ASTROPHYSICS

The local spiral structure of the Milky Way

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The nature of the spiral structure of the Milky Way has long been debated. Only in the last decade have astronomers been able to accurately measure distances to a substantial number of high-mass star-forming regions, the classic tracers of spiral structure in galaxies. We report distance measurements at radio wavelengths using the Very Long Baseline Array for eight regions of massive star formation near the Local spiral arm of the Milky Way. Combined with previous measurements, these observations reveal that the Local Arm is larger than previously thought, and both its pitch angle and star formation rate are comparable to those of the Galaxy's major spiral arms, such as Sagittarius and Perseus. Toward the constellation Cygnus, sources in the Local Arm extend for a great distance along our line of sight and roughly along the solar orbit. Because of this orientation, these sources cluster both on the sky and in velocity to form the complex and long enigmatic Cygnus X region. We also identify a spur that branches between the Local and Sagittarius spiral arms.

INTRODUCTION

The idea that the Milky Way is a spiral galaxy was proposed more than one and a half centuries ago (*1*). However, it was not until the 1950s that some spiral arm segments in the solar neighborhood were clearly identified (*2*, *3*). Since then, many models have been proposed (*4*) and debated (*5*). Popular models (*6*, *7*) suggest a grand design morphology with two- or four-armed spiral structure (*8*), such as M 51 or NGC 1232 (Fig. 1). Still, today, there is no general agreement on the number, locations, orientations, and properties of the Milky Way's spiral arms. The main impediments to determining spiral structure are the vast distances (up to about 60,000 ly) to stars across its extent and extinction by interstellar dust that precludes optical observations of distant stars in the Galactic plane. Recently, Very Long Baseline Interferometry (VLBI) at radio wavelengths has yielded near micro–arc second accurate position measurements to clouds of gas in regions of massive star formation, allowing estimation of distance through trigonometric parallax [astronomical "surveying" using Earth's orbit as a baseline (*9*)]. With the combined efforts of the U.S./European BeSSeL (Bar and Spiral Structure Legacy) Survey and the Japanese VERA (VLBI Exploration of Radio Astrometry) project, now more than 100 parallax measurements are locating large portions of spiral arms across the Milky Way (*10*, *11*).

The Local Arm is the nearest spiral arm to the Sun. Because the nearby Orion stellar association lies within this arm, it has been called the "Orion Arm" or "Orion spur" (*12*).

Until recently, most available optical and radio data suggested that the Local Arm was a "spur" or secondary spiral feature [for example, (*6*)]. However, a large number of star-forming regions were recently measured to be in the Local Arm, many of them previously thought to be in the next more distant Perseus Arm. This suggested that the Local Arm is a major spiral structure [(*13*), hereafter *Paper I*]. Following *Paper I*, we report eight new parallax measurements to stars with bright molecular maser emission at radio wavelengths. These provide a better understanding of the properties of the Local Arm, including defining its great extent, elucidating the nature of the well-studied Cygnus X region of massive star formation, and the discovery of a true spur connecting the Local and Sagittarius spiral arms.

RESULTS

Spiral arms are best defined by the high-mass star-forming regions (HMSFRs) that form within them. We focused our study on 6.7-GHz methanol (CH_3OH) and 22-GHz water (H_2O) masers that are associated with well-known HMSFR sources, such as ultracompact HII regions and bright far-infrared sources. Following previous BeSSeL Survey studies of other spiral arms (*11*), we identify masers associated with the Local Arm based on their coincidence in Galactic longitude (l) and velocities in the Local Standard of Rest frame (V) with a large lane of emission at low absolute velocities that marks the Local Arm in CO and HI l-V diagrams. Table 1 presents the measured parallax distances for the eight new masers. Their spatial distribution in projection onto the Galactic plane is shown by the blue circles with white outlines in Fig. 2;

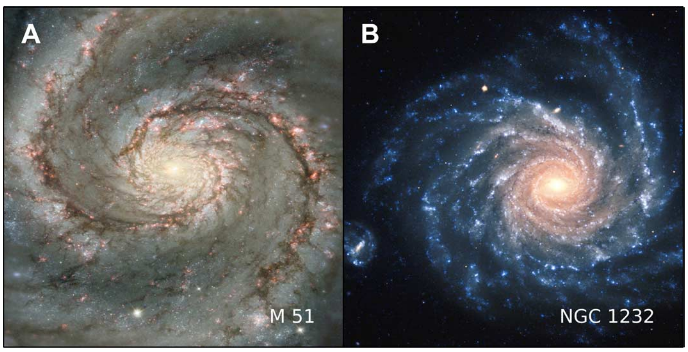

Fig. 1. Spiral galaxies. (**A**) M 51 [Credit: Hubble Space Telescope WFPC2]. (**B**) NGC 1232 [Credit: FORS, 8.2-meter Very Large Telescope Antu, European Southern Observatory].

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Table 1. Parallaxes and proper motions. Column 2 is the parallax in milli–arc seconds. Column 3 is the parallax converted to distance in kiloparsec (1 pc ≈ 3.26 ly). Columns 4 and 5 are proper motions on the sky, eastward ($\mu_x = \mu_\alpha \cos\delta$) and northward ($\mu_y = \mu_\delta$) in units of milli–arc second year^{-1}, respectively.

Maser	Π	D_Π	μ_x	μ_y
Name	(milli–arc second)	(kpc)	(milli–arc second year^{-1})	(milli–arc second year^{-1})
G054.10–00.08	0.231 ± 0.031	$4.33^{+0.67}_{-0.51}$	−3.13 ± 0.48	−5.57 ± 0.48
G058.77+00.64	0.299 ± 0.040	$3.34^{+0.52}_{-0.39}$	−2.70 ± 0.10	−6.10 ± 0.21
G059.47–00.18	0.535 ± 0.024	$1.87^{+0.09}_{-0.08}$	−1.83 ± 1.12	−6.60 ± 1.12
G059.83+00.67	0.253 ± 0.024	$3.95^{+0.42}_{-0.34}$	−2.92 ± 0.07	−6.03 ± 0.05
G071.52–00.38	0.277 ± 0.013	$3.61^{+0.18}_{-0.16}$	−2.48 ± 0.04	−4.97 ± 0.07
G108.18+05.51	1.101 ± 0.033	$0.91^{+0.03}_{-0.03}$	+0.16 ± 0.09	−2.17 ± 0.35
G109.87+02.11	1.208 ± 0.025	$0.83^{+0.02}_{-0.02}$	−1.03 ± 0.10	−2.62 ± 0.27
G213.70–12.60	1.166 ± 0.021	$0.86^{+0.01}_{-0.02}$	−1.25 ± 0.09	+2.44 ± 0.28

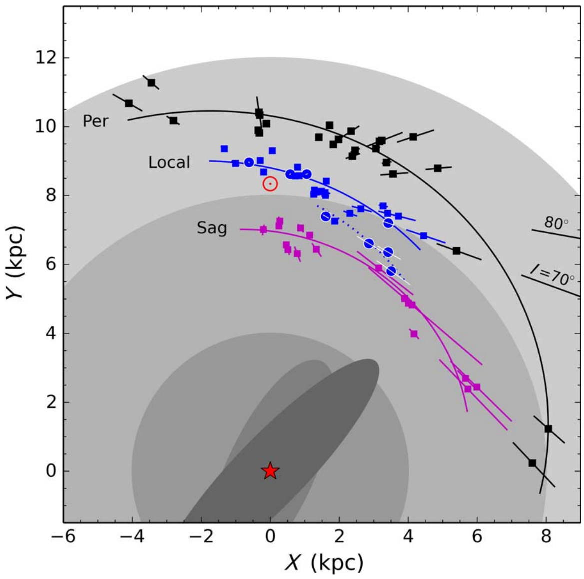

Fig. 2. Location of HMSFRs determined by trigonometric parallax. Sources presented in this paper are indicated with the blue circles with white outlines, and those from *Paper I* with blue squares. The parallax data in the Perseus (black squares) and Sagittarius (magenta squares) arms are also presented. The blue solid and dot lines are log spiral fits to the sources in the Local Arm and in the spur, respectively. They have pitch angles of 11.6° ± 1.8° and 18.3° ± 5.9°. The Galactic center (red star) is at (0,0) and the Sun (red Sun symbol) is at (0,8.34). Distance error bars (1σ) are indicated, but many are smaller than the symbols. The background gray disks provide scale, with radii corresponding in round numbers to the Galactic bar region (≈4 kpc), the solar circle (≈8 kpc), and corotation of the spiral pattern and Galactic orbits (≈12 kpc). The short Cosmic Background Explorer "boxy-bar" and the "long" bar (*19*–*21*) are indicated with shaded ellipses.

the blue squares are the sources from *Paper I.* For Galactic context, we also show HMSFRs in the surrounding Sagittarius and Perseus arms (*11*). Almost all of the sources in the Local Arm have a distance accuracy of better than ±10%, and half are better than ±5%, ensuring that the spiral structure near the Sun can be mapped with unprecedented accuracy.

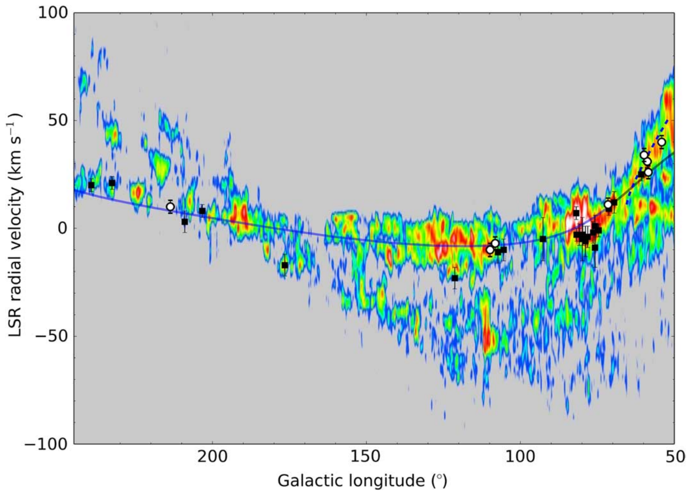

Fig. 3. Location of HMSFRs with parallaxes superposed on a CO *l-V* diagram from the CfA 1.2-m survey (*22*). Sources presented in this paper are indicated with white circles with black outlines, and others with black squares. Velocity error bars (1σ) are indicated. The solid line is a log spiral fit to the sources in the Local Arm (blue for $l > 70°$, black for an extrapolation at $l < 70°$), whereas the dotted line corresponds to the spur indicated in Fig. 2. LSR, Local Standard of Rest.

DISCUSSION

Our newly measured sources at $l > 70°$ strengthen the main conclusion of *Paper I* that the Local Arm is quite long and has a modest pitch angle and an abundant star formation. The addition of these sources improves the accuracy and robustness of our pitch angle estimate (blue solid curve) from 10.1° ± 2.7° to 11.6° ± 1.8°. We now know that the density of HMSFRs in the Local Arm is comparable to that of other major arms and that it stretches for >20,000 ly, almost reaching the Perseus Arm (11 and this paper). With standard density-wave theory for grand-design morphologies, it would be difficult to explain this large spiral arm segment located between the Sagittarius and Perseus arms, owing to its narrow spacing (*14*). This suggests that the Milky Way does not have a pure grand design. Also, recent large numerical simulations suggest that standard density-wave theory may not explain spiral structure in galaxies like the Milky Way (*15*).

The four new parallax-measured sources at $l < 70°$ do not follow the main arc of the Local Arm. Instead, these sources, as well as G059.78+00.06 and ON 1, branch off and curve inward in the Milky Way. As the dotted line in Fig. 2 suggests, these sources trace what appears to be a high-inclination spur bridging the Local Arm to the Sagittarius Arm near $l \approx 50°$. Additional evidence for this spur is provided by large-scale molecular emission from CO, as shown in the *l-V* diagram in Fig. 3. Assuming circular motion and a flat rotation curve for the Milky Way, we can calculate the velocity V of Galactic objects using $V = \Theta_0(R_0/R - 1)\sin l$, where R is the Galactocentric radius and R_0 and Θ_0 are the distance to the Galactic center and the circular rotation speed at the Sun, respectively (*11*). In this way, the spatial locations of the Local Arm and spur sources in Fig. 2 can be transformed into *l-V* space, as shown in Fig. 3. At $l < 70°$, velocities from the spiral fit fall significantly below some of the spur sources (G054.10−00.08 and G059.83+00.67). Note also that they follow a nearly continuous lane of CO emission that runs from the intense Cygnus X region near $l \approx 80°$, almost certainly part of the Local Arm, to the Sagittarius Arm near $l \approx 50°$. This lane has received little attention in the past because it does not correspond with any of the major spiral arm features of the inner Galaxy [for example, (*16*)].

At distances beyond the branch point of the spur, the HMSFRs in the Local Arm align almost linearly toward $l \sim 80°$ (Fig. 2). Because these sources straddle the solar orbit, they pile up at a point in the *l-V* diagram (Fig. 3) near zero velocity. CO emission associated with the arm likewise piles up to form the complex Cygnus X region. Whether this region is a superposition of HMSFRs strung along the line of sight [for example, (*17*)] or mainly a single giant molecular complex at one distance [for example, (*18*)] has been debated for decades. Our results strongly support the former view, with the sources toward Cygnus X extending more than 13,000 ly and nearly reaching the Perseus Arm.

MATERIALS AND METHODS

Observations with 7-hour tracks for 6.7-GHz CH_3OH and 22-GHz H_2O masers toward star-forming regions were performed with the National Radio Astronomy Observatory Very Long Baseline Array (VLBA), under programs BR149 and BR198 as part of the BeSSeL Survey. These are the first 6.7-GHz CH_3OH maser parallax measurements with the VLBA.

For 6.7-GHz CH_3OH masers, four observing epochs were selected to optimally sample the peaks of the sinusoidal parallax signature in right ascension over 1 year, maximizing the sensitivity of parallax detection and ensuring that the parallax and proper motion signatures are uncorrelated. For 22-GHz H_2O masers, six epochs were observed in 1 year to allow a parallax measurement with less than one full year of data, because water maser spots can have lifetimes shorter than a year. Details about the observations and data analysis are available in the Supplementary Materials.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/9/e1600878/DC1
Supplementary Text
table S1. Details of the epochs observed.
table S2. Positions and source properties of the reference maser spots and the background sources for the first epoch.
table S3. Parallaxes and proper motions.
table S4. Parallax and proper motion measurements.
fig. S1. Parallax and proper motion data and fits for G054.10−00.08.
fig. S2. Parallax and proper motion data and fits for G058.77+00.64.
fig. S3. Parallax and proper motion data and fits for G059.47−00.18.
fig. S4. Parallax and proper motion data and fits for G059.83+00.67.
fig. S5. Parallax and proper motion data and fits for G071.52−00.38.
fig. S6. Parallax and proper motion data and fits for G108.18+05.51.
fig. S7. Parallax and proper motion data and fits for G109.87+02.11.
fig. S8. Parallax and proper motion data and fits for G213.70−12.60.
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