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Possible Streams of the Globular Clusters in the Galaxy *

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Abstract We aim to retrieve ghost streams under the assumption that all the globular clusters in our Galaxy were formed in very early merge events. Our results are based on two speculations: that the specific energy and angular momentum of the globular clusters after merge are not changed in the course of evolution and that the globular clusters with a common origin would stay in the same orbit plane as the parent galaxy. After taking into account the apogalacticum distance of the orbits, we suggest with some confidence five possible streams. The number of streams is consistent with the previous results. Three of the four well established members of the Sagittarius stream were found to be in one of our streams. Several other globular clusters in our result were also thought to come from accretion by previous researchers. The orbital parameters of the streams are derived, which provide a way to test whether these streams are true with the help of more accurate measurement of proper motions of the globular clusters.

Key words: globular clusters: general — Galaxy: formation — Galaxy: halo

1 INTRODUCTION

The globular cluster (GC hereafter), as the oldest star group in the universe, has been a target that astrophysics has paid close attention to all the time. The near-field (Galaxy) cosmology makes contacts with the far-field cosmology by the Galaxy's GCs, and the origin of GCs has become an important component in the study of the Galaxy's formation and evolution (Freeman & Bland-Hawthorn 2002).

The earliest view on the Galactic formation is that a halo was created during a rapid collapse of a relatively uniform and isolated protogalactic cloud (Eggen, Lynden-Bell & Sandage 1962). Though challenged by some (Searle & Zinn 1978), the view that GCs originate from collapse of the Galactic molecular cloud is still upheld by some groups. Harris & Pudritz (1994) argued that GCs follow a power-law distribution by mass, $N \sim M^{-1.7}$, which is found to be virtually independent of the environment in a study of the connection between protogalactic and present-day cluster formation regarding the GCLF (globular cluster luminosity function) of several large galaxies in addition to the Milky Way.

However, according to the scenario of Cold Dark Matter (CDM) cosmology, the universe is built up hierarchically, i.e., the small structure forms first and the large structure forms later. Applied to our Galaxy, such scenario fits the view of Searle & Zinn (1978) that the Galactic halo was built up over an extended period from independent fragments. The discovery of the Sagittarius dwarf galaxy being accreted by the Galaxy supports the view that the halo of the Galaxy was built up at least partially by the accretion of similar dwarf galaxies (Ibata et al. 1994).

Schweizer (1987) first suspected that GCs were formed in mergers. Later, Ashman & Zepf (1992) predicted that the Hubble Space Telescope would reveal young GCs; these were later discovered in disturbed

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or interacting galaxies such as NGC 1275 (Holtzman et al. 1992), NGC 7252 (Whitmore et al. 1993) and the Antennae (Whitmore & Schweizer 1995). All these observations support the view that the GCs could be formed in mergers. In our Galaxy the proof continues. From the Hertzsprung-Russell diagram, Lee et al. (1999) identified multiple stellar populations traced by wide red giant branches in the most massive GC, ω Centauri, with different ages and argued that ω Centauri was once part of a more massive system which merged with the Milky Way. Indeed, Lynden-Bell & Lynden-Bell (1995) traced the ghostly streams of the outer-halo GCs and satellite galaxies starting from the opinion that they were all formed in early merge events.

Recently, there are several attempts to estimate the number of merges by comparing the characteristics of halo stars or GCs in the Galaxy with those in other galaxies. In 1996, Unavane et al. (1996) examined the fraction of stars in the halo which have colors consistent with a metal-poor, and intermediate-age population matching those typically observed in Local Group dwarf spheroidal galaxies. They concluded that the star counts imply an upper limit of $\sim$60 mergers with low-luminosity dwarf spheroidal, or $\leq$6 mergers with more luminous objects. Based on the survey of young blue halo stars, van den Bergh (2000) estimated that the total amount of captured stellar material in the halo is equivalent to 3–7 Sagittarius dwarfs. Mackey & Gilmore (2004) compared in details the properties of GCs between the old halo, young halo and bulge/disk subsystems, and the GCs in LMC, SMC, Fornax and Sagittarius dwarf spheroidal galaxies. They estimated the Galaxy may have experienced approximately seven merger events with cluster-bearing galaxies during its lifetime.

In this paper, we try to trace the streams, i.e., the satellite galaxies, of all the GCs in the halo from their kinetics rather than their other properties. The analysis presumes that some big satellite galaxies have several GCs which keep their specific energy and angular momentum, and move in the same orbital plane after merging with our Galaxy. We describe the data in Section 2 and present our methods in Section 3. Our results for the possible streams and a discussion are given in Section 4.

2 DATA

All the parameters of the GCs are taken from the web version of “A Catalog of Parameters for GCs in the Milky Way” (Harris 1996). As Harris (2003) have critically selected the best available measurements for each of the quantities included, the quality of the measurements can at least be regarded as one of the best. In addition, the electronic version is available through web and updated regularly, which guarantees the data of being the latest.

The catalog is consisted of three parts: positions, photometric parameters and kinetic parameters. It lists the cluster identifications, positions, integrated magnitudes, colors, morphology parameters, metallicities, radial velocities, and structural parameters. We make use of the parameters such as radial velocities, positions and distances. However, the necessary parameters are not fully available for three among the 150 GCs in the Harris catalog because they are faint, inside the Galactic plane, or lately found. So our analysis is directed to the 147 GCs for which the needed parameters are complete without consideration of the errors of the parameters.

3 METHOD AND CALCULATION

Two major criteria are set to identify common origin of GCs. The first is that the GCs of common origin should have the same specific energy and angular momentum. The second is that their orbits lie in the same plane. At the beginning, all the GCs are treated equally irrespective of differences in some characteristics such as metallicities or morphologies of horizontal branches that are usually used in classification. Specifically, they were all assumed to come from the accreted galaxies even if some of them were originally produced in the Galaxy. However, the final results from our analysis will screen out members that might be Galactic natives.

3.1 Hypotheses

Following Lynden-Bell & Lynden-Bell (1995), our analysis proceeds on the following several strong hypotheses:

- Sufficiently large satellite galaxies have GCs in their own halos. These GCs would be pulled off if the satellite galaxy is tidally torn. Indeed, this hypothesis is what motivates us to search for Galactic GCs of common parent galaxies. The origin of the GCs in the large satellite galaxies is another topic.
- In tidal tearing, the objects torn off pursue orbits in the same plane through the Galactic center as their parent's orbit.
- The objects were torn off at one or several close passages during a period in which the energy and angular momentum of the progenitor's orbit did not change very much.
- The initial orbits of the objects torn off had approximately the same specific energy and specific angular momentum as the progenitor.
- The gravitational potential in the Galactic halo has changed only slowly since that time and may now be taken to have a known form.

3.2 Specific Energy and Angular Momentum

As mentioned in the beginning of this section, the first criterion of the GCs from the same parent galaxy is that they have equal specific (per unit mass) energy E and angular momentum h. The equation of specific energy is

$$E_r = \frac{1}{2}v_r^2 - \psi = E - \frac{1}{2}h^2 r^{-2}, \tag{1}$$

where E_r is the radial component of the total energy, r, ψ and v_r are the Galactocentric distance, gravitational potential and Galactocentric radial velocity, respectively.

According to Equation (1), the GCs with the same specific energy and angular momentum can be identified, if we know the gravitational potential of the halo, ψ, Galactocentric distance, r, and the velocity v_r, because the GCs of the same origin, which have the same specific energy and angular momentum, are expected to lie on the same line expressed by Equation (1) with the gradient $-h^2/2$ and intercept E. Thus, we need determine ψ, r and v_r.

1. First, the gravitational potential ψ is calculated. Through the rotation curve of the Galaxy, we have the law of variation of the density in the Galactic halo with Galactocentric distance, thus have the equation of the gravitational potential. Assuming the density is positive everywhere and decreases as r^{-2} for $r \ll r_h$, and as r^{-5} for $r \gg r_h$, the form of the potential can be written as

$$\psi = V_0^2 \ln\Big(\frac{\sqrt{1+S^2}+1}{S}\Big), \tag{2}$$

where $V_0^2 = 220\,\mathrm{km\,s^{-1}}$ is the circular velocity of the Sun, $S = r/r_h$ and $r_h = 80\,\mathrm{kpc}$. Thus, for a given Galactocentric distance r, the potential can be calculated.
2. The Galactocentric distance r can be calculated from the solar distance and the Galactic coordinates from simple trigonometric relations.
3. From the distant halo the difference in direction of the Sun and Galactic center can often be neglected, so the radial velocity in the line of sight,v_l (after correction to the Galactic center of rest), is approximately the radial velocity that would be seen from the Galactic Center, v_r. Thus v_r can be regarded as known. It should be kept in mind that this approximation is virtually valid for GCs that are far away from the Galactic center; for those relatively close to the Galactic center, there will be about some uncertainties.

From the available data, 147 of all the 150 GCs have measured values of v_r^2 and r. The correlation of their radial energy E_r with Galactocentric distance r is shown in Figure 1, where the solid curve describes the variation of the potential ψ with r.

To determine the straight lines in Figure 1 through which some of the individual 147 points pass, a method called "Hough Transform (hereafter HT)" is adopted. Because there are 147 points in Figure 1, the number of possible lines is C_{147}^2 by connecting any two of the points. The HT method essentially calculates all the slopes and intercepts of these C_{147}^2 lines and finds out those lines which have close slopes and intercepts: the points making up a line would have a similar specific energy and angular momentum.

The analysis shows that the set of values of the slopes of lines was fairly concentrated while that of the intercepts had a large scatter, hence the grouping took into consideration mainly the scatter in the intercept.

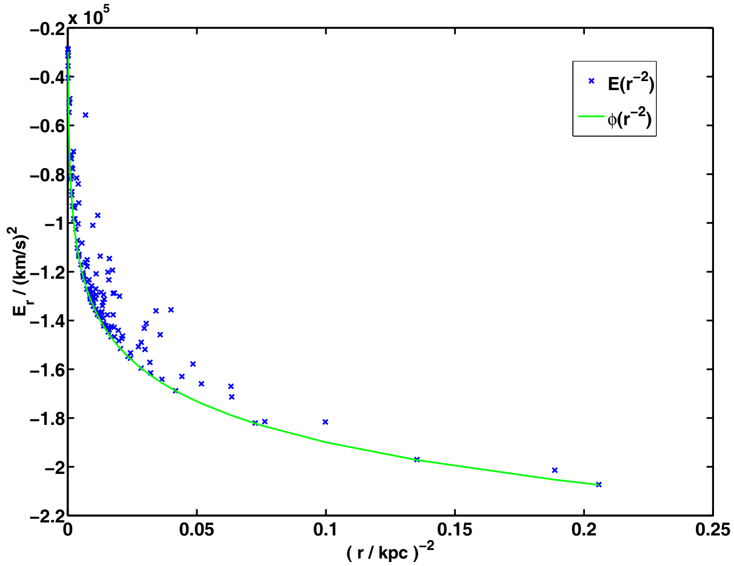

Fig. 1 $E_r = \frac{1}{2}v_r^2 - \psi$ plotted against r^{-2}. Members of the same stream should lie on one straight line in the diagram.

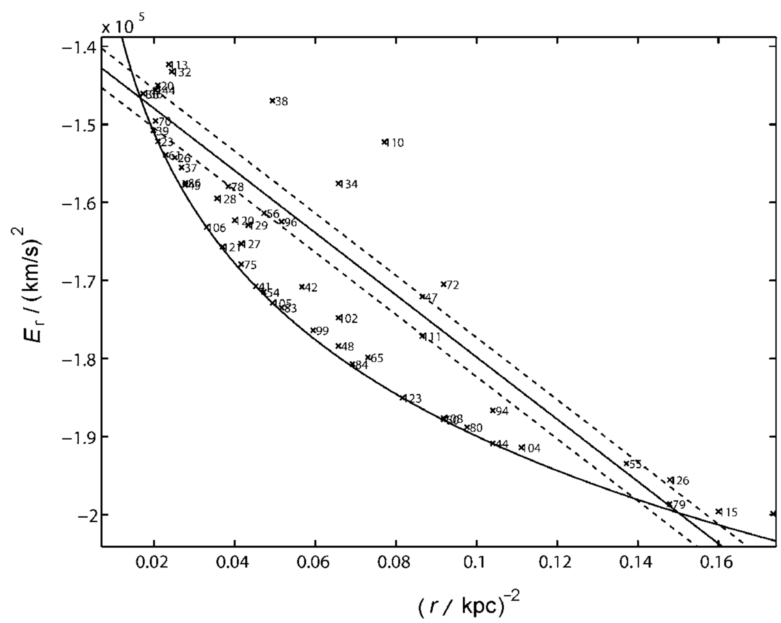

Fig. 2 Seven points between the upper and lower lines define Stream No. 16 in Table 1. Each cross marks a GC with its serial number in the Harris table.

Figure 2 shows an example of a grouping: the 1σ error lines are plotted and the points within the 1σ error lines are regarded to have the same specific energy and angular momentum, i.e., passing the first criterion. The analysis of the 147 points yielded 21 lines, which means there are 21 groups with the same E and h^2. The names and number of members of the groups (streams) are listed in Table 1, in order of decreasing intercept. The intercept represents the specific total energy E.

It can be seen from Table 1 that the number of members in a stream ranges from 3 to 14, and more than three points on a line is required to make a stream. As an example, one of the 21 streams is displayed in Figure 2, where the points belonging to the stream are enclosed between the upper line and lower line.

Table 1 Intermediate results from the specific angular momentum and energy of all the 147 GCs, including 21 streams. The columns are: stream serial number, number of members in the stream, NGC numbers (or names) of stream members.

Stream♯	Counts	Members' ID (NGC)
1	5	6539 6453 6352 5824 7492
2	3	6712 5824 7492
3	7	6517 Lynga 7 6496 6229 5824 7492 Terzan 3
4	9	6362 6656 6749 5986 3201 6229 5824 7492 Terzan 3
5	10	6544 Pal 10 6584 4590 6229 5824 7492 Terzan 3 6934 6981
6	7	IC 1276 4147 6715 Terzan 8 Terzan 7 6934 6981
7	6	Pal 8 6752 6101 1851 5466 5634
8	8	6517 Lynga 7 6254 1261 1904 Pal 5 IC 1257 Pal 12
9	5	6402 6535 6496 6205 6864
10	14	6426 6864 5272 2808 7089 6838 6584 Pal 10 6362 6760 6656 6218 6540 6388
11	4	288 Terzan 12 6453 6539
12	8	288 7078 104 6838 6496 6535 6316 6712
13	9	6779 104 6838 5286 6584 Pal 10 6144 6341 362
14	8	5286 4372 Pal 10 6254 6496 6341 6171 6553
15	6	6441 6352 4372 7099 5897 Pal 11
16	7	Liller 1 6235 6144 6496 6356 Pal 11 5897
17	6	6356 5946 4833 6284 5139 6809
18	8	6440 6681 6809 5946 4833 6284 5139 5904
19	8	Terzan 1 6558 5946 4833 6284 5139 5904 6362
20	7	6254 6656 6496 6760 6544 6749 6333
21	6	6712 6453 6558 6355 6553 6171

3.3 Polar-path Maps

Objects that satisfy the second criterion, i.e., moving in the same orbit, were selected from the Lambert equal-area projection. Different from the traditional projection, in Lambert projection the x-y plane's transform equations are

$$x' = \frac{x}{\sqrt{1+z}}, \tag{3}$$

$$y' = \frac{y}{\sqrt{1+z}}, \tag{4}$$

where (x', y') are coordinates transformed from the x-y plane. After such transformation the size of projected area is proportional to and thus retains the original relative sizes, which is important in present work because only its position is known for a given GC.

The poles of the countless orbits consistent with the limited information that the position of the GC and that the Galactic center is within the orbital plane form a set which is called the polar-path. The equation of the polar-path is described in the Cartesian coordinates by

$$x^2\Big(1+\frac{\cos^2 l}{\tan^2 b}\Big)+y^2\Big(1+\frac{\sin^2 l}{\tan^2 b}\Big)+2xy\frac{\sin l\cos l}{\tan^2 b}=1, \tag{5}$$

where (l, b) are the Galactic coordinates of the given GC.

Then, the search for the common orbit is converted to a search for the intersection points of the polar paths of the GCs. For each of the 21 groups in Table 1, the polar-path is plotted for each GC in the projected plane. It is then found by eye, that for eight of the groups, all or some of the members have intersections, i.e., they have the same orbits, while for thirteen of the groups no more than three members have intersections, and this was taken to mean that they do not move in the same orbit.

The eight groups with path-intersections are listed in Table 2, as well as the NGC serial numbers of the members (members in Table 1 are dropped if they do not intersect with the others). As examples, we show in Figure 3 the polar paths of one successful group (Group No. 8, left panel) and one unsuccessful group (Group No. 16, right panel).

Table 2 Final results include eight groups in which some or all members have a common orbital pole. The columns are the same as Table 1. The GCs that were regarded to come from accretion by other researchers are labeled and the corresponding references are shown in the footnotes. See the text for details.

Stream♯	Counts	Members' ID (NGC)				
5	3	Pal-10	7492[3]	6934		
6	4	IC-1276	6715[1]	Ter-7[1]	Ter-8[1]	
8	5	6517	6254	Pal-5[2]	Pal-12	IC-1257
9	3	6402	6535	6864		
10	4	5272	7089[3]	6838	Pal-10	
18	4	6440	6681	6809[3]	5904[3]	
19	4	Ter-1	6558	5904[3]	6284	
21	5	6453	6558	6355	6553	6171

Note: [1] Ibata et al. 1997; [2] Odenkirchen et al. 2003; [3] Mackey & Gilmore 2004.

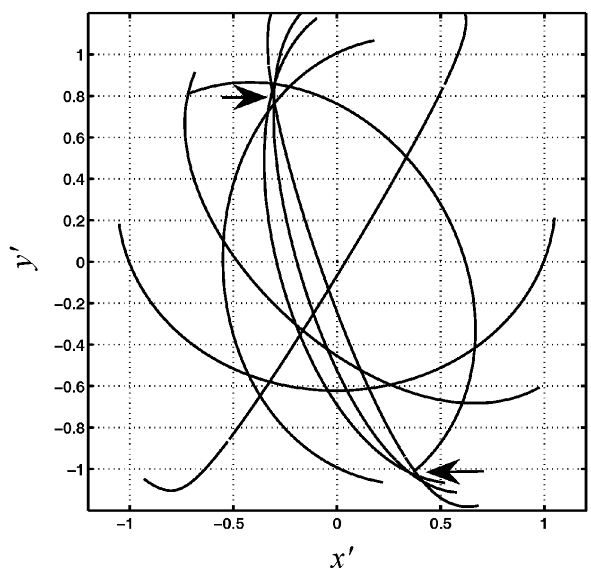

Fig. 3 Polar paths of two groups of globular clusters. Left: members of Stream No. 8 in Table1. Right: members of Stream No. 16. Each path is a great circle perpendicular to the galactocentric vector to the globular cluster, $x'^2 + y'^2 = 1$ (see text for details) is the Galactic plane. $x'^2 + y'^2 < 1$ is the northern Galactic sky. Multiple intersections of polar paths mean possible stream poles. The arrows in the diagram point out these poles.

3.4 Error Analysis

During the search for the groups, some errors are induced from the approximations or methods. First, the Galactocentric radial velocity is approximated by the line-of-sight velocity. This approximation is true only for the objects which are very distant from the Galactic center where the position difference between the Sun and the Galactic center has little effect on the velocity difference, but this brings about significant errors for nearby GCs. Secondly, error is induced from applying the HT method to pick out the points on one line. These errors have been utilized to restrict the ranges of points plotted in Figure 2 (dashed lines). Because there are uncertainties in the parameters of velocity and distance of GCs, we suffered some dispersion in the transformed slope-intercept diagram (see Sect. 3.2 for details) of the points. This means that the members in the same group may have some scatter in the specific energy and angular momentum. Thirdly, the common poles from the Lambert's equal-area projection are not exactly at one point, but only within some range. Whether the GCs have the same orbital pole is judged by the eye, with the difference in x' and y' less than 0.1 or so.

4 RESULTS AND DISCUSSION

4.1 The Orbital Parameters

From the analysis of the specific energy and angular momentum, and the polar path of the GCs, we found eight groups, with members that possibly having a common satellite origin. For each of the eight streams, the equation of the normal to the common orbital plane was solved from the positions of the members, the pole and the intersection in Figure 3. The results are shown in Table 3, listing in turn, the stream number (first appearing in Table 1), the apogalacticum, perigalacticum, eccentricity, specific angular momentum, specific total energy, period and coefficients of the orbital equation. Ambiguity of the direction of the normal to the orbital plane means the two combinations of the coefficients in the last two columns. This degeneracy can be removed by estimating the direction of the angular momentum; this work will be carried out in a more detailed future study.

It can be seen from Table 3 that the streams Nos. 18, 19 and 21 have their apogalacticum less than 8.5 kpc, the adopted solar distance to the Galactic center. For the members in these streams, the approximation of the solar radial velocity to the Galactic radial velocity could bring about large error in the calculation of the specific energy and angular momentum. Moreover, the GCs with orbits so close to the Galactic center should have been disrupted by the strong tidal force if they had been accreted long before. Another reservation about these three objects is that one object (NGC 5904 and NGC 6558) appears in two streams, which indicates inferior quality in the grouping. Therefore, these three streams should not be the ghost streams. They are separated by a line in Table 3 from the candidate streams. Finally, the five streams, Nos. 5, 6, 8, 9 and 10, are possible streams of GCs in the Galaxy from the kinetic point of view.

The eccentricity of GC orbits has been discussed widely because it is related to their origins as well as the evolution. Statler (1988) suggested that the GC orbital eccentricity decreases in the process of dissipative numerical simulation. Gnedin (2006) derived the average eccentricity of surviving model clusters to

Table 3 Results of eight orbital parameters: $r_{\rm max}$ and $r_{\rm min}$ are the orbital apogalacticum and perigalacticum distances, e is the orbital eccentricity, P is orbital period, a, b and c are the parameters of the normal to orbital plane expressed by $ax + by + cz = 0$.

Stream♯	$\frac{r_{\rm max}}{\rm kpc}$	$\frac{r_{\rm min}}{\rm kpc}$	e	$\frac{10^{-3}h}{\rm kpc\cdot km\ s^{-1}}$	$\frac{-10^{-5}E}{\rm (km\ s^{-1})^2}$	$\frac{P}{10^8 \rm yr}$	$\frac{b}{a}$	$\frac{c}{a}$
5	29.88	5.50	0.69	2.2414	0.8	3.11	$\mp$0.78	0
6	24.84	2.72	0.80	1.2604	0.9	2.76	$\mp$0.39	$\mp$2.31
8	19.15	4.00	0.65	1.5868	1.0	1.96	$\mp$3.08	$\mp$0.84
9	15.21	3.73	0.64	1.4142	1.1	1.45	$\mp$2.34	$\pm$0.29
10	14.75	4.46	0.54	1.5868	1.1	1.51	$\mp$0.71	$\mp$0.02
18	6.84	1.21	0.70	0.5018	1.5	0.71	$\mp$9.69	$\pm$0.64
19	6.73	1.42	0.65	0.5630	1.5	0.69	$\pm$58.29	$\pm$1.03
21	3.49	0.97	0.57	0.3552	1.8	0.35	$\mp$64.38	$\pm$3.94

concentrate between 0.4 and 0.8. This is consistent with the earlier result by Ninković (1983). In Table 3 the eccentricities of possible streams are between 0.5 to 0.8, which agrees well with the high probability eccentricities of GCs. This result indirectly confirms our calculation.

4.2 Number of Streams

Our analysis gives five streams for the origin of about 20% of the GCs in the Galaxy, which means there have been five relatively large and cluster-bearing satellite galaxies being accreted in early times. This number is well consistent with others. Unavane et al. (1996) concluded ≤6mergers with luminous galaxies, while van den Bergh (2000) estimated the total amount of captured stellar material is equivalent to 3–7 Sagittarius dwarfs. Mackey & Gilmore (2004) estimated the Galaxy may have experienced approximately seven merger events with cluster-bearing galaxies during its lifetime. All these results agree reasonably well with ours.

4.3 The Sagittarius Stream

As the best established stream, the Sagittarius stream has been investigated in greatest details. As a result, some GCs have been suggested as members of the Sagittarius stream. The discovery of Ibata et al. (1997) suggested NGC 6715 (also known as M54), Ter 8, Ter 7 and Arp 2 are associated with the Sagittarius stream. Bellazzini et al (2003) added Pal 12, NGC 4147. The 2MASS color-magnitude diagram (Bellazzini et al. 2004) strengthened their belief that the two GCs are members. Pal. 12 was also proposed to be a member by (Martínez-Delgado et al. 2002). Although numerous additional members have been postulated, there are only four well-established members, according to Ibata et al. (1997). From Table 2, Stream No. 6 includes three of the four established members, i.e., NGC 6715, Ter 8 and Ter 7, this is a good concordance with the previous results. The remaining member Arp 2 does not appear in this group, this may be caused by the error in our analysis or that it is not a member from the kinetic point of view. The other postulated members do not appear in Stream No. 6, either. The other member in Stream No. 6 is IC-1276 which is in the Galactic bulge (Barbuy et al. 1998), and thus possibly is not a member. We conclude that Stream No. 6 is at least part of the Sagittarius stream.

4.4 Other Members

In addition to the members of the Sagittarius stream, several more GCs in our streams also appear in previous identifications. NGC 7492, NGC 7089, NGC 6809 and NGC 5904, that appeared in Stream Nos. 5, 10, 18 and 19 (though Nos. 18 and 19 may not be streams due to their closeness to the Galactic center) were suggested to be similar to GCs in external galaxies by Mackey & Gilmore (2004). Appearing in Stream No. 8, Pal 5 was considered to lie in a stream from the SDSS-II data (Odenkirchen et al. 2003). Our result confirmed some of the GCs speculated to originate externally. However, the exact streams are difficult to configure. Besides, some of the GCs in our results have not been found to be of external origin by other methods. Because the method in our analysis suffers some uncertainty (especially lack of the accurate measurement of proper motions) and that the judgement only from the properties of GCs is not decisive, further investigations are needed to clarify the origins of the GCs in the Galaxy.

5 SUMMARY

The present work agrees with that the Galaxy has experienced several merges. Our result classified the GCs of possible external origin into five groups, this is well consistent with previous results. In particular, three of the four well established Sagittarius members were classified into one stream. As previous work identified the external origin of GCs mainly from their observed properties such as colors, metallicity or age, our work identified their origin from their kinematic properties. Since our view is different from others, the consistency of the conclusions is important.

Whether the stream found is true or imaginary needs further investigations, even if the uncertainties mentioned above could all be eliminated. This is because the features, the same specific angular momentum and the same orbit plane, can not guarantee the GCs originating from external galaxies, i.e., the GCs of the same origin inside the Galaxy would also preserve such characteristics. However, other properties will help to judge the correctness of our sort of grouping. For example, accurate determination of the GCs' proper motions will make it possible to calculate the three dimensional velocities and thus the actual orbits.

Presently, available data and observational techniques can yet provide such data. The launch of GAIA (Mignard 2005) will provide high precision measurements of proper motions to Galactic objects, we expect then our results will be tested.

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