sun, Y., Su, Y., & Xu, Y. 2019, ApJ, 885, 19
Yan, Q.-Z., Yang, J., Sun, Y., et al. 2020b, arXiv e-prints, arXiv:2012.09500
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Yu S.-Y., Ho L. C., Barth A. J., Li Z.-Y., 2018, ApJ, 862, 13
Yuan C., 1969, ApJ, 158, 871