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Debris of *Gaia*–Sausage–Enceladus that made a H I hole in the Milky Way ~ 20 million years ago

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The Perseus arm is known as one of the two¹⁻³ or four^{4,5} dominant spiral arms of the Milky Way. While there is a large number of Massive Young Stellar Objects in the outer portion of the arm, a lower density of those is found in the inner portion⁶⁻⁸. Inner Perseus arm shows a noncircular motion of $>70 \text{ km s}^{-1}$ at a Galactic longitude of $\sim 50^\circ$, and its origin remains unclear⁹. Here we report an analysis of the kinematics and spatial distribution of neutral hydrogen (H I) gas, star-forming regions (SFRs) and stars, together with an analysis of the star's chemical abundances. We discovered that H I gas with $\sim 10^6$ solar mass was lacked in the inner Perseus arm, and a similar amount of H I gas was distributed above the Galactic plane. The extended H I gas is well followed by retrograde low-metallicity stars, which are likely fossil stars from *Gaia*–Sausage–Enceladus¹⁰⁻¹³. Orbit integration shows that the fossil stars crossed the inner Galactic disk about 20 million years ago. The lower star-formation

1 **activity and noncircular motion of the inner Perseus arm could be attributed to the disk**
2 **crossing event.**

3 Six-dimensional (6D; position-velocity) phase space information of SFRs embedded in the
4 gaseous disk of the Milky Way, has been obtained by Very Long Baseline Interferometry (VLBI)
5 observations at radio wavelengths^{14,15}. These results have been used to delineate the detailed
6 structure of the spiral arms in the Galactic disk. To compare kinematics of the inner Perseus arm
7 with that of other spiral arms, we examined the velocity distribution of 35 SFRs at a Galactocentric
8 distance range of $6 \leq R \text{ (kpc)} \leq 7$ (Fig. 1; see Extended Data Table 1 for details). That specific
9 range is less affected by the bulge (Galactic bar)¹⁶ and thus is a good area for studying the effects
10 of spiral arms. Inner Perseus-arm sources tend to show slower azimuthal velocities (V_ϕ) compared
11 to other spiral-arm sources. In particular, G049.41+00.32 (hereafter G049.41) associated with the
12 inner Perseus arm⁹, is a statistical outlier (4σ) in terms of azimuthal velocity ($V_\phi = 160 \pm 17 \text{ km}$
13 s^{-1}). The peculiar (noncircular) motion of G049.41 is much larger than would be expected given
14 the gravitational potential of the spiral arm¹⁷. Thus, the origin of the peculiar (noncircular) motion
15 remains unclear, although the marginally significant vertical motion ($V_z = 31 \pm 14 \text{ km s}^{-1}$) of the
16 source could hint at the origin. The radial motion of G049.41 is not statistically significant ($V_R =$
17 $13 \pm 47 \text{ km s}^{-1}$).

18 To examine hydrogen gas (H I; 21cm) distribution around G049.41, we integrated the Lei-
19 den/Argentine/Bonn H I survey data¹⁸ over ± 2 degrees of Galactic latitude b . Fig. 2 shows that
20 G049.41 associated with the inner Perseus arm, is located in a faint area of the H I emissions. In-

deed, the faint area (~ 10 K; gray area) is more than two times as faint as the surrounding area (> 20 K). Physical size of the faint area scales as $1.2 \times (\frac{\Delta l [\text{deg}]}{10})(\frac{d [\text{kpc}]}{6.6})$ [kpc], where Δl is a range of Galactic longitude, and d is heliocentric distance. The distance of G049.41 is $6.6^{+1.1}_{-0.4}$ kpc¹⁴. Fig. 2 indicates an existence of H I hole with a size of ~ 1 kpc around G049.41. H I mass in the figure can be estimated with a general procedure¹⁹ as

$$M_{\text{H I}} \sim 2 \times 10^6 (\frac{T_b [\text{K}]}{10})(\frac{\Delta V_{\text{LSR}} [\text{km s}^{-1}]}{20})(\frac{\Delta l [\text{deg}]}{10})(\frac{d [\text{kpc}]}{6.6})^2 [M_{\odot}],$$

where T_b is the brightness temperature, ΔV_{LSR} is a range of LSR velocity, and $M_{\odot}$ is the solar mass. Thus, the mass difference between the faint and surrounding areas is $> 2 \times 10^6 M_{\odot}$ at the distance of G049.41. A similar shape (i.e., black polygon in Fig. 2), but with bright emissions, was discovered toward a high-velocity gas in M101²⁰. M101 is the nearly face-on spiral galaxy, and shows holes in H I distribution^{21,22}. The high-velocity gas is moving perpendicular to the disk of M101, and its origin is thought to be recent collisions of extragalactic gas clouds with the disk of M101²⁰.

To reveal the origin of the faint H I emissions, we integrated H I emissions over the velocity range in the black polygon of Fig. 2. Fig. 3a shows extended H I emissions above and below the Galactic plane at $0^\circ \leq l \leq 50^\circ$. Since local H I emissions are dominant²³ at $V_{\text{LSR}} \sim 0 \text{ km s}^{-1}$, we reintegrated H I emissions over a velocity range of $-20 \leq V_{\text{LSR}} [\text{km s}^{-1}] \leq -5$ in Fig. 3b. The figure displays patchy H I emissions especially above the Galactic plane at $0^\circ \leq l \leq 90^\circ$. Thus, extended H I emissions above the plane are likely excess over the local H I emissions. Relationship between the excess emissions above the plane and the faint emissions in the disk will be further discussed below.

To estimate the distance of the excess H I emissions, we obtained the 6D phase space information for stars from the early installment of the *Gaia*'s third data release (EDR3)^{24–26}. Stars that satisfied the LSR velocity range in the black polygon (Fig. 2) and a parallax accuracy of better than 20%, were selected (see **Methods** for details). The final sample was composed of 424,059 stars, of which 47,695 stars had metallicity information (the common logarithm of the iron-to-hydrogen ratio divided by the solar value; [Fe/H]). Stars with [Fe/H] < −1.0 dex (i.e., less than one tenth of the solar metallicity) are defined as “*low metallicity stars*” in this paper (430 stars identified). We found that the low metallicity stars were systematically distributed above the Galactic plane with a median Galactic height (z) of 1.8 kpc, whereas stars with [Fe/H] ~ 0 (i.e., solar metallicity) were distributed more closely to the plane (Extended Data Fig. 1). We examined the kinematics of the low metallicity stars, and found that retrograde low-metallicity stars (i.e., $V_\phi < 0$ km s^{−1}) are moving away from the Galactic plane with a median vertical velocity (V_z) of 68 km s^{−1} (Extended Data Figures 2 and 3). The retrograde low-metallicity stars and G049.41 are superimposed on $l - b$ plots of H I emissions (Figures 3a and 3b). Surprisingly, the distribution of the retrograde low-metallicity stars is well matched with those of H I emissions above the plane. Mass of H I emissions scales as $M_{\text{HI}} \sim 5 \times 10^6 \left(\frac{T_b[\text{K}]}{2} \right) \left(\frac{\Delta V_{\text{LSR}}[\text{km s}^{-1}]}{15} \right) \left(\frac{\Delta l[\text{deg}]}{90} \right) \left(\frac{\sin(b_{\text{max}}) - \sin(b_{\text{min}})}{\sin(60^\circ) - \sin(40^\circ)} \right) \left(\frac{d[\text{kpc}]}{5.5} \right)^2 [M_\odot]$, where $b_{\text{max}} - b_{\text{min}}$ is a range of Galactic latitude, and the others were explained previously. The median distance of the retrograde low-metallicity stars is 5.5 kpc. In Fig. 3b, mean brightness temperature is ~ 2 K at a Galactic latitude range of $40^\circ \leq b \leq 60^\circ$. The order estimation of the H I mass ($\sim 10^6 M_\odot$) above the plane is comparable to that of missing H I mass filling in the H I gap of $l - V_{\text{LSR}}$ plot (Fig. 2). Observational results indicate that H I gas in the disk was blown away to the

halo when the retrograde low-metallicity stars crossed the disk. In addition, the peculiar motion of G049.41 might originate in the disk crossing of the retrograde low-metallicity stars.

To reveal a progenitor of the retrograde low-metallicity stars, we examined physical properties of the stars (see Extended Data Figures 4a-4c for details). By comparing those with the literature²⁷, most retrograde low-metallicity stars (>75 %) are likely debris stars from *Gaia*-Sausage-Enceladus (hereafter GSE) as explained below. The GSE is a massive dwarf galaxy (with a virial mass of $>10^{10} M_{\odot}$), and the Milky Way experienced the last major merger with GSE ~ 10 Gyr ago^{10–13}. GSE stars show physical properties such as (1) slightly retrograde, (2) elongated trajectory with eccentricity (e) >0.7 , and (3) low [Fe/H] and [α /Fe] values. All the properties are well matched with those of the retrograde low-metallicity stars. A small fraction (<25 %) of the retrograde low-metallicity stars, satisfying low eccentricity and rich [α /Fe], are likely contamination by low-metallicity thick-disk stars. The low-metallicity thick-disk stars are thought to be born during or after the GSE merger²⁷.

We checked to determine when retrograde low-metallicity stars with $e >0.7$ crossed the Galactic disk, by orbit integration (see Extended Data Fig. 5 for details). The eccentricity cut was applied so that contamination by low-metallicity thick disk was removed. The stars frequently crossed the disk ~ 20 Myr ago under an assumed Galactic potential. Disk crossing places in 15–25 Myr ago are spread around the Galactic center as well as a past orbit of G049.41. Since G049.41 is associated with the inner Perseus arm, the H I gas in the arm could have been blown away toward the halo by the disk crossings. However, the conclusion of disk crossings in ~ 20 Myr ago

1 is inconsistent with a typical age of star forming regions, being 0.5–5 Myr²⁸. The discrepancy
2 could be resolved by referring to previous hydrodynamic simulations which examined collisions
3 of high-velocity clouds with the Milky Way^{29,30}. The simulations revealed that leading shock wave
4 continues to penetrate into the Galactic disk after the collision. Thus, star formation of G049.41
5 might have been triggered by leading shock wave in recent 5 Myr.

6 Finally, we summarize our interpretation about observational results. Very recently (~ 20
7 Myr ago), debris stars from *Gaia*-Sausage-Enceladus crossed the Galactic disk (Fig. 4). At that
8 time, H I gas with a mass of $\sim 10^6 M_{\odot}$ could have been blown away to the halo. Since stellar
9 system is collision less, GSE debris composed of stars and gas might collide with the Galactic
10 disk. Raw material for star formation in the inner Perseus arm could have been reduced by the disk
11 crossing, although relationship between the arm and the disk crossing should be further examined.
12 The parental cloud of G049.41 might be perturbed by shock wave induced by the disk crossing.
13 The above interpretation is schematically summarized in Fig. 4. New observational discoveries
14 compel us to reconsider the recent history of the Milky Way and understanding of the inner Perseus
15 arm.

Figure 1: **Histograms of azimuthal (V_ϕ , a) and vertical (V_z , b) velocities at a Galactocentric distance range of $6 \leq R \text{ (kpc)} \leq 7$.** Plotted are star-forming regions, among which G049.41+00.32 is emphasized by red. Median errors of V_ϕ and V_z are 6.6 and 6.3 km s^{-1} , respectively. Blue dashed curves are Gaussian distributions obtained by the unweighted least squares. Mean values of the distributions are $237.7 \pm 8.0 \text{ km s}^{-1}$ and $-1.4 \pm 7.5 \text{ km s}^{-1}$ for V_ϕ and V_z , respectively. The errors are the standard deviations. Differences between G049.41+00.32 and the Gaussian distributions are 4.1σ (statistically significant) and 2.1σ (marginally significant) for V_ϕ and V_z , respectively.

Figure 2: **Radio emission of neutral hydrogen gas in position-velocity diagram.** It is obtained by integrating over ± 2 degrees of Galactic latitude. Horizontal axis is Galactic longitude (l) while vertical one is line-of-sight (LSR) velocity. Color shows mean brightness temperature. Black polygon emphasizes faint (gray) area of the emission. White circle shows the star-forming region G049.41+00.32 associated with the inner Perseus arm.

Figure 3: **Extended neutral hydrogen gas in Galactic coordinates.** **a**, It is obtained by integrating over the LSR velocity range in the black polygon (Fig. 2). White and black circles represent G049.41+00.32 and retrograde low-metallicity stars (i.e., $V_\phi < 0 \text{ km s}^{-1}$ and $[\text{Fe}/\text{H}] < -1.0$), respectively. Arrows display motion vectors corrected for LSR (i.e., $\mathbf{V} - \mathbf{V}_{\text{LSR}}$). **b**, Same as (a), but with an integration range of $-20 \leq V_{\text{LSR}} (\text{km s}^{-1}) \leq -5$. It is less affected by local emissions at $0^\circ \leq l \leq 50^\circ$, compared to (a). Extended H I emissions are well followed by the retrograde low-metallicity stars.

Figure 4: **Cartoon for an interpretation of observational results.** **a-b**, Based on orbit integration (see Extended Data Fig. 5 for details), debris stars from *Gaia*-Sausage-Enceladus crossed the Galactic disk ~ 20 Myr ago, as shown in the upper figures. The crossing places are near to G049.41+00.32 associated with the inner Perseus arm. Edge-on (**a**) and face-on (**b**) views of the Milky Way are illustrated. Galactic rotation is clockwise in **b**. **c-d**, same as **a-b**, but for the current picture of the Milky Way.

Methods

Method summary: We used data sets consisting of neutral hydrogen (H I) gas, 35 star-forming regions (SFRs) and 424,059 stars in this paper. 6D (position-velocity) phase space information was obtained for the SFRs and stars by analyzing VLBI and *Gaia* astrometric data. For astrometric data reductions, we followed procedures^{31–34} in which coordinates (α , δ , J2000), parallax, LSR velocity and proper motion of each source are used. The required Galactic and solar motion parameters are given in Extended Data Table 2, and those associated with the source are defined in Extended Data Table 3. The parameters and the definitions are applied throughout the paper. Here, we only describe details about the stellar sample because we applied general procedures for H I and VLBI data analyses.

Chemo-kinematical stellar sample We refer to the early installment of the *Gaia*’s third data release (EDR3; **1.8 billion stars**)^{24–26}, which contains the parallax and proper motion results of **1.5 billion stars**. Radial velocity information for **7 million stars**, compiled from *Gaia* DR2, are listed in *Gaia* EDR3. Bright late type-stars (giants) are dominant among the 7 million stars³⁵. We checked to determine each radial velocity as a function of Galactic longitude satisfied the LSR velocity range in the black polygon (Fig. 2). Note that radial velocity in *Gaia* EDR3 is calculated in the solar barycentric reference frame ($\sim$ heliocentric radial velocity V_{Helio}), and thus we converted each radial velocity to LSR velocity (V_{LSR}) for the comparison.

Also, we added the restriction of a parallax accuracy better than 20% ($\frac{\pi}{\delta\pi} > 5$). This is because estimating distance by simply inverting the parallax can result in the Lutz-Kelker bias,

which becomes significant when the parallax error is large (e.g., $\frac{\pi}{\delta\pi} \leq 4$)³⁶. As a result, **424,059** stars were selected in a Galactic longitude range of $0^\circ \leq l \leq 90^\circ$ as shown in Extended Data Fig. 6 (gray histogram).

We conducted cross-matching between 424,059 stars and catalogs containing [Fe/H] information, with 1'' (arcsecond), where the nearer object was prioritized when multiple objects were cross-matched. The reference catalogs were Apache Point Observatory Galactic Evolution Experiment (APOGEE) DR16³⁷ and Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) DR5³⁸. We prioritized APOGEE DR16 when results were duplicated, because we experimentally confirmed that precision of APOGEE DR16 is better than that of LAMOST DR5. Finally, we obtained **47,695** stars as shown in Extended Data Fig. 6 (red histogram). Distance distributions of the both stellar samples range between 0 and ~ 20 kpc as shown in Extended Data Fig. 6. Among **47,695** stars, [Mg/Fe] information was available for **12,316** stars. Note that [Mg/Fe] information was available only in APOGEE DR16.

Extended Data Figure 1: $[\text{Fe}/\text{H}]$ vs. Galactic height. *Gaia* EDR3 stars that satisfy the LSR velocity range in the black polygon (Fig. 2) and a parallax accuracy of better than 20%, are plotted (see **Methods** for details). Gray indicates number of the stars in each bin. Red circles show mean values with error bars (standard errors). Low metalliity stars ($[\text{Fe}/\text{H}] < -1$) are systematically distributed above the Galactic plane. Median error of $[\text{Fe}/\text{H}]$ is 0.03.

Extended Data Figure 2: Velocity distribution of low metallicity stars. **a-b**, Azimuthal (V_ϕ) velocity is plotted as a function of the radial (V_R , **a**) and vertical (V_z , **b**) velocities, respectively, in Galactocentric cylindrical coordinates. Median errors of V_R , V_ϕ and V_z are 4.4, 4.4 and 3.0 km s^{-1} , respectively. Orbital eccentricity, shown by color, was calculated with the `galpy`³⁹, employing the (currently) recommended Milky Way potential, `MWPotential2014`³⁹. There are 91 retrograde stars (i.e., $V_\phi < 0 \text{ km s}^{-1}$), among which 70 (77%) stars show positive V_z .

Extended Data Figure 3: Spatial distribution and kinematics for G049.41+00.32 and retrograde low-metallicity stars. **a-c**, Color indicates eccentricity, and large white circle shows G049.41+00.32. The sample is plotted in XY (**a**), Xz (**b**), and Yz (**c**) of Galactocentric Cartesian coordinates. Arrows display motion vectors, corrected for LSR. Black curve is a model of the Perseus arm¹⁴. Origin is the Galactic center and solar position is $(X, Y) = (8.15, 0)$ kpc¹⁴ as indicated by the solar symbol ($\odot$).

Extended Data Figure 4: Physical properties of retrograde low-metallicity stars. **a**, Root sum square of the radial (V_R) and vertical (V_z) velocities is plotted as a function of the azimuthal (V_ϕ) velocity in Galactocentric cylindrical coordinates. Color represents eccentricity in **(a)** and **(c)**. Black curve distinguishes between kinematically halo and disk stars²⁷. **b**, 68 (75%) retrograde low-metallicity stars show an eccentricity larger than 0.7 in histogram. Elongated trajectories are matched with a typical property of *Gaia*-Sausage-Enceladus (GSE) stars⁴⁰. **c**, Gray indicates number of stars in $[Fe/H]$ vs. $[Mg/Fe]$ plot. Large circles show the retrograde low-metallicity stars. Error bars are statistical errors, taken from LAMOST DR5 and APOGEE DR16 catalogs. Small circles display GSE stars on alpha-poor sequence, taken from the literature¹¹.

Extended Data Figure 5: Orbit integrations for G049.41+00.32 and GSE stars. **a**, The orbit integrations were conducted backward in time for 120 Myr with the `galpy`³⁹, employing the (currently) recommended Milky Way potential, `MWPotential2014`³⁹. The open circle represents the current location of G049.41+00.32 in Galactocentric Cartesian coordinates. The color indicates the time and colored circles show disk crossing places for retrograde low-metallicity stars with eccentricities > 0.7 . Large colored circles emphasize stars with $-25 \leq t \leq -15$ Myr. Black crosses show intervals of -10 Myr on the orbit of G049.41. Galactic rotation is clockwise as indicated by the arrow. **b**, Histogram for the time since the stars crossed the disk.

Extended Data Figure 6: Histograms for heliocentric distance of stellar samples. *Gaia* EDR3 stars that satisfy the LSR velocity range in the black polygon (Fig. 2) and a parallax accuracy of better than 20%, are plotted (gray histogram; 424,059 stars; see **Methods**). Among 424,059 stars, 47,695 stars have [Fe/H] information (as shown by the red histogram).

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Extended Data Table 1: 35 VLBI astrometric results at $6 \leq R \text{ (kpc)} \leq 7$.

Name	$R \text{ (kpc)}$	$V_R \text{ (km s}^{-1}\text{)}$	$V_\phi \text{ (km s}^{-1}\text{)}$	$V_z \text{ (km s}^{-1}\text{)}$	Spiral arm	Ref.
G008.34-01.00	$6.61^{+0.09}_{-0.10}$	2 ± 5	228 ± 6	-5 ± 6	Sagittarius	14
G011.49-01.48	6.93 ± 0.05	1 ± 3	247 ± 4	-1 ± 3	Sagittarius	14
G014.63-00.57	6.39 ± 0.07	-2 ± 6	234 ± 10	-3 ± 10	Sagittarius	14
G015.03-00.67	$6.24^{+0.09}_{-0.10}$	-1 ± 3	241 ± 5	-5 ± 5	Sagittarius	14
G017.02-02.40	$6.37^{+0.30}_{-0.44}$	-4 ± 4	229 ± 7	-5 ± 6	Sagittarius	14
G017.55-00.12	$6.26^{+0.13}_{-0.15}$	-21 ± 10	242 ± 10	-1 ± 10	Sagittarius	14
G017.63+00.15	6.74 ± 0.04	-8 ± 10	241 ± 10	4 ± 10	Sagittarius	14
G018.34+01.76	6.28 ± 0.07	-5 ± 4	235 ± 6	2 ± 6	Sagittarius	14
G034.79-01.38	6.18 ± 0.09	7 ± 7	241 ± 7	-6 ± 8	Sagittarius	14
G035.02+00.34	$6.39^{+0.14}_{-0.16}$	-12 ± 8	242 ± 8	-1 ± 10	Sagittarius	14
G035.19-00.74	$6.48^{+0.14}_{-0.16}$	4 ± 7	229 ± 7	-8 ± 5	Sagittarius	14
G035.20-01.73	6.34 ± 0.05	-2 ± 5	237 ± 5	-8 ± 6	Sagittarius	14, 15
G037.42+01.51	6.75 ± 0.05	-8 ± 3	241 ± 3	-3 ± 3	Sagittarius	14
G037.50+00.53	$6.71^{+1.76}_{-0.98}$	6 ± 42	200 ± 38	4 ± 10	Perseus	15
G037.82+00.41	$6.93^{+2.55}_{-1.23}$	10 ± 54	212 ± 52	2 ± 8	Perseus	15
G038.03-00.30	$6.49^{+2.36}_{-1.03}$	8 ± 62	256 ± 51	-1 ± 4	Sagittarius	14
G040.50+02.54	$6.81^{+0.05}_{-0.06}$	9 ± 4	241 ± 3	6 ± 4	Sagittarius	15
G041.22-00.19	$6.02^{+1.22}_{-0.50}$	11 ± 48	232 ± 25	-1 ± 6	Sagittarius	14
G045.07+00.13	$6.11^{+0.16}_{-0.12}$	-9 ± 16	239 ± 7	8 ± 10	Sagittarius	14
G045.45+00.06	$6.40^{+0.70}_{-0.37}$	11 ± 38	237 ± 19	-21 ± 17	Sagittarius	14
G045.80-00.35	$6.06^{+0.55}_{-0.19}$	1 ± 38	238 ± 11	-14 ± 8	Sagittarius	14
G048.99-00.29	6.16 ± 0.05	0 ± 22	242 ± 10	-14 ± 14	Sagittarius	14

Extended Data Table 1: 35 VLBI astrometric results at $6 \leq R$ (kpc) ≤ 7 (*Continued*).

Name	R (kpc)	V_R (km s $^{-1}$)	V_ϕ (km s $^{-1}$)	V_z (km s $^{-1}$)	Spiral arm	Ref.
G049.04-01.07	$6.20^{+0.18}_{-0.05}$	-28 ± 30	218 ± 6	1 ± 8	Sagittarius	14
G049.19-00.33	6.17 ± 0.01	-8 ± 11	242 ± 5	10 ± 10	Sagittarius	14
G049.34+00.41	$6.29^{+0.10}_{-0.08}$	-12 ± 16	246 ± 6	-3 ± 6	Sagittarius	14
G049.41+00.32	$6.59^{+1.12}_{-0.35}$	13 ± 47	160 ± 17	31 ± 14	Perseus	14
G049.48-00.38	6.20 ± 0.01	9 ± 9	234 ± 4	5 ± 5	Sagittarius	14
G049.59-00.24	6.24 ± 0.02	-15 ± 8	239 ± 5	-12 ± 5	Sagittarius	14
G052.10+01.04	$6.52^{+0.10}_{-0.06}$	-6 ± 43	229 ± 40	-1 ± 40	Sagittarius	14
G054.10-00.08	$6.62^{+0.05}_{-0.01}$	-11 ± 21	227 ± 5	9 ± 12	Local arm spur	14
G055.37+00.19	$6.76^{+0.09}_{-0.05}$	-25 ± 23	225 ± 3	-10 ± 8	Local arm spur	15
G305.20+00.01	$6.70^{+0.10}_{-0.03}$	4 ± 27	228 ± 6	8 ± 6	Centaurus	14
G339.88-01.25	$6.24^{+0.27}_{-0.37}$	6 ± 4	239 ± 6	9 ± 5	Centaurus	14
G351.44+00.65	$6.84^{+0.11}_{-0.13}$	0 ± 3	239 ± 5	-2 ± 4	Sagittarius	14
G353.27+00.64	$6.47^{+0.15}_{-0.19}$	-6 ± 5	257 ± 7	9 ± 5	Sagittarius	15

Source name is listed together with Galactocentric distance (R), radial (V_R), azimuthal (V_ϕ), and vertical (V_z) velocities in Galactocentric cylindrical coordinates. Spiral-arm assignment is referred to the literature¹⁴ or position-velocity ($l - v$) diagram of CO⁴¹. Astrometric result (i.e., parallax and proper motion) and LSR velocity are taken from a reference as shown in the last column. Variance weighted parallax is assigned when there are independent results for the source. Note that all the sources satisfy a parallax accuracy of better than 25 % (i.e., $\frac{\pi}{\Delta\pi} > 4$).

Extended Data Table 2: Galactic and solar parameters.

Parameter	Value	Ref.
Distance to the GC ^a , R_0	8.15 kpc	14
Rotation speed of LSR ^a , Θ_0	236 km s ⁻¹	14
Right ascension of NGP ^a (J2000.0), α_{NGP}	12 ^h 51 ^m 26 ^s .2817	42
Declination of NGP ^a (J2000.0), δ_{NGP}	27°07'42".013	42
Position angle of $l = 0^\circ$ relative to NCP ^a , θ	122°.932	43
Standard solar motion ^a toward GC, $U_{\odot}^{\text{Std}}$	10.3 ^b km s ⁻¹	IAU ⁴⁴
Standard solar motion ^a toward $l = 90^\circ$, $V_{\odot}^{\text{Std}}$	15.3 ^b km s ⁻¹	IAU ⁴⁴
Standard solar motion ^a toward NGP, $W_{\odot}^{\text{Std}}$	7.7 ^b km s ⁻¹	IAU ⁴⁴
Best solar motion toward GC, $U_{\odot}$	10.6 km s ⁻¹	14
Best solar motion toward $l = 90^\circ$, $V_{\odot}$	10.7 km s ⁻¹	14
Best solar motion toward NGP, $W_{\odot}$	7.6 km s ⁻¹	14

^a GC: the Galactic center; LSR: local standard of rest; l : Galactic longitude; NGP: north Galactic pole; NCP: north celestial pole.

^b The values given above come from a solar motion of 20 km s⁻¹ toward R.A. (1900) = 18^h and Decl. (1900) = -30° processed to J2000.0¹⁴.

Extended Data Table 3: Definitions of source parameters.

Parameter	Definition
l	Galactic longitude [degree]
b	Galactic latitude [degree]
π	Trigonometric parallax [mas]
d	Heliocentric distance ($1/\pi$) [kpc]
V_{LSR}	LSR radial velocity [km s^{-1}]
V_{Helio}	Heliocentric radial velocity [km s^{-1}]
$\mu_{\alpha} \cos \delta$	Proper motion in R.A. [mas yr^{-1}]
μ_{δ}	Proper motion in Decl. [mas yr^{-1}]
β	Angle of Sun-GC-source ^a [degree]
V_R	Radial velocity in Galactocentric cylindrical coordinates [km s^{-1}]
V_{ϕ}	Azimuthal velocity ^b in Galactocentric cylindrical coordinates [km s^{-1}]
V_z	Vertical velocity ^b in Galactocentric cylindrical coordinates ^a [km s^{-1}]

^a β is positive in the direction of the Galactic rotation.

^b V_{ϕ} and V_z are positive in the direction of the Galactic rotation and toward the north Galactic pole, respectively.

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