THE KINEMATICS AND CHEMISTRY OF RED HORIZONTAL BRANCH STARS IN THE SAGITTARIUS STREAMS

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Received 2012 February 6; accepted 2012 March 27; published 2012 May 15

ABSTRACT

We have selected 556 red horizontal branch stars along the streams of the Sagittarius (Sgr) dwarf galaxy from Sloan Digital Sky Survey DR7 spectroscopic data using a theoretical model. The metallicity and $\alpha$-element distributions are investigated for stars in the Sgr streams and for Galactic stars at the same locations. We find that the Sgr stars have two peaks in the metallicity distribution while the Galactic stars have a more prominent metal-poor peak. Meanwhile, [$\alpha$/Fe] ratios of the Sgr stars are lower than those of the Galactic stars. Among the Sgr stars, we find a difference in the metallicity distribution between the leading and trailing arms of the Sgr tidal tails. The metallicity and [$\alpha$/Fe] distribution of the leading arm is similar to that of the Galaxy. The trailing arm is composed mainly of a metal-rich component and [$\alpha$/Fe] is obviously lower than that of the Galactic stars. The metallicity gradient is $-1.8 \pm 0.3\times10^{-3}$ dex deg$^{-1}$ in the first wrap of the trailing arm and $-1.5 \pm 0.4\times10^{-3}$ dex deg$^{-1}$ in the first wrap of the leading arm. No significant gradient exists along the second wraps of the leading or trailing arms. It seems that the Sgr dwarf galaxy initially lost the metal-poor component in the second wrap (older) arms due to the tidal force of our Galaxy and then the metal-rich component is disrupted in the first wrap (younger) arms. Finally, we found that the velocity dispersion of the trailing arm from $88^\circ < \Lambda < 112^\circ$ is $\sigma = 9.808 \pm 1.0$ km s$^{-1}$, which is consistent with previous work in the literature.

Key words: galaxies: dwarf – Galaxy: halo – stars: abundances

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The Sagittarius (Sgr) dwarf galaxy is the second nearest galaxy to our Milky Way (assuming the Canis Major dwarf galaxy is the nearest). The Sgr is currently being disrupted under the strain of the Milky Way. Studying the metallicity and kinematic distributions of Sgr stars has now become an important issue. Many works on chemical abundances of the Sgr stars have been done based on high-resolution spectra. Bellazzini et al. (2008) selected 321 RGB stars in the Sgr nucleus and give the average [Fe/H] $\sim -0.45$ dex from the infrared Ca II triplet. Carretta et al. (2010) derived homogeneous elemental abundances with 27 red giant stars belonging to the Sgr nucleus and found on average [Fe/H] $\sim -0.61$ dex to $-0.74$ dex. Keller et al. (2010) observed 11 M giant stars with the Gemini South telescope which indicated that the [Fe/H] of stars decreases along the tidal stream. Chou et al. (2007) present a reliable measurement on M giants with high resolution at different points along the tidal stream and show a significant metallicity gradient. They found a median [Fe/H] $\sim -0.4$ in the core that decreases to $-1.1$ dex over the leading arm.

However, these works based on high-resolution spectra have small samples of stars. Based on low-resolution spectra Yanny et al. (2009) traced the Sgr tidal streams with red K/M giants from the Sloan Digital Sky Survey (SDSS). They found an average [Fe/H] in the range $-0.8 \pm 0.2$ with 33 K/M-giant stars in two areas. Carlin et al. (2012) derived metallicity from low-resolution spectra of stars along a stretch of the Sgr stream and find a constant [Fe/H] $\sim -1.15$. Thus far, the metallicity and abundance studies of the Sgr tails have been less detailed in large samples of stars and in various locations, which are the advantages of the present work. We analyze the metallicity distribution at different points along the tidal streams of the Sgr with low-resolution data for a large sample of stars.

The SDSS spectroscopic survey and the LAMOST project (Zhao et al. 2006) will provide a large sample of red horizontal branch (RHB) stars with low-resolution spectra in the Sgr. Currently, the spectroscopic data of the SDSS survey provide stellar parameters, distances, radial velocities, and metallicities for many stars spread across a wide area. In this work, we investigate the properties of Sgr RHB stars from SDSS and compare them with stars in the Milky Way. We present the procedure for selecting the RHB stars in Section 2 and give the metallicity analysis in Section 3. In Section 4 we test the theoretical model and sample selection, and a summary is given in Section 5.

2. SAMPLE SELECTION

We obtained 8535 RHB stars, 5391 with (U, V, W) and 3144 stars without, from SDSS DR7 low-resolution spectral data (Chen et al. 2010). We choose the Sgr stars with the aid of a theoretical model by Law & Majewski (2010). Law & Majewski (2010) provide a model of the Sgr orbiting in a triaxial Galactic potential with $10^5$ points. The model divides the $10^5$ points into four parts: leading arms 1 and 2 and trailing arms 1 and 2. The model is based on observational data from 2MASS and SDSS (for more details please see Law & Majewski 2010).

We select our sample stars by using the Law & Majewski (2010) model as a reference to provide cuts on the RHB stars. First, we obtain 3512 stars from the full 8535 RHB star sample using R.A.–decl. positions. Second, we choose RHB stars in the Sagittarius leading and trailing tidal tails using a Distance–$\Lambda_\odot$
map of the Law & Majewski (2010) model. Here \( \Lambda_0 \) is the Sgr longitude scale along the orbital plane. We obtain 586 stars in leading arm 1, 585 stars in leading arm 2, 973 stars in trailing arm 1, and 502 stars in trailing arm 2 from the 3512 stars. The first and the second wrap of the Law & Majewski (2010) model is denoted by arms 1 and 2, respectively. Third, we select stars to likely be members of the Sgr stream based on their radial velocities (RVs), which are appropriate for the Sgr stream at these positions based on Sgr debris models (Chou et al. 2010). Specifically, we select stars with a \( V_{\text{gsr}} \) (the velocity in the Galactic standard of rest)–\( \Lambda_0 \) map (Figure 1). A local standard of rest rotation velocity of 220 km s\(^{-1}\) is adopted for the Sun for consistency with Law & Majewski (2010). We also calculate \( V_{\text{gsr}} \) with the same equation as Law & Majewski (2010) for consistency, i.e., \( V_{\text{gsr}} = r v + 9.0 \cos b \cos l + 232.0 \cos b \sin l + 7.0 \sin b \) km s\(^{-1}\). With the \( V_{\text{gsr}} \) criteria, 118 stars satisfy the cuts on leading arm 1 in both the Distance–\( \Lambda_0 \) and \( V_{\text{gsr}}–\Lambda_0 \) maps from 586 stars. In a similar way, 80, 329, and 47 stars in the leading arm group 2, trailing arm group 1, and trailing arm group 2 are selected from 585, 973, and 502 stars, respectively (see Figure 1). There are 18 RHB stars overlapped in the leading arm and trailing arm. We omit these overlapping stars from the leading and trailing arm groups. Finally, there are 102, 78, 327, and 31 RHB stars in leading arms 1 and 2 and trailing arms 1 and 2, respectively (shown in the \( X_{\text{GC}}–Z_{\text{GC}} \) map of Figure 2). We adopt 556 (including 18 overlapping stars) as the total number of RHB stars in our Sgr samples (see Table 1).

For comparison, we selected a sample of Galactic stars with the same positions but different velocities from the Sgr tidal stars. That is, we select Galactic RHB stars from the full 8535 star sample by finding stars that satisfy the R.A.–decl. criteria and the Distance–\( \Lambda_0 \) criteria of the Law & Majewski (2010) model, but do not satisfy the \( V_{\text{gsr}}–\Lambda_0 \) criteria mentioned above. In Figure 1, the yellow points indicate Galactic RHB stars. We excluded the high-density stars with a generalization which is shown as the black boxes in order to reduce the potential effect from the undetected stream stars in the Galaxy (see Figure 1). Again, 159 overlapping stars at the positions of the leading and trailing arms are removed from the leading and trailing samples. Finally, there are 202, 164, 347, and 129 Galactic stars at the positions of leading arms 1 and 2 and trailing arms 1 and 2, respectively (shown in the \( X_{\text{GC}}–Z_{\text{GC}} \) map of Figure 2). We

![Figure 1](https://example.com/figure1.png)
adopt 1001 (including 159 overlapping stars) as the total number of RHB stars in our Galaxy sample (see Table 2). In Tables 1 and 2, the following parameters are listed: star identification; right ascension; declination; [Fe/H]; [α/Fe]; distance; radial velocity and errors; the velocity in the GSR; \( \Lambda_2 \); \( X_{GC} \); \( Z_{GC} \); and Mark (T1, T2, L1, L2, and O mean trailing arm 1, trailing arm 2, leading arm 1, leading arm 2, and the overlap, respectively).

### Table 1

| Plate-MJD-Fiber | R.A. (deg) | Decl. (deg) | [Fe/H] (dex) | [α/Fe] (dex) | \( D \) (kpc) | \( V_r \) (km s\(^{-1}\)) | \( V_{gr} \) (km s\(^{-1}\)) | \( \Lambda_2 \) (deg) | \( X_{GC} \) (kpc) | \( Z_{GC} \) (kpc) | Mark |
|----------------|-----------|------------|--------------|--------------|--------------|----------------|--------------|----------------|--------------|--------------|-------|
| 2897-54585-350 | 189.8050  | -2.23403   | -1.38        | 0.27         | 17.644       | -18.982        | 267.308      | -4.091        | 15.355       | T1            |
| 2903-54581-382 | 204.3400  | 9.80199    | -1.21        | 0.32         | 17.269       | 19.2 ± 2.9     | 274.113      | -2.446        | 16.182       | T1            |
| 2045-53350-295 | 28.9932   | -0.94947   | -1.09        | 0.10         | 26.814       | -140.3 ± 2.3   | -103.139     | 102.574       | -20.422      | -23.124       | T1    |
| 2045-53350-314 | 28.6627   | -0.11991   | -1.26        | 0.21         | 25.397       | -154.5 ± 2.7   | -113.973     | 102.708       | -19.837      | -21.773       | T1    |
| 2045-53350-332 | 28.7795   | 0.70322    | -0.54        | 0.08         | 23.509       | -157.2 ± 2.1   | -114.510     | 103.226       | -19.155      | -19.987       | T1    |
| 2047-53732-21  | 38.6068   | -8.97331   | -1.55        | 0.10         | 29.028       | -103.7 ± 6.9   | -116.441     | 106.747       | -22.666      | -25.049       | T1    |
| 2047-53732-382 | 36.5672   | -7.84202   | -1.42        | 0.12         | 26.664       | -114.7 ± 3.8   | -118.570     | 105.579       | -21.149      | -23.184       | T1    |
| 2047-53732-439 | 36.8067   | -8.31038   | -0.74        | 0.09         | 23.164       | -128.2 ± 2.7   | -134.126     | 105.542       | -19.381      | -20.170       | T1    |
| 2047-53732-588 | 38.5169   | -8.00536   | -0.62        | 0.11         | 22.914       | -104.6 ± 3.3   | -114.188     | 107.173       | -19.772      | -19.658       | T1    |
| 2048-53378-130 | 46.9893   | -0.99905   | -0.75        | 0.11         | 24.199       | -127.9 ± 3.6   | -139.385     | 118.123       | -24.156      | -18.016       | T1    |

This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

### 3. RESULTS AND DISCUSSIONS

#### 3.1. Comparing the Kinematics and Chemistry of RHB Stars in the Sgr and in the Galaxy

In Figure 3, we plot the histograms of [Fe/H], \( V_r \), and [α/Fe] and the distribution map of [Fe/H]−[α/Fe] for RHB stars in the
Sgr (556) and Galaxy (1001). One sees that the value of $V_r$ for all RHB stars in the Sgr have a sharp peak at $-140$ km s$^{-1}$, while there is a large dispersion in the distribution for the Galactic RHB stars. This is mainly due to the selection effect. We set a dashed line at $-90$ km s$^{-1}$ in the $V_r$ histogram to define the lower velocity group and analyze the metallicity distribution of those lower velocity stars. Clearly, the lower velocity stars are more than half of all the stars in the Sgr, but the lower velocity stars are only a small part of all the Galactic stars. Meanwhile, the Galactic stars are dominated by a metal-poor component while the Sgr stars have a significant contribution from a more metal-rich component. The distribution of [Fe/H] in the Sgr stars has two peaks, one at $1.3$ dex and the other at $-0.8$ dex. There are also two peaks in the [Fe/H] distribution of Galactic RHB stars, which are at the same [Fe/H] value, but the peak at $-0.8$ dex is less pronounced and could be due to Sgr stars near the edges of our selection criteria. Yanny et al. (2009) show that the giant branch in the Sgr leading tidal tail is consistent with those of globular clusters with [Fe/H] of $-1.0 \pm 0.5$. They also find that the 33 identified Sgr K/M giant stars have metallicities of $-0.8 \pm 0.2$. Our results are similar to the distribution of [Fe/H] in Yanny et al. (2009). We also show the lower velocity stars with a dashed line in the histograms of [Fe/H] and [$\alpha$/Fe]. For the Sgr stars, the dashed line shows two peaks in the [Fe/H] histogram and the two components have equal contributions, while the solid line shows a bigger contribution from the peak at $1.3$ dex than that from the peak at $-0.8$ dex. For Galactic RHB stars, the dashed line is similar to the solid line.

From the [Fe/H]–[$\alpha$/Fe] map in Figure 3, we can see that the [$\alpha$/Fe] of most stars is lower than 0.2 dex in Sgr, while that of most Galactic stars is larger than 0.2 dex. The low [$\alpha$/Fe] stars mainly come from the metal-rich component of the Sgr tidal at $-0.8$ dex. These results are consistent with the results of early dwarf galaxy fragments. [$\alpha$/Fe] deficiencies were found by Smecker-Hane & McWilliam (2002), McWilliam & Smecker-Hane (2005), Sbordone et al. (2007), and Carretta et al. (2010) for the more metal-rich stars in the Sgr (McWilliam 2010). The existence of some Galactic stars in our sample may lead to analysis error, but they could also be real since there are plenty of examples of Galactic halo stars with low [$\alpha$/Fe] (e.g., Nissen & Schuster 1997; Brown et al. 1997).

3.2. Comparing the Properties of Sgr RHB Stars in the Leading and Trailing Arms

It is interesting to compare the properties of RHB stars between the leading and trailing arms of the Sgr tidal tails. First, the distribution of $V_r$ for the RHB stars have big differences between the leading and trailing arms (Figures 4 and 5). There are two peaks, $-20$ km s$^{-1}$ and $-100$ km s$^{-1}$, in the $V_r$ histogram of leading arm stars. The distribution of the Sgr leading arm stars is similar with that of the Galactic RHB stars, which also presents two peaks. Meanwhile, nearly all the trailing arm stars are centered around one peak near $-140$ km s$^{-1}$. The dashed line corresponds to low-velocity stars with $V_r$ less than $-90$ km s$^{-1}$ in the $V_r$ histogram, the same as in Figure 3. Again, this difference comes from the predictions of the Law & Majewski (2010) model. We find that the metallicity distribution of the stars also has large differences between the two arms (Figures 4 and 5). The metallicity distribution of RHB stars in the leading arm is similar to that of the Galactic stars both in the solid and dashed lines. The metal-rich peak is not clear and the metal-poor peak is prominent in the leading arm. The [Fe/H] distribution of the trailing arm stars has two peaks and the metal-rich peak is significant, as shown in the solid line and even more clearly for low-velocity stars as shown in the dashed line.

From the [$\alpha$/Fe] histograms of Figures 4 and 5, we can see that the distributions of leading arm RHB stars are also similar to that of Galactic stars both in the solid and dashed lines, while trailing arm stars show most stars have lower values of [$\alpha$/Fe], which is different from the Galactic stars. The properties of the trailing arm RHB stars are more consistent with the core of the Sgr: [Fe/H] is more metal-rich than that of the Galaxy and [$\alpha$/Fe] is lower than that of Galactic halo stars. It is unexplained that the leading arm stars do not follow the chemical history of the Sgr core. Further work is necessary to investigate the leading arm of the Sgr tidal.

3.3. The Metallicity Gradient Along the Leading and Trailing Arms

We would like to see if the metallicity is a function of orbital longitude along the Sgr leading and trailing tidal streams. Figures 6 and 7 give the distributions of $A_\odot$–[Fe/H] and $A_\odot$–[$\alpha$/Fe] for RHB stars. There is a metallicity gradient in trailing arm 1 while there is a lower one in leading arm 1. We find that in the trailing arm, when moving farther from the Sgr core along arm 1 and then to arm 2, the metallicity shifts to more metal-poor values, which suggests an evolution toward more ancient stars since metal-poor RHB stars must be older than metal-rich RHB stars. This is in agreement with dwarf galaxy formation theories where the more metal-rich core of the galaxy is surrounded by older and more metal-poor stars since it.

| Plate-MJD-Fiber | R.A. (deg) | Decl. (deg) | [Fe/H] (dex) | [$\alpha$/Fe] (dex) | $D$ (kpc) | $V_r$ (km s$^{-1}$) | $V_{\phi}$ (km s$^{-1}$) | $A_\odot$ (deg) | $X_{GC}$ (kpc) | $Z_{GC}$ (kpc) | Mark |
|----------------|-----------|------------|-------------|-------------------|---------|-------------------|-------------------|----------|------------|-------------|------|
| 521-52326-282  | 189.3720  | 1.29835    | -1.25       | 0.37              | 17.511  | 206.2 ± 3.6       | 121.813          | 265.203  | -4.754     | 15.733      | T1   |
| 2393-54156-196 | 168.7060  | 9.31168    | -1.37       | 0.33              | 17.976  | 65.4 ± 2.1        | -33.057          | 242.718  | -11.487    | 15.732      | T1   |
| 2475-53845-253 | 204.8630  | 27.58950   | -1.29       | 0.13              | 17.168  | -227.6 ± 6.4      | -192.876         | 265.199  | -5.502     | 16.871      | T1   |
| 2558-54140-115 | 186.8030  | -0.44967   | -1.18       | 0.22              | 17.215  | 257.8 ± 1.9       | 162.467          | 263.717  | -5.216     | 15.174      | T1   |
| 2895-54567-386 | 188.0690  | 0.45355    | -1.56       | 0.20              | 18.502  | -23.7 ± 2.5       | -113.546         | 264.433  | -4.797     | 16.475      | T1   |
| 2920-54562-390 | 189.0690  | 0.45355    | -1.53       | 0.25              | 18.397  | -23.7 ± 1.6       | -113.546         | 264.433  | -4.815     | 16.382      | T1   |
| 2045-53350-5   | 31.0273   | -0.86264   | -1.00       | 0.18              | 24.695  | 83.5 ± 4.2        | 115.548          | 104.372  | -20.098    | -21.050     | T1   |
| 2045-53350-273 | 28.8993   | -0.63687   | -1.27       | 0.20              | 21.075  | -18.0 ± 2.4       | 20.350           | 102.651  | -17.794    | -18.132     | T1   |
| 2048-53378-337 | 45.9597   | 0.69496    | 1.38        | 0.19              | 24.940  | 117.0 ± 3.6       | 113.378          | 118.069  | -24.756    | -18.455     | T1   |
| 2050-53401-366 | 54.6862   | -5.53984   | -1.14       | 0.23              | 26.858  | 245.4 ± 4.5       | 200.218          | 122.747  | -26.698    | -18.874     | T1   |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 3. We compare all RHB stars (red solid lines) in the Sgr (556) and Galaxy (1001). Blue dashed lines show the stars whose \( V_r \) is less than \(-90 \) km s\(^{-1}\). Left (right) panels show RHB stars in the Sgr (Galaxy).

(A color version of this figure is available in the online journal.)
Figure 4. Same as Figure 3 but for comparing RHB stars in the leading arm of the Sgr (180) and Galaxy (366).

(A color version of this figure is available in the online journal.)
Figure 5. Same as Figure 3 but for comparing RHB stars in the trailing arm of the Sgr (358) and Galaxy (476).
(A color version of this figure is available in the online journal.)
Figure 6. [Fe/H] as a function of angular distance from the main body of Sgr along the leading arm (left panels) and trailing arm (right panels). The upper panels show the individual points. In the lower panels, the distribution of [Fe/H] is displayed as the median. The solid line shows the result of a least-squares linear fit to the median data. The metallicity gradient is $-(1.5 \pm 0.4) \times 10^{-3}$ dex deg$^{-1}$ in leading arm 1 and $-(1.8 \pm 0.3) \times 10^{-3}$ dex deg$^{-1}$ in trailing arm 1. The fitted line shows that the metallicity is nearly flat in leading arm 2 and trailing arm 2.

Figure 7. [$\alpha$/Fe] as a function of angular distance from the main body of Sgr along the leading arm (left panels) and trailing arm (right panels). The [$\alpha$/Fe] gradient is $(0.67 \pm 0.15) \times 10^{-3}$ dex deg$^{-1}$ in leading arm 1 and $(0.86 \pm 0.12) \times 10^{-3}$ dex deg$^{-1}$ in trailing arm 1. There is no obvious trend in leading arm 2 or trailing arm 2 except for the fluctuations of individual points.

is this outer, older, and metal-poor population that will be tidally stripped before the younger, inner component. Our results also agree with the gradient found by Chou et al. (2007) and is similar to Figure 15 of Law & Majewski (2010), which gives the distribution of $\Lambda_\odot$–[Fe/H]. However, Yanny et al. (2009) have studied the metallicity of blue horizontal-branch BHB stars as a function of $\Lambda_\odot$ and find that there is no significant trend in the BHB metallicity. It is possible that the BHB stars in Yanny et al. (2009) are the old and metal-poor component of the Sgr, which is not easily distinguished from the Galactic components with the same properties, in contrast with our comparison sample.

3.4. Sgr RHB Stars in the Bright and Faint Streams

A recent paper by Koposov et al. (2012) suggests that the tidal debris of the Sgr is actually two separate streams of stars separated by $\sim 10$° in the Sgr orbital coordinate system. Their work is an extension of the work of Belokurov et al. (2006), who found two branches of the leading arm debris in the north Galactic cap. The brighter and thicker stream is claimed to have more than one stellar population with a large fraction being metal-rich. The fainter and thinner stream is said to be primarily a single, metal-poor population. No estimate of the metallicity of either stream is given by Koposov et al. (2012), but using our RHB sample we can make a qualitative comparison.

As we have shown, our Sgr RHB sample is somewhat metal-rich. Further, since the brighter stream is also the more metal-rich one according to Koposov et al. (2012), we expect our RHB sample to be composed primarily of stars from this stream.

To check if this is the case, we separate our sample into stars belonging to the bright and faint streams using the positions and distances given in Tables 1 and 2 of Koposov et al. (2012). There are 84 stars (80, 2, and 2 from trailing arm, leading arm, and overlapping group, respectively) in the bright stream and 5 stars (all from the trailing arm) in the faint stream. The metallicity distribution of the stars in the bright stream is shown in Figure 8. As expected, most of the stars are metal-rich.

We do not have enough stars in the faint stream to make a meaningful comparison. This could be due to a couple of factors. One reason we may not have many stars corresponding to the faint stream is because our selection criteria are based on the model of Law & Majewski (2010). This selection
may preclude these stars simply based on positions and/or kinematics. Another possibility is that the metal-poor faint stream has little or no RHB component. A more detailed description of the two streams is necessary in order to distinguish between these two possibilities.

4. ERROR ESTIMATE AND MODEL TEST

4.1. Comparing avec Besançon Model

In order to estimate the level of contamination from halo RHB stars we use the Besançon model of the Galaxy (Robin et al. 2003). We selected stars from all possible Galactic components and applied our selection criteria mentioned above.

We find that the possible contribution from the halo in our sample varies greatly depending on the area. In particular, the leading arm areas we select will suffer from more contamination than the trailing arm areas because of the closer distances, lower velocities, and wider spread in velocities, all of which will increase the number of expected halo stars. Further, in the second wraps of the tidal tails the model constraints are not as strong and therefore allow for more contamination. Our cleanest sample is for trailing arm 1 in part because of the larger distances, but more importantly, from the narrow range of velocities with large negative values. We also have the largest sample of RHB stars in trailing arm 1 so we expect the results from this area to be the best and most robust.

The fact that our metallicity gradients for trailing arm 1 and leading arm 1 are so similar and agree within errors means that contamination in our sample is small and/or has little effect on our results. We also point out that halo contamination is not unique to our RHB sample and disentangling the halo component is very difficult since the stars are at the same distances and have the same velocities. Previous work using similar selection criteria as our work will also suffer from the same problem (such as Yanny et al. 2009; Monaco et al. 2007; Keller et al. 2010; Correnti et al. 2010; Carlin et al. 2012; Koposov et al. 2012).

4.2. Error Analysis

In the current models (especially in Law & Majewski 2010), the younger segments of tidal debris are constrained to match the 2MASS/SDSS observations while the older segments are regarded as predictions for where tidal debris might be expected if it extends beyond that which is currently traced by 2MASS/SDSS. The dynamical “age” of a particle in the Law & Majewski (2010) model is given by the parameter “Pcol” where values of Pcol < 3 correspond to tidal debris observed by 2MASS/SDSS. In our analysis, we use stars whose “Pcol” range from 1 to 7 in the model. For more accuracy we could only use the tidal debris previously observed by 2MASS/SDSS. These parts nearly correspond to the first wrap of the leading and trailing arms. This would restrict our results to only arm 1 of the leading and trailing arms. With this sample, the results become stronger and thus our results are reliable. In particular, the metallicity and [α/Fe] gradients are only detectable in arm 1 of the leading and trailing arms.

We vary our ranges by 10% in distance and velocity for the sample selection to obtain a larger or smaller sample and perform the same analysis procedure. The results are very similar with the original ones. This indicates that the sample selection criteria are reasonable and the results are robust.

4.3. Distance Distributions for Stars with \( \Lambda_\odot < 130^\circ \) as a Model Test

In our sample there are a significant number of stars in trailing arm 1 with \( \Lambda_\odot < 130^\circ \), but not enough stars for good statistics in other areas. We thus investigate the distance distributions of our RHB stars and compare them with model predictions since we expect that Galactic stars have a broad distribution and there should be an overdensity when the Sgr stream passes through the Galactic field. Figure 9 shows the distance distributions of RHB stars and dashed lines show the distance range given in the model for Sgr trailing arm 1 for \( \Lambda_\odot < 130^\circ \) with a bin width of 10°. One sees that almost all bins show distance peaks within the model-predicted ranges despite the significant selection effect of the SDSS spectroscopic survey. It seems that the distance prediction in the Law & Majewski (2010) model is correct and our sample selection of RHB stars based on this model is reasonable.

4.4. The Velocity Dispersion at \( 88^\circ < \Lambda_\odot < 112^\circ \) as a Model Test

Our sample has the largest number of stars at \( 88^\circ < \Lambda_\odot < 112^\circ \), which covers a similar area as Majewski et al. (2004) and Monaco et al. (2007). Thus, we investigate the velocity dispersion for this area so that we can compare our result to these works and provide a test to the model prediction. In the left panel of Figure 10, we plot \( V_{\text{gsr}} \) as a function of the Sgr longitude \( \Lambda_\odot \). The solid line is a polynomial fit to the data and it describes a characteristic trend of decreasing \( V_{\text{gsr}} \) with increasing \( \Lambda_\odot \) along the Sgr trailing tail, as already discussed by Majewski et al. (2004) and Monaco et al. (2007). The fit is for \( 88^\circ < \Lambda_\odot < 112^\circ \) because for \( \Lambda_\odot < 90^\circ \) an increase of the velocity dispersion is evident (see Majewski et al. 2004; Monaco et al. 2007). The right panel shows residuals of our sample stars with respect to the polynomial fit. The distribution is fit with a Gaussian of width \( \sigma = 9.808 \pm 1.0 \text{ km s}^{-1} \) using 119 stars. Monaco et al. (2007) give a velocity dispersion of \( \sigma = 8.3 \pm 0.9 \text{ km s}^{-1} \) using 41 stars with high-resolution spectroscopy and Majewski et al. (2004) give \( \sigma = 10.4 \pm 1.3 \text{ km s}^{-1} \) for stars with low-resolution spectroscopy. These three values are consistent within errors. The agreement indicates that the Law & Majewski (2010) model prediction is reasonable, which is what our sample star selection is based on. These parts of the trailing tail are dynamically colder.
than the Sgr core, which has dispersions of 11.17 km s\(^{-1}\) and 11.4 km s\(^{-1}\) in Monaco et al. (2005).

5. SUMMARY

In this paper, we present the properties of the metallicity and \(\alpha\)-abundance distributions for a large sample of RHB stars belonging to the Sgr tidal streams. The Sgr stars have two components in [Fe/H] while Galactic stars have a more prominent metal-poor one. [\(\alpha/\text{Fe}\)] is lower for the Sgr stars than for Milky Way stars, especially along the trailing arm. There are metallicity gradients along the streams of Sgr, with a value of \(- (1.8 \pm 0.3) \times 10^{-3} \) dex deg\(^{-1}\) in trailing arm 1 and of \(- (1.5 \pm \)
0.4) \times 10^{-3} \text{ dex deg}^{-1} \text{ in leading arm 1. No significant gradient exists along trailing arm 2 or leading arm 2. Stars belonging to more ancient wraps of the streams in arm 2 are more metal-poor.}

We test the model and sample selection in four aspects as follows. First, by comparing with the Besançon model of the Galaxy we find that contamination from the Galactic halo is small for the largest sample of RHB stars in trailing arm 1. Then we change the selection range for the width of the leading and trailing arms and find no significant difference. Third we investigated the distance distribution of RHB stars in trailing arm 1 (Λ⊙ < 130°) and the peaks fall within the model prediction ranges. Fourth, we test the velocity dispersion for the Sgr trailing tail at 88° < Λ⊙ < 112° and found a value of \( \sigma = 9.808 \pm 1.0 \text{ km s}^{-1} \), which is consistent with the results of Majewski et al. (2004) and Monaco et al. (2007).

With the upcoming LAMOST spectroscopic survey, we can expect to analyze RHB stars in the Sgr for an even larger sample and in different Galactic locations in order to further study the chemical history of the Sgr galaxy.

We thank the referees for their helpful comments which significantly improved the paper. This work was supported by the National Natural Science Foundation of China (grant Nos. 11178013, 11073026, 11150110135, and 10978015) and by the Provincial Natural Science Foundation of ShanDong (Y2008A08 and ZR2010AM006).

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