Search for streams in thick disk and halo of the Milky Way

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Abstract. Study on the substructures of Milky Way is very important because it can be used as the stage indicator in the formation process of the Galaxy. Substructures are made by clumps of stars with similar velocity, called as stellar streams. We searched for the stellar streams in thick disk and stellar halo of the Milky Way using data from Geneva-Copenhagen survey. We built velocity curves from data and applied the wavelet transform to find dense area in the velocity distribution. For the significance test, peaks on the wavelet transform of the data are reduced using wavelet transform based on Monte Carlo simulation. We found five streams on thick disk and two in stellar halo. Based on the metallicity distribution, it is shown that both thick disk and halo streams have similar range of metallicity, thus we classified them as dynamical stream.

1. Introduction
Two most well-known theories about the formation of galaxies are bottom-up and top-down scenarios. In bottom-up scenario [1], galaxies are formed through merger of small clumps into larger structure. While in top-down scenario [2], galaxies are the result of a giant structure splitting up into smaller scale. The right scenario should be justified by how well it can explain the observed facts of galaxies, for instance, the components observed in Milky Way.

We could constrain each scenarios through the analysis of metallicity distribution and the stellar kinematics in the galaxy. Existence of structures and substructures observed in the Galactic components are very important to constrain the formation scenarios. These structure(s) appear as a group of stars moving with similar velocity, known as stellar streams. There are two kinds of stellar streams: tidal streams and dynamical streams. Tidal streams consist of stars with similar velocities suspected to have similar origin, for example from globular cluster or galactic satellite. Dynamical streams consists of stars from different origin but trapped in the certain phase space because of the dynamic resonance.

This paper focused on the method of stellar stream search on the thick disk and halo of the Milky Way from Geneva-Copenhagen survey. The thick disk member is classified based on elemental abundance trends [3] while the halo member is classified based on metallicity of the stars. We applied wavelet transform on the stellar velocity distribution to search for streams as explained by [4].

2. Data and method
To detect stellar streams as the substructures in the space configuration, there are two conditions should be fulfilled. First, the disruption process on the stream occurred not so long ago, less than 10 Gyr [5], so that the structure are still not diluted and can be observed as clumps of data. Secondly, the survey should be conducted on a wide field of the sky. Therefore we used the data from Geneva-Copenhagen survey [6] via VizieR website. We got the parameters from 13.382 members of Milky Way in solar neighborhood. The important parameters that we used in this paper are metallicity[Fe/H] and velocity.
component in three directions: radial velocity (U), tangential velocity (V), and the velocity component to the north galactic pole (W).

2.1. Thick disk members classification
To find the possibility that a star is a member of a component of the Milky Way (we called it D, TD and H for the possibility of disk, thick disk and halo membership, respectively), we should constrain two relative possibility of the membership of thick disk compare to those in disk and halo:

\[
\frac{TD}{D} = \frac{X_{TD} f_{TD}}{X_{D} f_{D}}, \quad \frac{TD}{H} = \frac{X_{TD} f_{TD}}{X_{H} f_{H}}
\]

(1)

X is fraction of the component member in the solar neighborhood and f is the Gaussian distribution function of stellar population velocity on each components. Stars are classified into thick disk if the fraction TD/D and TD/H is more than 4 [3]. There are 360 out of 13,382 data that fulfill these conditions and therefore we classified those stars as thick disk.

2.2. Halo members classification
Classification of halo is done using metallicity selection. Stars with log [Fe/H] less than -1 is classified as halo member. Only 64 stars in the Geneva-Copenhagen catalog that fulfill the criteria. Halo stars have high orbital inclination with respect to galactic plane.

2.3. Search for streams in thick disk and halo
Then we searched for the region with higher densities, then we called it clumps. To detect the stellar streams, we plot the eccentricity and angular momentum distribution of stars. In this plot, stellar streams will appear as clumps of datas. Unfortunately, we do not generally know the orbital parameters of stars in the solar neighborhood. Then we used Kepler approach to project the stellar stream members in plot consists of components analogue to the orbital parameter. Stellar stream in thick disk is detected by plotting data in diagram with V as the horizontal axis and \(\sqrt{U^2 + 2V^2}\) as y-axis. V is the analogue of angular momentum and \(\sqrt{U^2 + 2V^2}\) is the analogue of eccentricity. Velocity component in W direction is ignored because in thick disk, strong phase mixing will dilute the feature in W direction even in a short time. In halo, the Kepler approach angular momentum is analogued as \(V_{az}\) \(\left( V_{az} = \sqrt{(V + V_{LSR})^2 + W^2} \right)\) and eccentricity is analogued as \(V_{\Delta E} = \sqrt{U^2 + 2(V_{az} - V_{LSR})^2}\). In [4], it is stated that tidal streams is concentrated in \((V_{az}, V_{\Delta E})\) around the progenitor orbital.

Then we applied the wavelet transform on the data to detect clumps clearly. Wavelet transform that we used is adopted from [4]. Data are divided into 10,000 bin. Wavelet transform then applied in each bin using Mexican-hat-shaped kernel. Parameter scale valued on 5 km/s.

We used Monte Carlo simulation using the same number of data with the sample (360 stars). Simulated data are generated using normal distribution function with velocity dispersion shown in table 1. U component peaked at 0, V component peaked at asymmetric drift velocity. Wavelet transform applied on the peak of simulation data based on Poisson noise, Monte Carlo simulation was done 5 times and then averaged. Bin number and parameter scale that we used in the simulation is similar with those we used in the data.

Wavelet transform from the data then is subtracted by the wavelet from Monte Carlo simulation. We only detect the positive value with significance bigger then 2\(\sigma\). Wavelet transform after subtraction shown in figure 1 and 2.
3. Result and analysis

3.1. Stellar streams in thick disk

Figure 1 shows several peak densities in velocity distribution with significance higher than 2σ. We compare these peaks with thick disk’s stellar streams in [4]. The highest density peaked on V = -95 km s\(^{-1}\) and V = -120 km s\(^{-1}\). The first peak is found by [7], namely AF06. The second peak is known as Arcturus stream. Both streams are correlated with the presence of resonance in the galactic bar.

Around V = -50 km s\(^{-1}\), Hercules stream is detected. Hercules stream formed by the Outer Lindblad resonance with the galactic bar. At V = -20 km s\(^{-1}\), there is a weak indication of the presence of Hyades-Pleiades stream. We did not detect the Sirius stream that peaked at V = 4 km s\(^{-1}\). At V = -110 km s\(^{-1}\), we found a new peak with significance level around 7.5σ. This stream is not mentioned in [6]. We then count the number of stars, average and standard deviation of star’s metallicity in each streams to analyse whether the streams are dynamical or tidal. Table 2 shows the data.

![Figure 1. Stellar density in thick disk after subtraction by result from Monte Carlo simulation. The shown density have significance higher than 2σ. Colors signify the stellar density (seen in the colorbar)](image1)

![Figure 2. Stellar density in halo after subtraction by result from Monte Carlo simulation. Significance of the peak is larger than 2. Colors signify the stellar density (seen in the colorbar)](image2)

| Streams | N  | [Fe/H] | σ_{[Fe/H]} |
|---------|----|--------|------------|
| AF06    | 86 | -0.38  | 0.32       |
| Arcturus| 26 | -0.41  | 0.38       |
| Hercules| 5  | -0.45  | 0.36       |
| Hya-Plei| 2  | -0.24  | 0.17       |

From table 2, we can conclude that Geneva-Copenhagen survey shows significant detection on AF06 and Arcturus streams with number of data 86 and 26. Hercules and Hyades-Pleiades is detected weakly with only 5 and 2 data points. From this finding and previous literature, AF06, Arcturus and Hercules streams have large metallicity distribution, indicates that the stars in these streams have different origin. Therefore, these streams classified as dynamical stream. The new stream that we found at V = -110 km s\(^{-1}\) have 31 data points and large metallicity distribution. Therefore, this new significant stream is classified as dynamical stream.
3.2. Stellar streams in halo

Figure 2 shows the peak in wavelet transformed velocity distribution from Geneva-Copenhagen survey after subtraction by result from Monte Carlo simulations. Substructure number in stellar halo is much less than in thick disk sample. This is primarily because the number of sample in galactic halo from Geneva-Copenhagen survey is so small. Overall, we only detected two substructure in halo component. The first stream ranged between \( V_{\Delta z} \approx -140 \text{ km s}^{-1} \) and \(-100 \text{ km s}^{-1} \) and \( V_{\Delta E} \) from 460 \text{ km s}^{-1} and 530 \text{ km s}^{-1}. We found 11 data points in this stream with average metallicity -1.5 and the standard deviation of metallicity 0.33. This stream is detected as S3 in [8] and as \( \omega\text{Cen} \) in [9] and [10].

[5] and references there in did not detect the second stream that we found. With \( V_{\Delta z} \) between -230 \text{ km s}^{-1} and -180 \text{ km s}^{-1} and \( V_{\Delta E} \) between 550 \text{ km s}^{-1} and 650 \text{ km s}^{-1}, this stream have 14 data points with average metallicity -1.23 and standard deviation 0.17. Metallicity of streams in galactic halo is far smaller than thick disk. Generally, this shows that thick disk is richer in metal (iron) than halo. Similar range of standard deviation of metallicity shows that stars in galactic halo could possibly come from different origins, therefore we classify them as dynamical stream.

4. Conclusion

Milky Way consists of several components: thin disk, thick disk, bulge and stellar halo. Presence of substructure in each component could be the tracer on the evolution and formation process in each component. Substructure can be observed as clumps in velocity distribution curve. Substructure is known as stellar stream since it consists of stars moving with similar velocity components.

There are two kind of stellar streams. Tidal stream consists of stars with similar velocity component and origin. Dynamical stream consists of stars from different origin but trapped on similar velocity distribution because of the dynamical resonance.

Here, we present the search for stellar stream in thick disk and halo using data from Geneva-Copenhagen survey. We detect 5 streams in thick disk, four of which had been detected by [4]: Hercules, Hyades-Pleiades, AF06 and Arcturus. We also found one stream that had not been detected in [4], this stream peaked on \( V = -110 \text{ km s}^{-1} \). Metallicity distribution in thick disk streams is quite large that we confidently conclude that stars in those streams have different origin, thus classify them as dynamical streams.

In galactic halo, we found two streams. The first is detected as S3 in [8] and the second is detected as \( \omega\text{Cen} \) in [9] and [10]. Metallicity distribution in both stream is quite large, indicates that origin in each stream is different, therefore we also classify them as dynamical stream.

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