Tracing the Origin of Moving Groups. III. Detecting Moving Groups in LAMOST DR7

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Abstract

We revisit the moving groups (MGs) in the solar neighborhood with a sample of 91,969 nearby stars constructed from LAMOST DR7. Using the wavelet technique and Monte Carlo simulations, five MGs together with a new candidate located at V≃−130 km s−1 are detected simultaneously in V − √U2 + 2V2 space. Taking into account the other known MGs, we conclude that MGs in the Galactic disk are spaced by approximately 15–25 km s−1 along V velocity. The origin of detected MGs is analyzed through the distributions of [Fe/H]−[Mg/Fe] and ages. Our results support attributing the origin to the continuous resonant mechanisms probably induced by the bar or spiral arms of the Milky Way.

Unified Astronomy Thesaurus concepts: Milky Way disk (1050); Milky Way dynamics (1051); Milky Way evolution (1052); Solar neighborhood (1509)

1. Introduction

Moving groups (MGs) are detected as kinematic substructures in the solar neighborhood whose member stars share similar velocity components. Different kinds of hypotheses have been put forward to interpret the origin of them. It was previously believed that they came from dissolving open clusters (e.g., HR1614; De Silva et al. 2007). However, this interpretation is incompatible with most of the known MGs for the inhomogeneity of age and chemistry within them (e.g., Famaey et al. 2005; Ramya et al. 2012; Kushniruk & Bensby 2019). Later, dynamical mechanism of internal resonances caused by the Galactic bar or spiral arms was proposed (e.g., Dehnen 2000; Quillen & Minchev 2005; Monari et al. 2019). Specifically, the existence of Hercules is highly consistent with the effects of the bar resonances (Bensby et al. 2007). Some structures with low angular momenta below Hercules were reproduced, considering spiral arms plus a bar with a pattern speed of Ω0 = 45 km s−1 kpc−1 and a hot disk with a velocity dispersion of ~40 km s−1 at R⊙ = 8.5 kpc as the initial condition (Figure 1(i) in Antoja et al. 2009). Some retrograde MGs pertaining to the Galactic halo or spiral arms were also related to resonant orbits created by the bar (Schuster et al. 2019). Furthermore, MGs can be explained as relics of disrupted satellite galaxies or products of perturbations by external accretion events (Minchev et al. 2009). For example, Navarre et al. (2004) attributed the Arcturus group to remnants of a dwarf galaxy merged with the Milky Way since a tight sequence in the [Fe/H]−[α/Fe] plane was found, although this argument has been disproved using more unbiased data (Kushniruk & Bensby 2019).

Nowadays, the Gaia mission (Gaia Collaboration et al. 2018a, 2021), along with spectroscopic surveys such as LAMOST (Cui et al. 2012; Zhao et al. 2006, 2012; Zhao & Chen 2021) and APOGEE (Majewski et al. 2017; Ahumada et al. 2020), has provided ample stellar astrometric, photometric, and spectroscopic information, and unprecedented details of MGs have been revealed. These large data sets also allow the derivation of stellar age, which plays another crucial role in order to better understand the MGs. In Antoja et al. (2008), ages were used to study the evolutionary state of the nearby kinematic substructures. The origin of Hercules was investigated through the age distributions in Bensby et al. (2007, 2014).

In Liang et al. (2018, Paper I) and Zhao et al. (2018, Paper II), the origins of the γ Leo moving group and LAMOST-N1 (Zhao et al. 2015) were investigated through detailed abundance analysis. In this work, we detect MGs in the solar neighborhood with samples constructed from LAMOST DR7. We further discuss the origin of the MGs by analyzing their chemical properties and ages. Section 2 describes the data process. Section 3 characterizes MGs detection in detail. Section 4 analyzes the origin of MGs through chemistry and age. A summary is presented in Section 5.

2. Data

LAMOST DR7 provides stellar atmospheric parameters and radial velocities for 6,159,427 stars, including 94,908 A-type stars, 1,893,014 F-type stars, 3,099,821 G-type stars, and 1,071,684 K-type stars. The data are cross-matched with Gaia eDR3 to get proper motion. Distance comes from a Bayesian estimate (Bailer-Jones et al. 2021), which is derived using the parallax, color, and apparent magnitude of a star (called “photogeometric distance”).

Heliocentric velocities and corresponding uncertainties, together with angular momenta and actions, are computed using galpy5 Python package (Bovy 2015) by adopting the Galactic potential model MWPotential2014. We adopt (r_hi − r_lo)/2 as the error estimate of r_med, corresponding to the 84th, 16th, and 50th percentiles of the photogeometric distance posterior, respectively. Solar distance to the Galactic center and circular velocity at the Sun are set to 8 kpc and 220 km s−1 (Bovy et al. 2012), consistent with the values adopted for the MWPotential2014. Finally, velocities (U, V, W)4 are given relative to the local standard of rest.

5 Available at http://github.com/jobovy/galpy.
4 U points toward the Galactic center. V is along the direction of the Galactic rotation. W points at the north Galactic pole.
(LSR) using solar peculiar motion \((U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \, \text{km s}^{-1}\) (Schönrich et al. 2010).

For reduced data, we require that uncertainties of three velocity components \(\sigma_{U}, \sigma_{V}, \text{and } \sigma_{W}\) are <10 km s\(^{-1}\) and distance \(d\) is <2 kpc. Considering that MGs of the thin disk have been well studied, we further select stars with \([\text{Fe}/\text{H}] < -0.7 \, \text{dex}\) to mainly focus on the MGs of the thick disk.\(^5\) It should be noted that the metallicity cut cannot totally rule out the thin-disk stars but the thick disk will become dominant after this cut. Our final samples consist of 91,969 stars. Figure 1 shows the distributions of \(V\) velocity of LAMOST data, in which the blue line denotes the selected samples and the red line represents the data without \([\text{Fe}/\text{H}]\) limit.

### 3. Moving Group Detection

#### 3.1. Wavelet Transform

The wavelet transform (WT) technique can provide distinct signatures of substructures and has been widely used in the detection of MGs. If we denote the 2D distribution of data as \(F(x, y)\), the WT coefficient at a certain point \((x', y')\) can be obtained by

\[
w(x', y') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Psi(x, y) F(x, y) \, dx \, dy,
\]

where \(\Psi(x, y)\) is a Mexican-hat function used as the mother wavelet, which is given by

\[
\Psi(x, y) = 2 \left( \frac{(x-x')^2 + (y-y')^2}{s^2} \right) \exp \left( - \frac{(x-x')^2 + (y-y')^2}{2s^2} \right).
\]

\(\text{where } s\) is the scale.

In this work, we perform WT on our samples in \(V - \sqrt{U^2 + 2V^2}\) space. Exploring the MGs in \(V - \sqrt{U^2 + 2V^2}\) was first proposed by Arifyanto & Fuchs (2006) and successfully applied in Klement et al. (2008) and Zhao et al. (2014). \(V\) is proportional to vertical angular momentum \(L_z\), and \(\sqrt{U^2 + 2V^2}\) is related to orbital eccentricity \(e\), in Dekker’s theory (Dekker 1976).

#### 3.2. Construction of a Model Velocity Distribution

An inevitable problem in MGs detection is Poisson noise. In Klement et al. (2008), they created a “smooth” reference model velocity distribution that matched the overall velocities of the data. Two hundred fifty Monte Carlo simulations were randomly drawn from the distribution, differences among which were due to Poisson noise. A feature detected in the data was compared to these simulations, in wavelet space, to see whether it was still significant. Here we employ the above method.

Considering the large number of our samples and asymmetries in velocities, especially in the \(V\) component, it is nearly impossible to design a Galactic model consisting of three Schwarzschild distributions that match the samples well. Instead, we run a Gaussian mixture model, realized by an extreme deconvolution (XD)\(^6\) algorithm (Bovy et al. 2011), to construct the smooth velocity distribution. The Bayesian information criterion (integrated in scikit-learn; Pedregosa et al. 2011) is calculated to determine how many Gaussians are needed. The criterion decreases rapidly as the number of Gaussians is increased to five, after which it stabilizes. Hence we run XD with five components, and in this case, \(U, V\) and \(W\) are considered simultaneously.

The components derived by XD have mean \((U, V)\) of (9.9, 2.4), (−9.1, −55.1), (−1.3, −55.6), (20.9, −96.9), and (2.0, −214.8) km s\(^{-1}\), with corresponding weights of 0.23, 0.27, 0.29, 0.15, and 0.06, respectively. It can be seen that the Gaussian mixture is focusing on modeling the stars around the Sirius and Hercules groups. The model distribution is shown in Figure 2, along with our samples as a comparison. Generally, the distribution fits the samples well, especially for the slope in the range between \(V \approx -200 \, \text{km s}^{-1}\) and \(-60 \, \text{km s}^{-1}\), where

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\(^5\) In this work, the terms “thin disk” and “thick disk” refer to the chemical thin and thick disks of the Milky Way (see Figure 8).

\(^6\) Available at https://github.com/jobovy/extreme-deconvolution.
the Galactic thick disk is roughly located. However, the model does not seem to be ideal below \( V \leq -200 \text{ km s}^{-1} \), which might be due to the fact that the stars here are quite sparsely distributed in velocity space. Hence, we avoid speculating about this part.

3.3. Detecting Moving Groups

We bin the data in pixels of 2 km s\(^{-1}\) width in \( V - \sqrt{U^2 + 2V^2} \) space and calculate the WT coefficient of each pixel \( w_{\text{data}} \) through Equation (1). Since we are concerned about overdense regions, negative coefficients are set to zero. The left panel in Figure 3 shows a 2D histogram of the samples, and the right one displays the corresponding WT coefficients at scale \( s = 10 \text{ km s}^{-1} \).

Two hundred fifty Monte Carlo (MC) simulations are generated by drawing, each time, 91,969 mock stars from the model distribution built in the previous section. We proceed to apply the same WT on the simulations and calculate the mean \( \bar{w}_{\text{MC}} \) and the standard deviation \( \sigma_{\text{MC}} \) of the 250 MC WT coefficients in each pixel, \( \bar{w}_{\text{MC}} \) is set to 0 whenever it is <0 and \( \sigma_{\text{MC}} \) is set to 1 whenever it is \(<1\), for the case that some pixels have no counts. Figure 4 displays the WT of simulations at scale \( s = 10 \text{ km s}^{-1} \). The left and right panels show the results of \( \bar{w}_{\text{MC}} \) and \( \sigma_{\text{MC}} \), respectively.

The significance \( \xi \) of a signal is defined as

\[
\xi = \frac{w_{\text{data}} - \bar{w}_{\text{MC}}}{\sigma_{\text{MC}}}.
\]

We calculate \( \xi \) at various scales, and signals with \( \xi \geq 2 \) are displayed in Figures 5 and 6. We focus on the results at scale \( s = 10 \text{ km s}^{-1} \) since the structures of this scale are the most detectable. As is shown, several features stand out, some of which, however, should be treated with caution. Specifically, features in the range between \( V \leq -60 \) and 0 km s\(^{-1}\) are more likely caused by the smoothness of the model velocity distribution (see Figure 2), which is also the reason why the Sirius and Hercules do not show up.

We match the remaining features with the MGs that have been studied in the literature. In the range of the thin disk, an MG with \( V \approx 40.7 \text{ km s}^{-1} \) is detected, corresponding to “A1” found by Ramos et al. (2018). In the range of the thick disk, several overdensities arise in our LAMOST samples. The feature located at \( V \approx -82.4 \text{ km s}^{-1} \) is described as AF06 (Arifyanto & Fuchs 2006). At \( V \approx -105.5 \text{ km s}^{-1} \), there exists the Arcturus moving group (e.g., Bensby et al. 2014). In addition, the feature at \( V \approx -156.0 \text{ km s}^{-1} \) corresponds to KFR08 detected by Klement et al. (2008), and the one at \( V \approx -173.1 \text{ km s}^{-1} \) corresponds to V3 in Zhao et al. (2014). Note
that $V$ velocities of AF06, KFR08, and V3 are a little higher than the values in the literature\(^7\) because different solar peculiar velocities were used ($V_\odot = 12.24$ km s\(^{-1}\) in this work).

At $V \approx -130.4$ km s\(^{-1}\), there is a new feature arising just as the other identified MGs. It is also detected at other scales shown in Figure 6. To our knowledge it has not been confirmed yet. Given that we successfully detect the known MGs in the thick disk, we are able to claim that the feature located at $V \approx -130.4$ km s\(^{-1}\) should be a candidate for a new MG.

Now we summarize the known MGs as follows. In Ramos et al. (2018), two new arches are detected: one is “A1” with $V \approx 38$ km s\(^{-1}\) and the other is “A2” with $V \approx -15$ km s\(^{-1}\). The Sirius has $V \approx 0$ km s\(^{-1}\). The Pleiades/Hyades stream is located between $V \approx -10$ and $-20$ km s\(^{-1}\). The Hercules has $V$ between $-40 \sim -50$ km s\(^{-1}\). HR1614 is at $V \approx -65$ km s\(^{-1}\).

Together with AF06, the Arcturus, the new feature in this work, KFR08, and V3 as described above, we conclude that MGs in the Galactic disk are spaced by approximately 15–25 km s\(^{-1}\) along $V$ velocity, taking into account velocity uncertainties and sizes of the structures.

### 4. Chemistry and Age

We investigate the detected MGs through distributions of chemistry and age, based on APOGEE DR16 and isochrone ages from Sanders & Das (2018). For the data, $\sigma_U$, $\sigma_V$, and $\sigma_W < 10$ km s\(^{-1}\) and $d < 2$ kpc are required. Then the candidate member stars of each MG are selected progressively in three planes defined by combinations of velocity, angular momentum, and action components: $V - \sqrt{U^2 + 2V^2}$ plane, $L_z - L_\perp$ plane (Helmi et al. 1999), and $L_z - \sqrt{J_r}$ plane (Trick et al. 2019; where $J_r$ is radial action). This will give us stronger criteria on the selection of member stars. Figure 7 illustrates an example of this selection for the new detected feature. Stars within 5 km s\(^{-1}\) around $V = -130.4$ km s\(^{-1}\) are selected (blue...
dots). They are explored in $L_z - L_\perp$ space, and stars within the most concentrated region are picked out (green dots). These stars are further plotted in the $L_z - \sqrt{J_z}$ plane, and ones in the densest area are chosen as the members (red dots). The aim of this procedure is to select the stars concentrated in kinematics and dynamics, although it is somewhat subjective since the level of concentration is judged by eye.

Figure 8 shows the distributions of MG members in the $[\text{Fe}/\text{H}] - [\text{Mg}/\text{Fe}]$ plane. Apparently, “A1” belongs to the thin disk alone. AF06 is a mixture of the thin and thick components. Arcturus, together with the new feature, KFR08, and V3, is related to the thick disk and even halo. In addition to these MGs, we also know that the Sirius and the Pleiades/Hyades are the ones in the thin disk (e.g., Ramya & Reddy 2014; Famaey et al. 2007), and the Hercules as well as HR1614 is a mixture of thin- and thick-disk stars (e.g., Bensby et al. 2007; Kushniruk et al. 2020). It can be seen that MGs have gone through a coherent transitional process from only containing the thin-disk stars, to being a mixture of the thin and thick disks, and then to containing the thick-disk and even halo stars. This trend is reasonable because the different Galactic components have different rotational offsets from the LSR (e.g., Bensby et al. 2003). The thin-disk stars have higher $V$ while the thick-disk stars have lower $V$. Hercules, HR1614, and AF06 are located in the range of a mixture of the thin and thick disks. What’s more, there is no sign indicating that any of these MGs follow a distinct chemical sequence from the background Milky Way stars. So we can infer that MGs mentioned here should not be treated as remnants of accreted galaxies.

The histograms of age are presented in Figure 9, for which the errors are less than 2 Gyr. As is shown, MGs with lower $V$ tend to be dominated by older stars, which is caused by different concentrations of age of stars populated in different Galactic components. It is worth noting that very young stars (<2 Gyr) are contained in the MGs. Minchev et al. (2009) attributed the origin of MGs with low angular momenta to the
5. Conclusion and Discussion

We detect MGs in the solar neighborhood with a sample of 91,969 nearby stars constructed from LAMOST DR7. The origins of MGs are analyzed through chemistry and age.

One candidate for a new MG is detected using the wavelet technique and Monte Carlo simulations. The new feature is centered at \( V \approx -130 \) km s\(^{-1}\). Together with other known substructures, we conclude that MGs in the Galactic disk are spaced by approximately 15–25 km s\(^{-1}\) along \( V \) velocity.

The wide spreads of chemical abundances and ages within MGs can rule out their dissolved open cluster origin. No existences of distinct [Fe/H]–[\( \alpha/Fe \)] trends from the background Milky Way stars exclude the remnants of accreted galaxies. The hypothesis of perturbation induced by a past merger is disfavored given that very young stars are contained in MGs. It is the resonant mechanism that does not contradict the results here. Therefore, we attribute the origin of MGs to the continuous resonances caused by the Galactic bar or spiral arms of the Milky Way.

In chemistry, the compositions of MGs change from the thin-disk stars, to mixtures of the thin and thick disks, and then to the thick disk and even halo stars. In terms of age, MGs with lower \( V \) tend to be older than those with higher \( V \). This seems to be a coherent transitional process, implying that they might be linked together rather than treated separately.
AF06 used to be considered as an MG in the thick disk. With \([\text{Fe}/\text{H}]-[\alpha/\text{Fe}]\) information here, it is clear that AF06 contains both the thin- and thick-disk stars.

Why are the MGs spaced by 15–25 km s\(^{-1}\) along \(V\)? There should be a mechanism that will trap stars in velocity space as long as their motions coincide with some certain conditions. Thus, answering what the mechanism is will be the key to uncovering the mystery of MGs. In addition, some clump substructures with low angular momenta were reproduced in the \(U-V\) space in Antoja et al. (2009) considering the bar and/or spiral arms together with a hotter disk as the initial condition (panels (f) and (i) in their Figure 1). Will it be a good scenario if we connect a “hotter disk” to the Galactic thick disk that was once heated by Gaia–Enceladus–Sausage (Belokurov et al. 2018; Helmi et al. 2018)? Modeling how the MGs with low angular momenta are generated should also play a vital role.

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