對銀河系內球狀星團的形狀分析

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摘要

我們以 2 微米近紅外全天搜尋（Two Micron All Sky Survey; 2MASS）點源目錄資料庫，對銀河系內 110 個球狀星團進行形狀分析。我們計算星團的等效星球密度，再以橢圓對其外圍結構之等密度線進行擬合以得到星團的半長軸、半短軸，並進而導出星團的扁平率以及等效半徑。結果顯示球狀星團的外部扁平率的中值爲 0.1，亦即絕大部分的球狀星團接近圓形。我們發現接近銀心的星團形狀比較圓，尺寸上也比較小，這可能是受到銀心橢球的強大潮汐力的影響。此外我們也發現絕對亮度越大（亦即質量較大）的球狀星團，有形狀較圓的趨勢，顯示這些系統的自有萬有引力能有效抗拒外在的擾動。

在所有樣本中有六個形狀特別扁的星團（扁平率>0.3），其中（1）Arp 2 及 Pal 12 位於銀河系與人馬座矮星系（Sagittarius Dwarf galaxy）的潮汐帶上；（2）Pal 5 一般相信因受到銀河盤面的潮汐效應，正逐漸瓦解當中；（3）UKS 1 及 NGC 6355 乃相當接近銀心橢球的球狀星團；（4）NGC 2419 則位於銀暈上。此外我們發現了兩個位於銀心橢球附近的球狀星團 NGC 6293 以及 NGC 6440 呈較扁的形狀，而此發現亦與 Nordquist et al. (1999) 的理論預測相符合。在文中我們分別探討造成這些星團極度扁平的可能原因。

Morphology of Galactic Globular Clusters

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Abstract

We study the morphology of the halo of 110 Galactic globular clusters with the 2MASS Point Source Catalog. Morphological parameters such as the flattening and average radius of the halo of each globular cluster were estimated by fitting the effective density contours with ellipses. The globular clusters in our sample in general have spherical halos, with a median flattening ($f=1-b/a$) of 0.1, equivalent to an aspect ratio of 0.9. Those closer to the Galactic bulge show more circularized shapes and have smaller physical sizes. Among the most 6 elongated globular clusters with $f \geq 0.3$ (1) Arp 2 and Pal 12 are known to be associated with the streamer of the Sagittarius dwarf galaxy, (2) Pal 5 is being cannibalized by the Milky Way, (3) UKS 1 and NGC 6355 are known bulge globular clusters, and (4) NGC 2419 is a halo member with a Galactocentric distance ~ 90 kpc. Furthermore, the distortion of the two bulge GC, NGC 6293 and NGC 6440, suspected by Nordquist et al. (1999) has been detected. We discuss possible mechanisms which might have caused the flattening of globular clusters.

關鍵字（Key words）：球狀星團（globular cluster）、潮汐力（tidal force）、潮汐形變（tidal distortion）、銀暈（halo）、形狀分析（morphology）

1. Introduction

Globular clusters (GCs) are believed to form in the early stage of the life of a galaxy so they play an important role in galaxy formation. The destruction of GCs on the other hand are also crucial to the evolution of the host galaxy. Gnedin and Ostriker (1997) studied the mechanism which destroy GCs, i.e. internal cluster evaporation, dynamical friction, and tidal shocking from disks, bulges, and super massive black holes. They concluded that between 52 and 86 percent of the current Milky Way GCs will be destroyed by the combination of these internal or external mechanisms over the next Hubble time. They also claimed that the initial population of GCs was substantially higher than the current one but the clusters closer to the bulge would have higher mortality due to bulge shocking. Stars from disintegrated GCs were accreted to, and likely dominate the present stellar populations of, the bulge and halo of the Milky Way galaxy.

Nordquist et al. (1999) investigated the effect of the tidal force from a bulge on the shape of a GC in a close encounter and concluded that a typical GC passes within several hundred pc from the bulge would suffer substantial distortion. They suggested the effect to be detectable in the bulge GCs NGC 6293 and NGC 6440.

Observationally, Galactic star clusters are found to have flattened shapes. Chen et al. (2004) analyzed the shape of 31 galactic open clusters and found that most of the sampled star clusters are elongated, even for the youngest ones of a few million years old. They also noticed that the inner part of an open cluster tends to be circularized but the overall radius gets larger and the stellar density becomes sparser as the cluster ages. This shows the competitive effects between internal stellar relaxation dynamics (to circularize the shape) and external tidal distortion (to elongate the shape). Conceivably only massive clusters could have survived the tidal disruption. Open clusters away from the Galactic disk, i.e., with large heights, are less vulnerable to distortion. Not only open clusters show elongated shape, NIR observation of a young-compact star cluster in the galactic center, Arches shows its flattened morphology as well. Its morphology evidences the strong tidal forces which Arches cluster suffered (Stolte et al., 2005).

For globulars, Meylan and Mayor (1986) noticed that 47 Tuc and ω Cen are flattened, likely due to their overall rotation. White & Shawl (1987) determined the overall axial ratios and orientations of 100 GCs with blue sensitive plates and found a mean axial ratio of 0.93±0.01, which they attributed to the rotation of the clusters rather than to Galactic tidal interactions.

With the wide availability of infrared data, we are just at a right moment to revisit the issue of the shape GCs. Our main goal is to determine the shapes of GCs. In turn, we would use the sample to explore the mechanisms that would change the shape of a GC during its evolution and passage through the Galactic environment. The possible distortion of NGC 6293 and NGC 6440 conjectured by Nordquist et al. could be checked. Specifically we are interested in the extent tidal interaction, e.g., from the Galactic bulge or the Sagittarius dwarf galaxy which affect the shape or stellar distribution of a GC.

To make a comprehensive study on the morphology of the halo of GCs, we selected GCs from Harris's catalogue (Harris 1996) and download the 2MASS point source catalogue in the corresponding fields. The infrared data suffer weaker interstellar extinction and have less brightness contrast between the luminous and faint members than in visible wavelengths. The angular resolution of the 2MASS data, about 2", however, is insufficient to resolve the core of a GC. Only the halo can be studied. King (1962) provided an empirical law, aka the King's model, to describe the stellar projected density distribution of some globular clusters, rich open clusters and dwarf elliptical galaxies. The model is now understood as a combination of an inner isothermal sphere core and a tidally truncated outer part. Our halo is conceptually similar, but not identical, to the tidal part in the King's model.

2. Methodology

Without membership information for individual stars, we investigate the structure of a star cluster with a star counting method. As outlined in Chen et al. (2004), we estimate a clustering parameter for each star in the field, which is a good measure of the membership probability. The computation procedure is briefed below.

The clustering parameter for each individual star i is defined as $P_i=(N_t-N_f)/N_t=1-N_f\ /N_t$, where N_t is the total number of neighbors within a specific angular size around the i-th star and N_f is the average field star number in the same area. The area used is a circular region which contains 50 field stars. Obviously the neighborhood around a true member star is more populous ($N_t >> N_f$) than that around a field star ($N_t \approx N_f$). The clustering parameter behaves like a membership as it gives a measure of the local stellar density enhancement ranging from $P_i \sim 0$ in a field region to $P_i \sim 1$ in a cluster.

The stellar surface number density is estimated by summing up the clustering parameters of stars within a sky-coordinate grid. We focus on the halo of a GC, defined where the density drops to

5σ times the background fluctuations. The boundary of the halo is then fitted with an ellipse whose flattening ($f=1-b/a$, where a and b are semi-major and semi-minor axes respectively) and average physical size ($r=(a+b)/2$) could be derived. Our calculation of the size of a cluster depends on the density fluctuation of the background fields, through r_p and the grid size used to analyze the stellar density distribution. This tends to overestimate the size for a cluster, particularly in a generally low density background, but the flattening remains unaffected.

3. Morphology of Globular Clusters

We select in every GC field stars brighter than K_s ~ 15.6, which corresponds to 3σ detection in the 2MASS data. A total of 110 clusters with high enough density contrast --- higher than 5 times the background fluctuation --- are analyzed. Fig. 1a shows the frequency distribution of the flattening. The uncertainty of the flattening depends on the density contrast between the cluster and field stars; the error is smaller for a cluster with a higher density contrast. In general, the typical error is a few percent. Forty percent of our samples of globular clusters have flattening less than 0.1, with the median value being 0.12. This suggests that globular clusters generally have spherical halos. Six highly flattened GCs were found and the possible mechanisms will be individually discussed in the next section.

Flattening distribution function of inner (galactocentric distance, d_g < 10kpc) and outer (d_g > 10kpc) GCs are demonstrated in Fig. 1b. Information about distance and absolute visual magnitude (Fig. 1d) was taken from Harris's

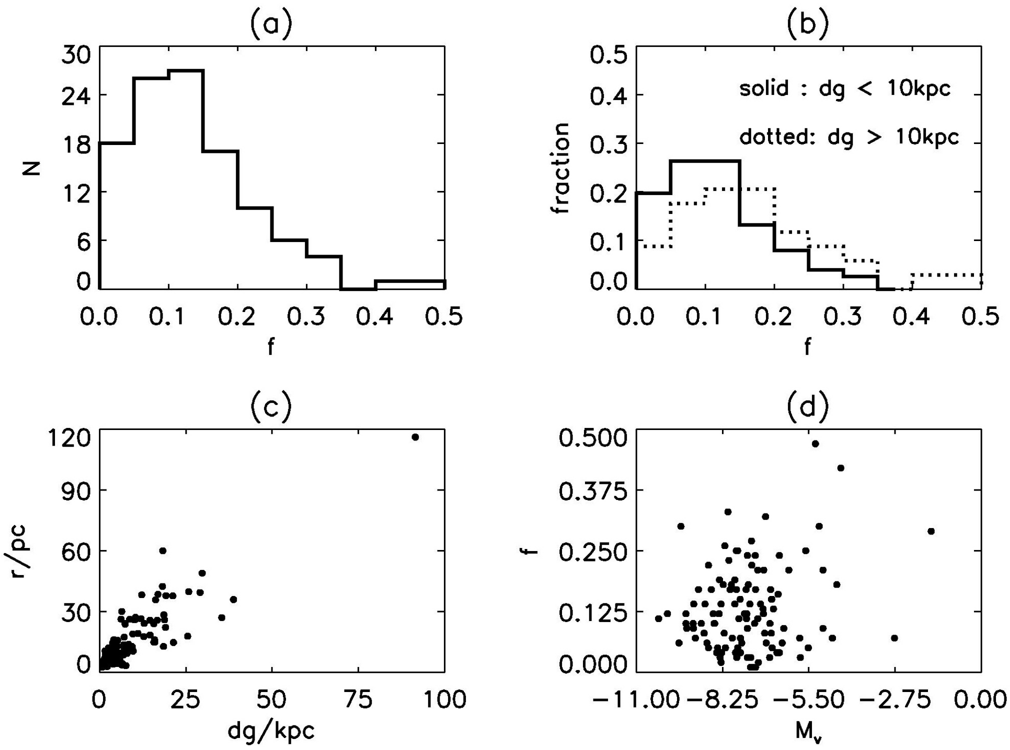

Fig. 1: (a) Distribution of flattening of GCs. (b) Flattening of GCs close to and away from the bulge. (c) The physical size vs d_g. (d) flattening vs absolute visual magnitude.

catalogue (Harris, 1996). The inner group tends to have more circular shapes than the outer group does. Fig. 1c shows the physical size versus the Galactocentric distance. It is obvious that GCs closer to the Galactic center tend to be smaller. Fig. 1d is the flattening vs. absolute visual magnitude. The data are scattered and noisy, and it is difficult to draw any obvious correlation from it.

3.1. NGC 6293 & NGC 6440

The two bulge GCs, NGC 6293 (*l*=357.62, *b*=7.83) and NGC 6440 (*l*=7.73, *b*=3.80), because of their proximity to the Galactic bulge (d_g of 1.4 kpc for NGC 6293, and 1.3 kpc for NGC 6440), are suspected to have detectable distortion of their shapes (Nordquist et al., 1999). Our morphological analysis of these two GCs is shown in Fig. 2 and 3. In each figure, the left panel is the spatial distribution of stars in Galactic coordinates and the right panel shows the computed effective density contour. Only the outer part, which is not too crowded to be resolved by 2MASS, is considered. The flattening of NGC 6293 and NGC 6440 are 0.05 and 0.06, respectively, i.e., with little elongation. Because the two bulge GCs however are seen against high background regions with high density fluctuations, the elongated structure in each case is lower than 5 times the background density fluctuation. An alternative analysis, for which the halo is defined by the density profile of the cluster itself, instead of by the background stellar field, did bring out the elongated structure, as seen in Fig. 4, and Fig.5.

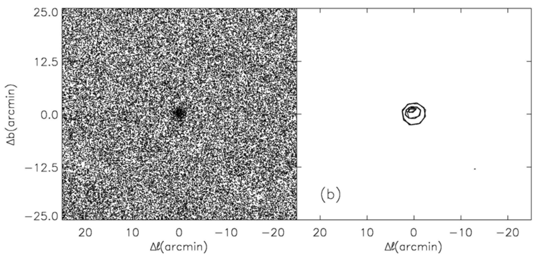

Fig. 2: (*Left*) Spatial distribution of stars in the NGC 6293 field in Galactic coordinates; (*Right*) Effective stellar density contour. Our study only focus on the halo of the cluster (outer contour) as the core cannot be resolved by 2MASS.

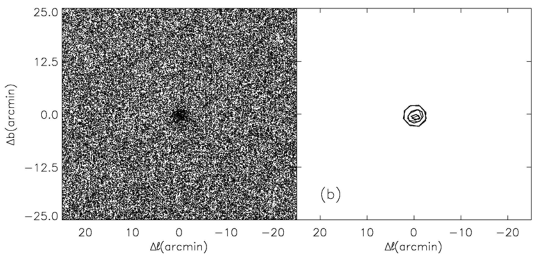

Fig. 3: The same as Fig. 2 but for NGC 6440, for which the flattening of the halo is determined to be 0.06.

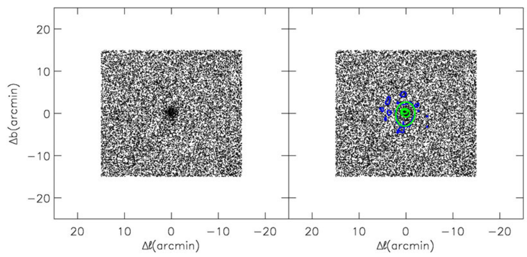

Fig. 4: The elongation of NGC 6293 is detected by the cluster density profile. The blue curve is the contour plot and the green one is the ellipse fitted to the contour.

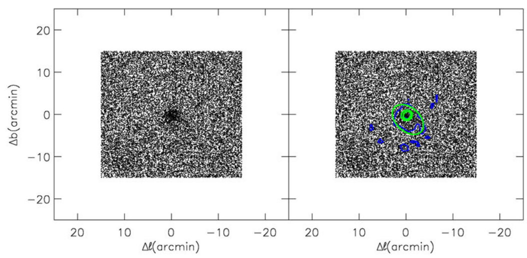

Fig. 5: The same as Fig. 4 but for NGC 6440.

3.2. Highly flattened globular clusters

Six out of the processed 110 GCs have highly flattened shapes with $f > 0.3$. These 6 GCs, together with NGC 6293 and NGC 6440 are listed in Table 1, for which the first 5 columns give, respectively, the name of the cluster, galactic

Table 1: Morphological Parameters of Globular Clusters

Name	(l,b) (deg,deg)	d_s (kpc)	d_g (kpc)	M_V	θ (arcmin)	R (pc)	f
NGC 6293	(357.62, +07.83)	8.8	1.4	-7.77	2.60	6.7	0.05
NGC 6440	(007.73, +03.80)	8.4	1.3	-8.75	2.54	6.2	0.06
Arp 2	(008.55, -20.78)	28.6	21.4	-5.29	1.76	14.6	0.47
Pal 12	(030.51, -47.68)	19.1	15.9	-4.48	2.88	16.0	0.42
Pal 5	(000.85, +45.86)	23.2	18.6	-5.17	4.19	28.3	0.30
UKS 1	(005.12, +00.76)	8.3	0.8	-6.88	1.02	2.3	0.32
NGC 6355	(359.58, +05.43)	9.5	1.8	-8.08	1.89	5.2	0.33
NGC 2419	(180.37, +25.24)	84.2	91.5	-9.58	4.74	116.1	0.30

coordinates, heliocentric distances (d_s), galactocentric distances (d_g) and absolute magnitude, all taken from Harris (1996). The last 3 columns list the evaluated average angular size (θ), physical size (r) and flattening (f) from our analysis.

Fig. 6 and 7 illustrate, respectively, the results for Arp 2 and Pal 12, both known to be associated with the Sagittarius tidal stream. The elongation of these two GCs is obvious. A density enhancement 8 arcmin away from Arp 2 toward the Galactic plane is found. There is no literature in the SIMBAD entry about this stellar grouping. It is not clear whether it is a bound star cluster. Fig. 8 shows the results for Pal 5, a globular cluster

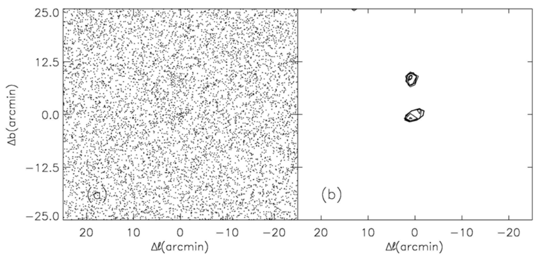

Fig. 6: The same as Fig. 2 but for Arp 2. Arp 2 was known to be potentially associated with Sgr tidal Stream. There is no literatures from SIMBAD entry about the density enhancement 8' away from Arp 2.

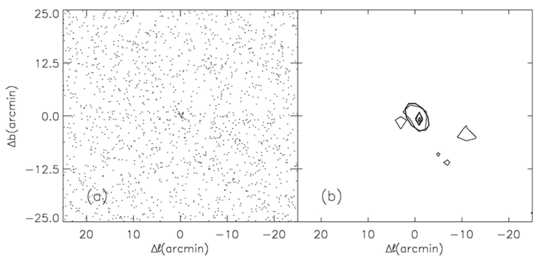

Fig. 7: The same as Fig. 2 but for Pal 12 which was known to be potentially associated with Sgr tidal Stream.

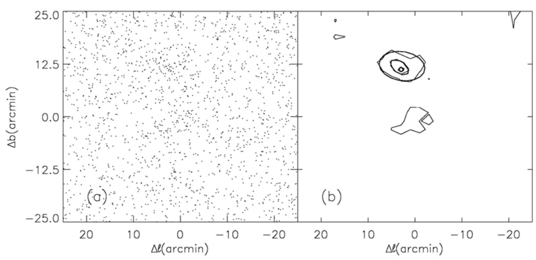

Fig. 8: The same as Fig. 2 but for Pal 5. This cluster was known to be cannibalized by Milky Way. The whole cluster, plus its tail, may well have a extended shape.

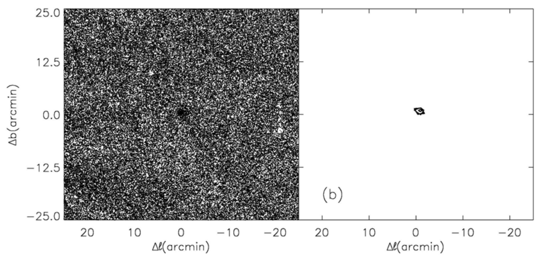

Fig. 9: The same as Fig. 2 but for a bulge globular cluster UKS1.

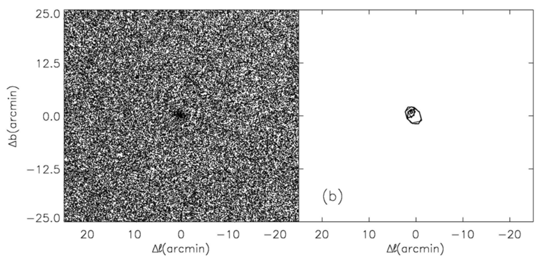

Fig. 10: The same as Fig. 2 but for a bulge globular cluster NGC6355.

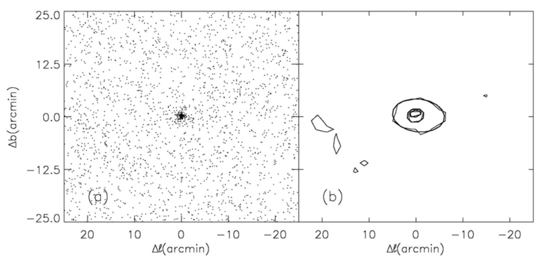

Fig. 11: The same as Fig. 2 but for a halo globular cluster NGC 2419.

being cannibalized by the Milky Way galaxy (Odenkirchen et al., 2003). Fig. 9 and 10 show respectively UKS 1 and NGC 6355, which are known bulge globular clusters. The last entry on our list of flattened GCs is NGC 2419 (Fig. 11). Contrary to other GCs, which experience either the tidal force from the bulge or perhaps dynamical friction from the tidal streams, NGC 2419 is a halo member, away from the Galactic disk or the bulge, with a galactocentric distance ~ 90 kpc. In the next section we discuss possible mechanism which might have caused the flattening of these clusters.

4. Discussion and conclusion

Among our sample clusters, there are 40% with $f < 0.1$ and 80% with $f < 0.2$. The fraction of non-circular GCs is higher in our sample than that in White and Shawl (1987), who claimed a distribution, when converting the axial ratio used in their analysis to our flattening parameter, of 78% with $f < 0.1$ and 95% with $f < 0.2$. We note that the shape analyzed by White and Shawl (1987) is relatively close in to the core of a GC, whereas our analysis focuses on the halo. The result is consistent with the theoretical notion (Binney & Tremaine, 1987) that the core of a GC tends to circularize by the internal stellar encounter, and the halo is vulnerable to distortion by external perturbation.

Two bulge GCs, UKS 1 and NGC 6355, with a galactocentric distance d_g ~ 0.8 kpc and 1.8 kpc, respectively, have been found flattened. The true flattening can only be the lower limit because the projection effect can only make the shape appear more circular. Remarkably, the projected elongation in either case points to the direction of the Galactic bulge, a clear manifestation of tidal distortion. The kinematics information of member stars in these two GCs would be valuable to constrain their merging history.

Arp 2 and Pal 12 are probably associated with the Sagittarius dwarf spheroidals (van den Bergh & Mackey, 2004). These two clusters are quite distant from the Sun ($d_g > 15$ kpc), thus only a few stars are brighter than the 2MASS detection limit. Although the density contrast is low, both of these GCs show possible elongated halos. Pal 12 is elongated roughly toward the direction of the tidal stream, but Arp 2 points roughly orthogonal to the stream.

Odenkirchen et al. (2003) found with the Sloan DSS data a tidal tail associated with Pal 5 which extends more than 10 deg. The stellar debris of Pal 5 sets tight constraints on the geometry of the cluster's Galactic orbit, from which Odenkirchen et al. deduced that the cluster is presently near the apocenter but has undergone several disk crossings in the inner part of Milky Way, resulting in strong tidal shocks. Our data on Pal 5, limited by the 1 degree field of view set by the 2MASS database interface, evince a flattening only for the inner part of the cluster. The whole cluster, plus its tail, may well have an extended shape.

NGC 2419, located 90 kpc from the Galactic center, is one of the five most luminous Galactic globular clusters. Besides, its [Fe/H] ~ -2.4 puts it in the most metal-poor group of globular clusters in the Milky Way (Harris et al., 1997). Because of its long distance from the bulge and large height above the Galactic plane (35.9 kpc) there is no obvious cause for its flattened shape. Contrary to the other outer halo globulars and most of the dwarf spheroidals around Milky Way, NGC 2419 has a uniformly populated horizontal branch ubiquitous in classic low-metallicity GCs (Harris et al., 1997). The origin of NGC 2419 remains an open question. The distorted shape implies that NGC 2419 may be in the late stage of disintergration, or may well be the remnant of a dissolved satellite galaxy.

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