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Search for Stellar Streams in The Galactic Halo From Gaia DR2, GALAH DR2, RAVE DR5 and LAMOST DR4 Data

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Abstract. Stellar streams are stars which are trapped in the same potensial caused by dynamical resonance or tidal force. We aim to analyze kinematic substructures (streams) in the Galactic halo by V vs $\sqrt{U^2 + 2V^2}$ planes of Arifyanto & Fuchs. We crossmatched data from Gaia DR2, GALAH DR2, RAVE DR5 and LAMOST DR4 based on positions. We have 3D kinematics and metallicity data of halo stars selected from kinematics criteria from ratio of probability of thick disk (TD) over halo (H) less than 0.01. Substructures are detected by using wavelet transformation and corrected using 15 Monte Carlo simulations. We obtained four kinematic structures on V vs $\sqrt{U^2 + 2V^2}$ plane which two of them are associated to BB17-1 and BB17-2 streams. All the streams had a high probability from the extragalactic origin.

1 Introduction

There are two scenarios of galactic formation. First is monolithic collapse by Eggen, Lynden-Bell, and Sandage [1]. In monolithic collapse, a galaxy is formed from the same protogalaxy cloud which collapsed and every part of galaxy, such as bulge, disk, and halo, is formed at the same time. The second one is hierarchical scenario [2]. In this scenario, each part of galaxy is formed from different clouds then merge into one and forming a galaxy. This scenario can explain that stars in bulge, disk, and halo have different typical age. Hierarchical scenario is supported by a proof that Sagittarius dwarf spheroidal (Sgr dSph) deformed because of tidal force from Galactic center [3]. Some globular clusters such as M54, Arp2, Terzan7, and Terzan8 are suggested that came from Sgr dSph. Helmi and White [4] also showed that local stellar halo is builded by disrupted satellites.

Eggen introduced "moving group" as stars from an open cluster or from the same protostar cloud. The stars then escaped from the system so they are detected as a group of stars with the same velocity [5]. In 1978, Eggen introduced "retrograde group," stars that expected came from ω Centauri cluster [6]. Metalicity and age of stars in retrograde group are broad in range so this suggests that ω Centauri was a galaxy and stripped into Milky Way [7].

There are two types of streams: dynamical stream and tidal steam [8]. Stars that trapped into the same dynamical resonance, such as bar resonance and spiral arm resonance, is called

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dynamical stream. Stars that came from the same bounded object, such as satellite galaxy, can escaped from the system and enter the Milky Way forming tidal stream. Search for stellar streams are using star grouping in velocities space or integral of motion space. Dehnen [9], Skuljan [10], and Kushniruk et al. [11] use U vs V space for streams in Galactic disk. Several well-known streams are Hyades, Pleiades, and Sirius. These streams were thought to be originated from disrupted open cluster but their isochrone showed possibility of dynamical resonant origin [12]. Arifyanto & Fuchs [13] and Klement [8] use V vs $\sqrt{U^2 + 2V^2}$ space to identify streams in disk. Bajkova and Bobylev [14] use V vs $\sqrt{U^2 + 2V^2}$ space for searching streams in Galactic halo. Another integral of motion spaces for searching streams are V_{az} vs $V_{\Delta E}$ ([15], [16]), L_z vs $L_\perp$ [8], and L_z vs E ([17], [18]).

In this work, stellar streams are searched using V vs $\sqrt{U^2 + 2V^2}$ planes. U is velocity vector towards Galactic center, V is velocity vector in the direction of rotation of Galaxy and $\sqrt{U^2 + 2V^2}$ is related to eccentricity of star's explained in Section 3.

2 Data

To get velocities, we use parallax and proper motion data from Gaia DR2 [19] and radial velocity data from LAMOST DR4 [20], RAVE DR5 [21], and GALAH DR2 [22]. LAMOST DR4, RAVE DR5, and GALAH DR2 are crossmatched into Gaia DR2 data based on star's position with 0.8" radius. We select solar neighborhood stars with galactocentric radius within 7 to 10 kpc and distance from galactic plane $Z < 5$ kpc. We also eliminate stars with total velocity more than 580 kms^{-1} which is the Galactic escape velocity [23]. The selected stars are transformed to UVW velocities using matrix from [24] as shown in equation 1.

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = \mathbf{T}.\begin{bmatrix} +\cos\alpha\cos\delta & -\sin\alpha & -\cos\alpha\sin\delta \\ +\sin\alpha\cos\delta & +\cos\alpha & -\sin\alpha\sin\delta \\ +\sin\delta & 0 & +\cos\delta \end{bmatrix}\begin{bmatrix} V_r \\ k\mu_\alpha/\varpi \\ k\mu_\delta/\varpi \end{bmatrix} + \begin{bmatrix} U_\odot \\ V_\odot \\ W_\odot \end{bmatrix}, \quad (1)$$

where $\mathbf{T}$ is transformation matrix from galactic coordinates to equatorial coordinates, α and δ are equatorial coordinates, V_r is radial velocity, k is 4,74057 to transform all the units into kms^{-1}, μ_α and μ_δ are proper motion in equatorial coordinates, and ϖ is parallax of the stars. We use Sun's velocity component is $(U, V, W)_\odot = (11.1, 12.24, 7.25)$ kms^{-1} [25].

Galactic halo stars are selected kinematically as performed in [26]. We use probability of thick disk over halo $TD/H = \frac{X_{TD}}{X_H}\frac{f_{TD}}{f_H} < 0.01$ to reduce contamination from thick disk. Each X_{TD} and X_H is fraction number of thick disk and halo respectively. Each f_{TD} and f_H is Gaussian distribution function for stars in thick disk and halo respectively. The function of Gaussian distribution of 3D stellar kinematics is

$$f = \frac{1}{(2\pi)^{3/2}\sigma_U\sigma_V\sigma_W}\exp -\frac{U^2}{2\sigma_U^2} - \frac{(V - V_{asym})^2}{2\sigma_V^2} - \frac{W^2}{2\sigma_W^2}, \quad (2)$$

where σ_U, σ_V, and σ_W is velocity dispersions of each stellar population and V_{asym} is asymmetric drift relative to LSR. Value of σ_U, σ_V, σ_W, and V_{asym} in equation 2 is shown in Table 1.

3 Search Method

To find streams, we identify groupings on V vs $\sqrt{U^2 + 2V^2}$ space. Value of $\sqrt{U^2 + 2V^2}$ represents eccentricity of the star. Using Taylor expansion around $1/R$ and $1/R_0$ until second

Table 1: Fraction number and characteristics of Gaussian distribution for stars in thick disk and halo.

	X	σ_U	σ_U	σ_U	V_{asym}
		kms^{-1}			
Thick Disk (TD)	0.09	67	38	35	-46
Halo (H)	0.0015	160	90	90	-220

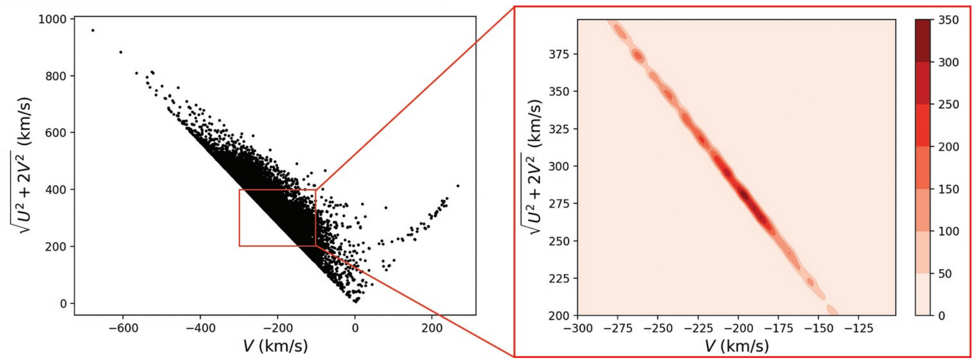

Fig. 1. Sample data distribution on V vs $\sqrt{U^2+2V^2}$ space (*left panel*). Wavelet transformation of the data in range of the red box is shown on the *right panel*.

order, Dekker's definition of angular velocity $\Omega(R) = \sqrt{\frac{1}{R}\frac{d\Phi}{dR}}$ [27], and energy of stars in the guiding center $E_0 = \Phi(R_0) + \frac{1}{2}R_0^2\Omega^2(R_0)$, Arifyanto & Fuchs [13] got eccentricity of stars is

$$e = \sqrt{\frac{2(E-E_0)}{R_0^2\kappa_0^2}} = \sqrt{\frac{U^2 + \frac{\kappa_0^2}{\Omega_0^2}V^2}{R_0^2\kappa_0^2}}. \tag{3}$$

For flat rotation curve, $\frac{\kappa_0^2}{\Omega_0^2} = 2$ and $R_0^2\kappa_0^2 = 2V^2$ so $e \propto \sqrt{U^2+2V^2}$.

Distribution of the data on V vs $\sqrt{U^2+2V^2}$ space is shown on left panel of Fig. 1. The groupings on this distribution are found using Mexican-hat wavelet transform from Skuljan [10]. Wavelet is a powerful way to extract signal from data distribution. We divide the data into several bins and calculate the wavelet coefficient of each bin using equation 4. For a two-dimensional distribution $f(x,y)$ at any point (ξ,η), the function of wavelet coefficient is

$$w(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\psi\Big(\frac{x-\xi}{a}, \frac{y-\eta}{a}\Big)dxdy, \tag{4}$$

where ψ is the analysing wavelet function. Here we use two-dimesional Mexican hat $\psi(d/a) = (2-(d/a)^2)\exp(-d^2/(2a^2))$, where $d = \sqrt{x^2+y^2}$ or the distance from bin to the data. The bin is square with 2 kms^{-1} width and scale parameter a is 4 kms^{-1}. The result of the transformation is shown in right panel of Fig. 1. We show significant groupings in range $V = [-300,-100]$ kms^{-1} and $\sqrt{U^2+2V^2} = [200,400]$ kms^{-1} because otherwise is relatively smooth.

The detected groupings are corrected using Monte Carlo simulation to reduce the statistic fluctuation. We generate 15 simulations, each simulation has the same number of stars as

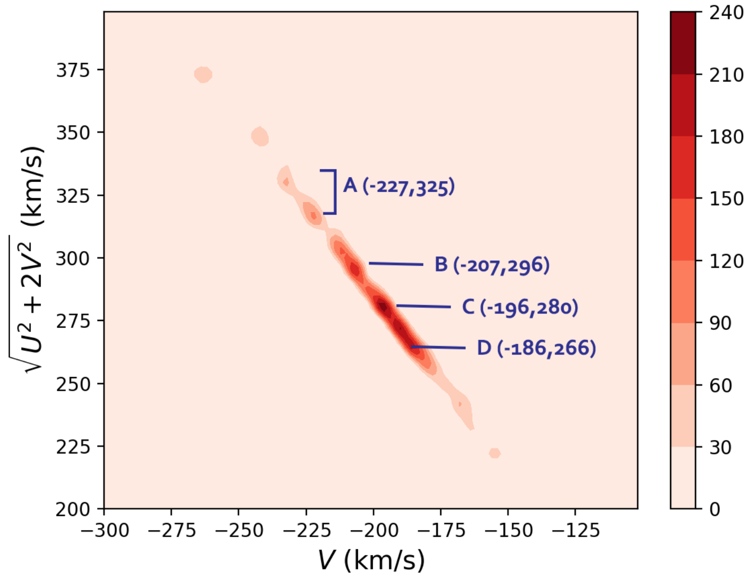

Fig. 2. Four groupings found after cleaning the data using Monte Carlo simulation.

our data. The synthetic data from simulation have the same Gaussian distribution as Galactic halo. Each simulation is treated the same as the data to get the wavelet transformation with the same size of bin. Each simulation is subtracted with transformed data. The mean of each substraction is shown in Fig. 2.

Table 2: Streams found and associated streams.

Streams found	Coordinates kms^{-1}	Associated streams	Coordinates of associated streams kms^{-1}
A	(-186,266)	BB17-1 [14]	(-170,250)
B	(-196,280)		
C	(-207,296)		
D	(-227,325)	BB17-2 [14]	(-220, 330)

4 Results

In this work, we found four streams or groupings as shown in Fig. 2 and Table 2. We labeled the groupings as A, B, C, and D. We suggest that two of them, A and D, are associated to BB17-1 and BB17-2, high velocity streams in Galactic halo by Bajkova & Bobylev [14]. Bajkova & Bobylev found three streams named BB17-1, BB17-2, and BB17-3. BB17-1 and BB17-2 are correlated to VelHel-6 and VelHel-7 streams by Helmi et al. [17]. Several streams found by Helmi et al., named VelHel-1, 2, 3, 4, 5, 8, and 9, have positions close to ω Centauri globular cluster. Properties of this cluster support the idea of ω Centauri probably was a galaxy and stripped into Milky Way. ω Centauri have a high mass ($\sim 7 \times 10^6$ $M_\odot$), flattened shape or tidal features, wide range of abundance and age, and retrograde orbit [7]. Other streams in Galactic halo may be the result of dwarf satellite galaxy. On the next work, we will analyze more about origin of these streams.

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