BUILDING UP THE GLOBULAR CLUSTER SYSTEM OF THE MILKY WAY: THE CONTRIBUTION OF THE SAGITTARIUS GALAXY

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ABSTRACT

We demonstrate that there is a clear statistical correlation between the (X, Y, Z, V_r) phase-space distribution of the outer halo Galactic globular clusters (having 10 kpc $\leq R_{GC} \leq 40$ kpc) and the orbital path of the Sagittarius dwarf spheroidal galaxy (Sgr dSph), as derived by Ibata & Lewis. At least four of the sample of 35 globular clusters in this distance range were formerly members of the Sagittarius galaxy (at the 95% confidence level) and are now distributed along the Sagittarius Stream, a giant tidal structure that surrounds the Milky Way. This is the first instance that a statistically significant structure associated with the Sgr dSph has been detected in the globular cluster population of the Galactic halo. Together with the four well-known globular clusters that are located near the center of this tidally disrupting dwarf galaxy, these clusters constitute $\gtrsim 20\%$ of the population of outer halo ($R_{GC} \geq 10$ kpc) clusters. The Sgr dSph was therefore not only an important contributor to the halo field-star population, but it also had a significant role in building up the globular cluster system of the Milky Way.

Key words: galaxies: dwarf — Galaxy: formation — Galaxy: halo — Galaxy: structure — globular clusters: general

1. INTRODUCTION

The quest to find ordered structures in the system of satellites of the Milky Way galaxy dates back to 30 years ago when possible alignments of globular clusters and/or dwarf galaxies along wide streams were first noted (Hodge & Michie 1969; Lynden-Bell 1976; Kunkel & Demers 1977; Kunkel 1979; Lynden-Bell 1982). The mounting consensus for scenarios in which the accretion of satellites has a major role in the formation of the outer halo of the Galaxy (Searle & Zinn 1978; Zinn 1993) prompted a new burst of such studies since the mid-'90s up to the present day (Majewski 1994; Lynden-Bell & Lynden-Bell 1995; Fusi Pecci et al. 1995; Dinescu, Girard, & van Altena 1999; Palma, Majewski, & Johnston 2002, hereafter PMJ02). Despite the many interesting suggestions, none of the quoted studies were able to provide a conclusive proof of the reality of the alignments, mainly because of the overwhelming difficulty of assessing the statistical significance of structures formed by inherently small numbers of objects.

However, recent theoretical and observational achievements may help us to look into the problem from a different and more fruitful perspective:

1. *N*-body simulations of the process of Galaxy assembly, starting from standard cosmological conditions (cold dark matter; CDM), strongly suggest that the hierarchical merging of satellites is the main driver of galaxy formation (see Moore et al. 1999; Klypin et al. 1999, and references therein).

2. Independent of the assumed cosmology, it has been demonstrated that the accretion or disruption of satellites into the halo of a larger galaxy may leave long-lived relics in the form of streams of stellar (and/or dark matter) remnants that remain aligned to the orbital path of the parent satellite (Johnston, Hernquist, & Bolte 1996; Johnston et al. 1999; Ibata et al. 2001b; Ibata & Lewis 1998, hereafter IL98; Mayer et al. 2001).

3. Convincing observational evidence of the clumpy and "filamentary" nature of the Galactic halo have been provided by many different groups (e.g., Newberg et al. 2002; Vivas et al. 2001; Dohm-Palmer et. al. 2001; Yanny et al. 2000; Ivezic et al. 2000; Ibata et al. 2001b; Helmi et al. 1999; Helmi 2001; Majewski et al. 1999).

The in vivo example of a satellite accretion or disruption is provided by the Sagittarius dwarf spheroidal galaxy (Sgr dSph; Ibata, Irwin, & Gilmore 1994; Ibata et al. 1997), which is currently merging with the Milky Way and is carrying its own globular cluster system (i.e., M54, Ter 8, Arp 2, and Ter 7, previously believed to be normal Galactic globular clusters). There is now clear observational evidence that the Sgr dSph is losing stars under the strain of the Milky Way tidal field. These tidally removed stars are found along a huge (and quite coherent) stream extending all over the sky (the Sagittarius Stream; see Ibata et al. 2001b; Dohm-Palmer et al. 2001; Martínez-Delgado et al. 2001; Newberg et al. 2002, and references therein), tracing the orbit of the parent galaxy.

IL98 and Ibata et al. (2001b) have simulated the evolution of the Sgr dSph over several orbital periods ($P \sim 1$ Gyr), computing the orbit of the galaxy, as well as the phase-space distribution of the debris under different assumptions about the flattening of the CDM halo. The initial conditions of the simulations were based on the known position and radial velocity of Sgr dSph and on its proper motion as estimated by Ibata et al. (1997, 2001b). The orbit has a planar rosette structure, with the pole of the orbit located at ($l = 90°$, $b = -13°$) (i.e., a nearly polar orbit), and peri- and apogalactic distances of 15 and 60 kpc, respectively. The derived

orbit has been successfully compared with the observed position of the Sagittarius Stream (Ibata et al. 2001a, 2001b), providing also remarkable indications that the dark halo of the Milky Way is nearly spherical.

In this framework it is a tantalizing application to look for other halo globulars that may be correlated with the orbital path of the Sagittarius dwarf and which could be lying in the Sagittarius Stream. In particular, we look for the phase space coincidence of outer halo globulars with the computed orbit of the Sgr dSph from 1 Gyr ago up to the present day, searching for the most recent episodes of globular cluster loss, i.e., the ones whose traces are most likely to be still detectable.

2. LOOKING FOR STRUCTURES

For our comparison we selected from the catalog by Harris (1996) the 35 globular clusters in the range of galactocentric distance $10 \, \text{kpc} \leq R_{GC} \leq 40 \, \text{kpc}$. Among these, 33 have also measured radial velocity V_r. For the sake of brevity and clarity we will call this sample the outer halo sample (OHS), in the following. With this selection we avoid the central part of the Galactic halo where it is less likely that ordered structures can survive for a long time and we leave out of the sample the handful of clusters lying outside $R_{GC} \geq 60$ kpc, a region that lies beyond the Sagittarius Stream according to the IL98 orbit.[1] The adopted OHS *does not include the known Sagittarius globulars*, to avoid the detection of the obvious signal of their clustering around the center of the Sagittarius galaxy.

In Figure 1 we show the OHS clusters (*small filled circles*) and the Sagittarius orbit in the planes formed by the rectangular Galactocentric coordinates[2] [(X, Y, Z) in kiloparsecs] and in the R_{GC} (in kiloparsecs) versus V_r (in kilometers per second) plane. The large filled circles are the known Sagittarius globulars, which we also show in the plots for completeness. Note that these clusters lie around the end of the orbit corresponding to the present time ($t = 0$). We highlight (*encircled filled points*) six more clusters that lie remarkably close to the orbit in all the considered planes. These clusters are Pal 12 (whose association to the Sagittarius Stream has been already established by Dinescu et al. 2000 and Martínez-Delgado et al. 2002), Pal 5, NGC 4147, NGC 5053, NGC 5634, and Ter 3. Is this association *real* or could it be the mere occurrence of a chance alignment? Though chance alignments in the four-dimensional phase space (X, Y, Z, V_r) are not expected to be very likely, the key point is to quantify the probability that the observed structure could have originated from a statistical fluctuation. To do this we will compare the observed distribution—and its phase space distance to the Sagittarius orbit—with synthetic samples (having the same dimension as the OHS)

extracted from a model representing an unstructured parent halo.

The most conservative comparison that can be made is with a model that closely resembles the observed radial and velocity distribution of the OHS. Figure 2 (*top*) shows that the cumulative radial distribution of the OHS is well reproduced by a spherical halo model with a density distribution $\propto R^{-1.6}$. A Kolmogorov-Smirnov (KS) test shows that the probability that the OHS is drawn from the $\Phi \propto R^{-1.6}$ model is $\simeq 90\%$. On the other hand, the probability that the same sample is drawn from the other two models shown for comparison ($\Phi \propto R^{-1.0}$ and $\Phi \propto R^{-2.5}$) is $\leq 15\%$. Doubts may be cast on the appropriateness of a spherical model. It may be conceived that if the *true* parent halo is flattened, some excess of clustering of the observed points along an orbit with low inclination may artificially emerge in the comparison with a spherical model. This is clearly not the case, however, since the IL98 orbit is nearly polar; i.e., it is almost perpendicular to the Galactic plane (see Fig. 1). In Figure 2 (*bottom*) it is shown that the observed distribution of radial velocity of the OHS is well reproduced by a Gaussian distribution with $\langle V_r \rangle = -38 \, \text{km s}^{-1}$ and $\sigma_V = 175 \, \text{km s}^{-1}$. According to a KS test the probability that the observed sample is drawn from the model distribution is $\simeq 90\%$.

In the following simulations we extract all the synthetic samples from a spherical and isotropic model with $\Phi(R_{GC}) \propto R_{GC}^{-1.6}$ and with the Gaussian distribution of radial velocities shown in Figure 2. For each simulated cluster (as well as for all the OHS ones) we computed the spatial distance from the nearest point in the Sagittarius orbit (D_{orb} in kiloparsecs) and the difference between their radial velocity and the one predicted from the computed orbit at that point [$\Delta V_r = V_r(\text{obs}) - V_r(\text{orb})$].

In Figure 3, the D_{orb} values of the selected clusters (*large circles*) are plotted against their ΔV_r. The encircled points are the six clusters highlighted in Figure 1. A sample of 10,000 synthetic clusters (*dots*) extracted from the adopted model is also shown for comparison in Figure 3 (*top*). The OHS clusters show a remarkable overdensity toward the Sagittarius orbit, which lies in the origin of the axis in the considered plane. The dash-dotted lines enclose the points whose observed radial velocity is within $\pm 60 \, \text{km s}^{-1}$ of the velocity predicted by the IL98 orbit. Note that the expected velocity dispersion of the Sagittarius debris along the Sagittarius Stream is $\sigma \sim 60 \, \text{km s}^{-1}$, according to Ibata et al. (2001a). The vertical segments are placed at $D_{orb} = 6, 12$, and 18 kpc.

Figure 3 (*bottom*) is arranged in the same way, but in this case the dots represent the distribution of the points in the best-fitting Ibata et al. (2001b) simulation that retains a bound core to the present day. The heavy dots are the particles that remain bound to Sagittarius *or were bound less than 3 Gyr ago*, while the light dots are particles that were already unbound at that time. Note the remarkable similarity to the distribution of the OHS clusters. In particular, the correlation between the particles that have flown in the Sagittarius Stream in recent times (less than 3 Gyr ago) and the OHS clusters with $|\Delta V_r| < 60 \, \text{km s}^{-1}$ at any D_{orb} is quite striking.

We define $N_{D<x}$ as the number of synthetic or real clusters having $-60 \, \text{km s}^{-1} < \Delta V_r < +60 \, \text{km s}^{-1}$ and $D_{orb} < x$ kpc. For example, it can be seen from Figure 3 that there are five OHS clusters with $|\Delta V_r| < 60 \, \text{km s}^{-1}$ and $D_{orb} < 6$ kpc, thus $N_{D<6} = 5$. In the same way we find $N_{D<12} = 10$ and

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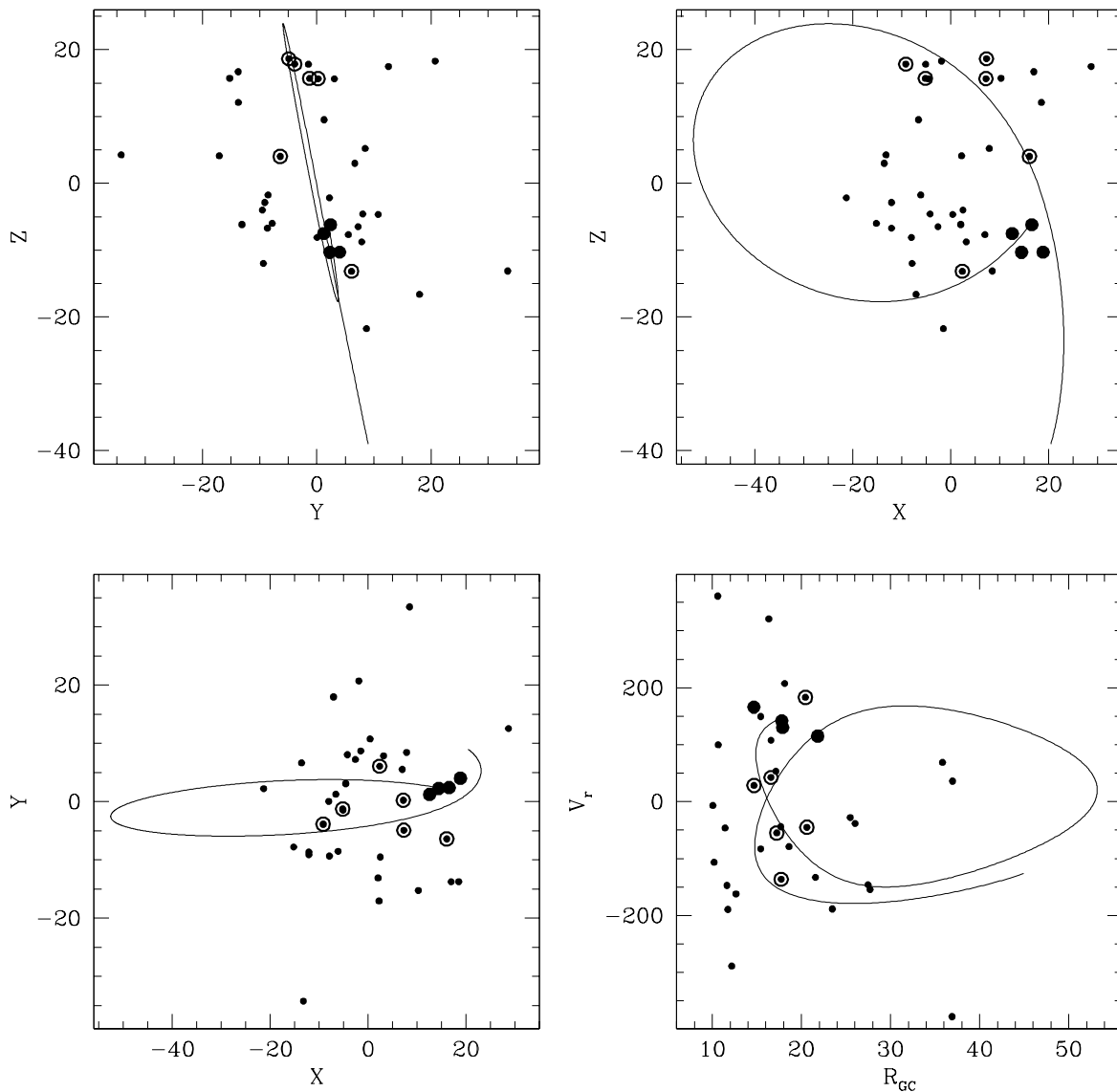[1] There is a 28 kpc–wide gap in the radial distribution of Galactic globular clusters (see, e.g., Zinn 1985, and references therein). There are only five clusters beyond $R_{GC} = 40$ kpc, namely, Pal 14, Eridanus, Pal 3, NGC 2419, Pal 4, and AM 1. Their respective galactocentric distances are $R_{GC} = 65$, 83, 90, 98, 99, and 117 kpc, much beyond the apogalacticon of the Sagittarius orbit. The adopted outer radial threshold ($R \leq 40$ kpc, quite similar to the one adopted by PMJ02, i.e., $R_{GC} \leq 36$ kpc) provides for the selection of a homogeneous sample without significant gaps.

[2] This Galactocentric coordinate system is defined such that the origin lies at the Galactic center; at the solar position, $(-8, 0, 0)$, the Y-axis points in the direction of Galactic rotation, while the Z-axis toward the north Galactic pole.

Fig. 1.—Distribution of Galactic globular clusters with 10 kpc $\leq R_{GC} \leq 40$ kpc (OHS; *small circles*) in the Y vs. Z, X vs. Z, X vs. Y, and V_r vs. R_{GC} planes. The large circles are the known Sagittarius globulars M54, Arp 2, Ter 8, and Ter 7, while the encircled points mark the clusters that are near the Sagittarius orbital path in all the planes shown here (NGC 4147, Pal 12, NGC 5634, Pal 5, NGC 5053, and Ter 3). The line is the orbit of the Sgr dSph since the present time (at the position of the Sagittarius clusters) to 1 Gyr ago, according to IL98.

$N_{D<18} = 14$ from the observed sample. Now the question is *what is the probability that a sample having $N_{D<x}$ greater or equal to the observed one ($N_{D<x}^{obs}$) is drawn from the assumed unstructured model?* To answer this question we randomly extracted 10,000 samples of 32 synthetic clusters from the assumed model, and for each of them we measured $N_{D<6}$, $N_{D<12}$, and $N_{D<18}$.

Figure 4 reports the distributions of $N_{D<6}$ (*top*), $N_{D<12}$ (*middle*), and $N_{D<18}$ (*bottom*) for the 10,000 simulated samples. The respective observed values are indicated by a dashed line. In all the considered cases the mean and modal $N_{D<x}$ values of the distribution are much smaller than the observed ones. $N_{D<6} \geq 5$ occurs for only 200 simulated samples in 10,000 (2% of the cases), $N_{D<12} \geq 10$ occurs for only 42 samples in 10,000 (0.4%), and $N_{D<18} \geq 14$ occurs only in two cases in 10,000 (0.02%). It can be concluded that it is highly improbable that the observed clustering of the OHS globulars around

the Sagittarius orbit occurs by chance alignment. It is important to remark again that the model from which the simulated samples have been extracted has the same R_{GC} and V_r distribution of the observed sample. Thus *the Sagittarius orbit appears to be a strongly preferred subset of the phase space for the Galactic globulars* in the considered range of R_{GC}.

Finally, we note that the simulated samples that have a significant probability of realization (e.g., $P \geq 20\%$) have $N_{D<6} \leq 3$, $N_{D<12} \leq 6$, and $N_{D<18} \leq 8$, significantly lower than the observed values. Hence, the significance of the detected phase space structure cannot be due to the actual correlation of just a couple of clusters with the Sagittarius orbit. According to the distributions shown in Figure 4, the probability that $N_{D<18} \geq 10$ is $P \simeq 5\%$. Therefore it can be stated with 95% confidence that at least four real associations are needed to produce the observed signal of $N_{D<18} = 14$.
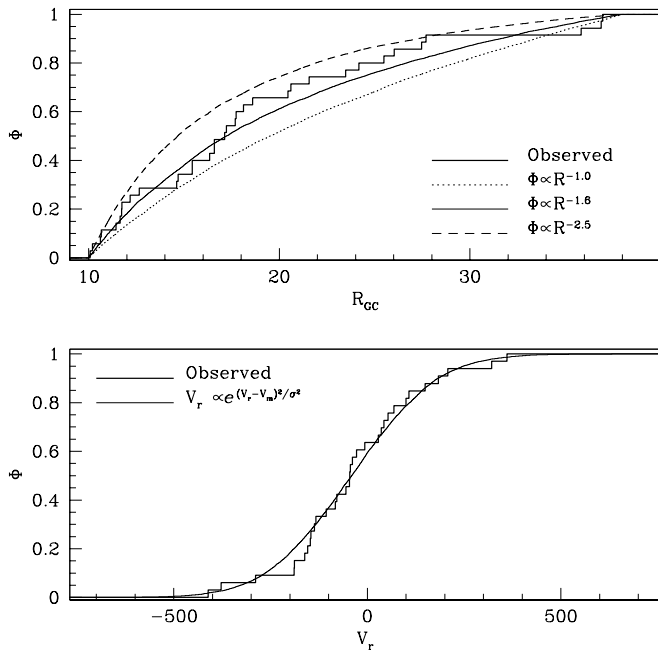
FIG. 2.—*Top*: Cumulative radial distribution of the OHS globulars (*thick continuous line*) compared with three different model distributions in the considered radial range ($10 \text{ kpc} \leq R_{GC} \leq 40 \text{ kpc}$). According to a Kolmogorv-Smirnov test, the probability that the observed distribution is drawn from the model $\Phi \propto R^{-1.6}$ is $P \simeq 90\%$, while the other two models shown score $P \leq 15\%$. *Bottom*: Observed cumulative distribution of radial velocities for the same clusters (*thick continuous line*) compared with a Gaussian distribution with $\langle V_r \rangle = -38 \text{ km s}^{-1}$ and $\sigma_V = 175 \text{ km s}^{-1}$. Also in this case the probability that the observed distribution is drawn from the considered model is $P \simeq 90\%$.
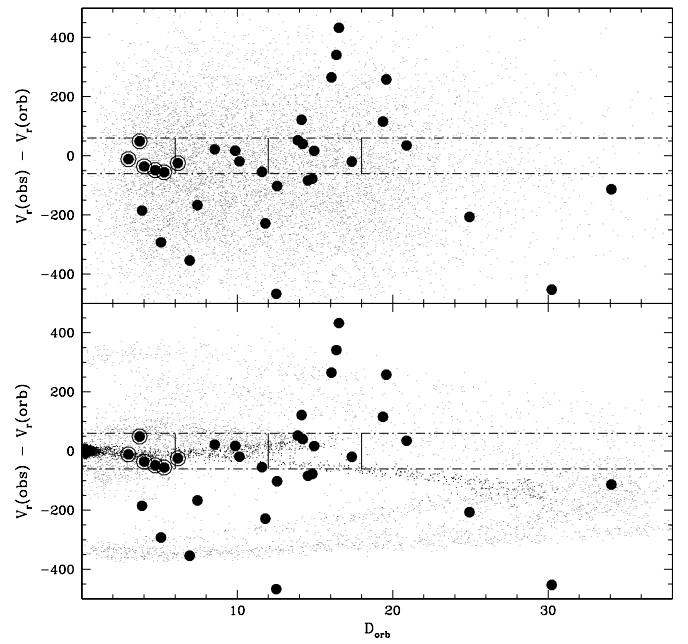

FIG. 3.—Distribution of the OHS globular clusters about the predicted orbit of Sagittarius. The parameter D_{orb} is the distance of the cluster from the nearest point of the orbit, while $V_r(\text{obs}) - V_r(\text{orb})$ is the difference between the observed radial velocity and the prediction of the computed orbit (at the nearest point in the orbit). The observed distribution (*large circles*) is compared with the distribution of 10,000 points randomly drawn from our assumed halo model (*top*) and with the distribution of the Sagittarius debris as computed by Ibata et al. (2001b; *bottom*). This *N*-body simulation displayed in the bottom panel is the model by IL98 that gives the best fit to the positions and velocities of the carbon stars observed in the Sagittarius Stream, while retaining a bound center (their dwarf galaxy model "D1" and halo model "H2," integrated in a Galactic potential with circular velocity $v_c = 200 \text{ km s}^{-1}$ at 50 kpc). The heavy dots show particles that remain bound to Sagittarius or were bound less than 3 Gyr ago, whereas the light dots were already unbound at that time. Clearly, several clusters in the OHS follow the expected trend of the recently disrupted Sagittarius debris. The encircled points represent the clusters similarly put in evidence in Fig. 1. The horizontal dash-dotted lines enclose the range $-60 \text{ km s}^{-1} \leq \Delta V_r \leq 60 \text{ km s}^{-1}$, while the continuous vertical segments are located at $D_{orb} = 6, 12,$ and 18 kpc.

The above test demonstrates that the observed phase space clumping around the orbit of the Sagittarius dwarf galaxy is highly unlikely to have occurred by a chance coincidence, if the halo globular cluster population is indeed distributed according to the simple spherical model described above. To address this concern, we performed a second test, using "bootstrapped" artificial data sets constructed from the real OHS. The artificial samples were constructed by rotating the position of each real globular cluster by a random azimuthal angle about the Galactic center and introducing a random flip perpendicular to the Galactic plane. This implicitly assumes, of course, that the globular cluster distribution is symmetric about the Galactic center, as well as above and below the Galactic plane. A slight complication arises from the fact that we do not know the proper motion of many of the clusters, so we cannot deduce the heliocentric radial velocity that the cluster should have at its new position. We therefore have to assume some model for the halo velocity distribution; we take a simple Gaussian model and draw random realizations of the total space velocity $\vec{V}$ consistent with the observed heliocentric velocity V_r (that is, we calculate the conditional probability of $\vec{V}$ given V_r). Having defined thereby the three-dimensional velocity vector, we rotate the vector to the new position and project it along the line of sight to the Sun (corrections for the peculiar motion of the Sun and for Galactic rotation are made). With a Gaussian model that has $\sigma = 175 \text{ km s}^{-1}$ and $V_r = -38 \text{ km s}^{-1}$, we find that out of 10,000 artificial data sets, $F(N_{D<6} \geq 5) = 399, F(N_{D<12} \geq 10) = 102,$ and $F(N_{D<18} \geq 14) = 18.$ For

comparison, for a model with $\sigma = 110 \text{ km s}^{-1}$ (or $\sigma = 150 \text{ km s}^{-1}$) and $V_r = 0 \text{ km s}^{-1}$, the statistics are as follows: $F(N_{D<6} \geq 5) = 463 \ (425), F(N_{D<12} \geq 10) = 140 \ (121),$ and $F(N_{D<18} \geq 14) = 35 \ (28),$ where the result in brackets refers to the higher velocity dispersion model. According to these tests using "bootstrapped" random data sets, the observed phase space clumping is highly unlikely to have occurred by chance, in agreement with our previous test. The fact that the observed structure has a slightly lower statistical significance with the "bootstrapped" samples than was deduced from the previous test with its perfectly isotropic and isothermal random samples is not surprising. This is presumably a consequence of occasional chance reappearances of (part of) the structure of the real OHS in the "bootstrapped" samples.

As a final remark, we note that the region of the $\Delta V_r - D_{orb}$ plane with $|\Delta V_r| < 60 \text{ km s}^{-1}$ and $D_{orb} < 18 \text{ kpc}$ is also populated by particles that became unbound more than 3 Gyr ago. Thus the possibility has to be considered that some of the OHS clusters found in that region drifted into the Sagittarius Stream in more ancient times. For instance, this can be the case for NGC 5634, as we argue elsewhere (Bellazzini, Ferraro, & Ibata 2002). On the other
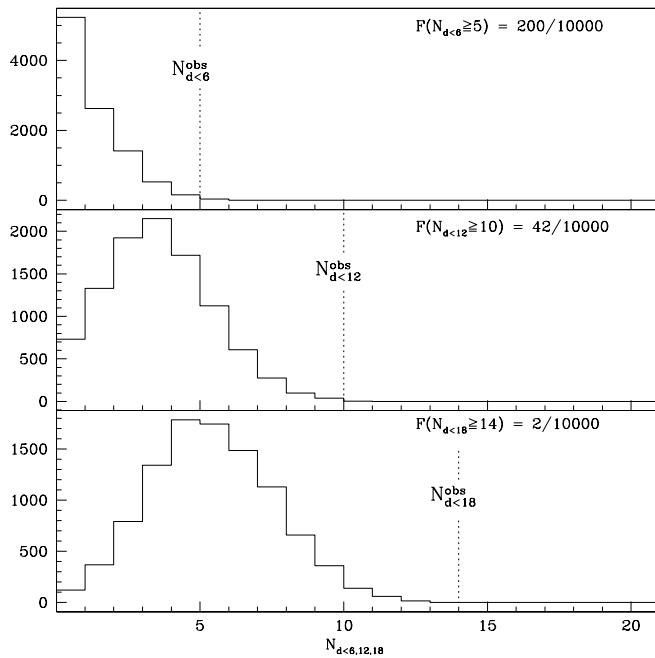
Fig. 4.—Results from the random drawing of 10,000 synthetic GC samples (equivalent to the observed one) from the assumed halo model.

hand, the discussion of the individual OHS clusters is beyond the scope of the present analysis.

2.1. Proper Motions

Thanks to the painstaking effort of a few teams of astronomers, estimates of the proper motions (PMs) of 41 Galactic globular clusters are now available (see Dinescu et al. 1999 and PMJ02 for complete lists and references). Most of these measures have quite sizeable uncertainties, ranging from ∼0.2 to ∼2 mas year. Moreover, subtle and unaccounted for systematics may still affect them, as suggested by the large differences between independent estimates of the motion of the same cluster. In the list by PMJ02 there are 14 clusters with more than one PM estimate. The average absolute differences among independent estimates for the same cluster are 1.72 ± 1.29 mas yr^{-1} in $\mu_\alpha \cos \delta$ and 2.90 ± 2.50 mas yr^{-1} in the μ_δ component. Differences much larger than the quoted errors (up to ∼10 times) are common, and a reasonable assumption of the *minimum* uncertainty of the proper-motion estimates is probably ∼1 mas yr^{-1} in each component. Hence, while available PMs may be very valuable, for instance, to characterize the *kind* of orbit followed by a given globular, they are expected to have a modest constraining power in the application presented in this paper. Such constraining power is also lowered by the fact that PMs predicted by the model we are comparing with carry their own nonnegligible uncertainty (typically ∼0.85 mas yr^{-1} in each component, which we estimate from the intrinsic dispersions in distance, position, and velocity in the N-body stream models, assuming a 20% uncertainty in the Galactic circular velocity at 50 kpc). Radial velocities, being unaffected by uncertainties in the distance, are more reliably predicted by the model and are easily and much more accurately measured. For these reasons we preferred to limit the bulk of our analysis to the (X, Y, Z, V_r) phase space.

Yet it may be interesting to compare the PMs predicted by the IL98 model for the clusters that are candidate members of the Sagittarius Stream (listed in Table 1; see below) with the observational estimates. The orientations (directions) of the PM vectors are expected to be less sensitive to systematics with respect to the actual moduli. In Figure 5 we compare the predicted and observed *directions* of the PM vectors of the seven clusters listed in Table 1 for which PM estimates are available. Four of these seven clusters have two independent PM estimates: in these cases we report the comparison with both values (see Fig. 5 legend). We stress that this kind of comparison *cannot have a serious impact on our previous conclusions* unless both the following conditions were simultaneously fulfilled: (a) if accurate PM estimates were available for all the considered clusters (or the large majority of them) and (b) if less than three or four clusters were found to have observed PMs in agreement with the predictions. This case would imply that the correlation among OHS clusters and the Sagittarius orbit we detect in the (X, Y, Z, V_r) phase space is largely due to a very unlikely (but not impossible) chance alignment in four dimensions. On the other hand some (up to ∼10, actually) of the clusters listed in Table 1 *are expected not to belong to the detected structure.*

In (a) the predicted proper motions include a correction for the solar reflex motion (hereafter SRM), assuming a
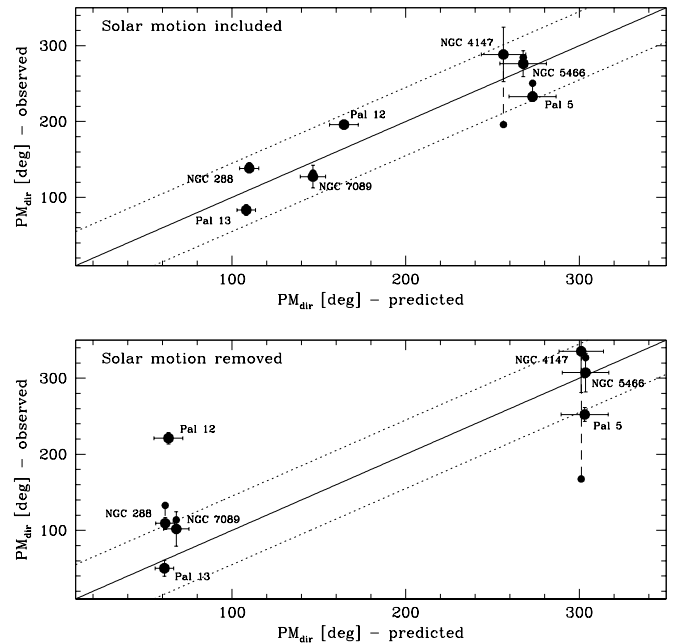

Fig. 5.—Predicted direction of proper motions compared with the observed ones for the subset of candidate Sagittarius Stream clusters for which estimates of proper motion are available (from the list by PMJ02). When two independent estimates of proper motion are available for the same cluster we report both: one as a large circle and the other as a small circle, and the two symbols are joined by a dashed line. The large dot of Pal 5 is the estimate quoted by PMJ02 as in Cudworth et al. (2001, private communication); the small dot is from Schweitzer, Cudworth, & Majewski (1993). The solid line is the locus of perfect agreement between predictions and observation; the dotted lines are displaced by ±45°. The error bars are derived from the propagation of the uncertainties in the PM estimates of clusters as reported by Dinescu, Girard, & van Altena (1999) and PMJ02 and from the uncertainties in the model predictions as described in § 2.1. *Top*, Comparison between PMs including the SRM; *bottom*, comparison between PMs corrected for the SRM.

TABLE 1
OHS CLUSTERS IN THE SAGITTARIUS STREAM

Name	D_{orb} (kpc)	ΔV_r (km s^{-1})	$\mu_\alpha \cos \delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	$\mu_l \cos b$ (mas yr^{-1})	μ_b (mas yr^{-1})
Pal 12......................	3.00	−11.2	0.67	−2.41	−2.324	−0.934
NGC 4147..............	3.72	49.1	−2.99	−0.73	−2.284	−2.061
Pal 5........................	4.01	−36.0	−4.68	0.25	−3.468	3.146
NGC 5634[a]	4.72	−48.6	−4.64	0.25	−3.579	2.968
NGC 5053..............	5.30	−55.7	−3.78	−0.28	−3.754	0.494
Terzan 3.................	6.18	−24.8	−4.09	−0.29	−2.858	2.941
NGC 5466..............	8.55	21.9	−3.97	−0.16	−3.818	1.104
NGC 288	9.88	17.2	3.37	−1.22	1.235	−3.368
NGC 7089..............	10.14	−18.9	1.47	−2.23	−2.037	−1.727
NGC 6426..............	11.59	−54.4	−4.15	−0.25	−2.891	2.981
NGC 5824..............	13.90	52.5	−4.34	−0.09	−3.023	3.119
Pal 13	14.21	40.4	3.47	−1.14	1.695	−3.237
Pal 2.......................	14.95	16.9	3.99	0.20	2.933	2.707
Rup 106	17.37	−19.4	−4.67	0.24	−3.439	3.176
Known Members:						
NGC 6715..............	0.45	−4.2	. . .	. . .	. . .	. . .
Terzan 7.................	1.89	34.0	. . .	. . .	. . .	. . .
Terzan 8.................	2.04	−2.0	. . .	. . .	. . .	. . .
Arp 2.......................	5.13	−26.6	. . .	. . .	. . .	. . .

NOTE.—Distance from the nearest point in the orbital path followed by the Sgr dSph during the last gigayear (D_{orb}) and difference in radial velocity between the considered cluster and prediction of the computed orbit at that point (ΔV_r) for the OHS clusters having $|\Delta V_r| < 60$ km s^{-1} and $D_{orb} < 18$ kpc. The clusters are ordered with growing D_{orb}. The known members of the Sagittarius system are also reported at the end of the table for comparison. The first six clusters of the list are the ones put in evidence in Figs. 1 and 3. The four known members of the Sagittarius globular cluster system are also reported for comparison in the last four rows of the table. The proper motions predicted by the IL98 model (under the hypothesis that [a] the clusters belong to the Sagittarius Stream and [b] they have been lost during the last orbit of Sagittarius; see § 2) are also reported, in both the equatorial and galactic reference system. The intrinsic dispersion of the modeled stream, combined with estimated 20% uncertainties in the Galactic mass model, translate to uncertainties of ∼0.85 mas yr^{-1} on each PM component.

[a] Bellazzini et al. 2002 argue that NGC 5634 was likely lost before the last pericentric passage of Sagittarius, so the proper-motion predictions listed here may be substantially in error.

Galactocentric distance of 8 kpc, a circular velocity of 220 km s^{-1}, and the peculiar motion of the Sun as derived by Dehnen & Binney (1998). The predicted PM directions of all the seven clusters agree with the observed values to within ±45°. The adoption of alternative PM estimates does not change significantly the observed correlation. However, the result of this comparison may be affected by the inclusion of the solar reflex motion. Hence, in (b) we present the comparison between the plain (uncorrected for the SRM) model predictions and the observed PM directions after correction for the SRM. The result is very similar to that presented in (a) despite the larger errors involved. The only cluster whose predicted and observed PM directions differ by more than 45° is Pal 12, e.g., the only one for which independent evidences of membership in the Sagittarius Stream are already available (Martínez-Delgado et al. 2002).

In conclusion, it is found that the available proper motion estimates are fully compatible with the results presented earlier in § 2. Given the high degree of correlation among predicted and observed PM directions shown in both panels of Figure 5 one may also be tempted to draw a firm conclusion about the actual membership of individual clusters. Nevertheless, in our view, this may still be a hazard. If one looks at the amplitude of the individual corrections it is found that (a) all the considered clusters have at least one component of the PM vector that is corrected by more than 50% of the observed value, (b) four out of seven clusters have at least one component whose SRM correction is larger that 100% of the observed values, and (c) corrections as large as 200%–

400% are indeed applied in some cases. Given the remarkable uncertainties in the observed PMs and the uncertainties involved in the SRM correction it is easy to conclude that currently measured PMs are not good tracers of the actual motion of the considered clusters and are instead predominantly measures of the solar reflex motion. These considerations fully support the approach followed earlier in § 2, e.g., by using only positions and radial velocity measurements in the search for statistical structures in the globular cluster system of the Milky Way.

2.2. Comparison with Previous Analysis

The possible association of Galactic globulars with the Sgr dSph galaxy has been considered before (Irwin 1999; Dinescu et al. 1999, 2000; Siegel at al. 2001; PMJ02). All these studies strongly rely on PM estimates. Furthermore they are centered on testing the actual association of individual clusters with the Sagittarius galaxy and its remnants. On the other hand our approach and our results are statistical in nature. We find a statistically significant clustering of OHS clusters along the Sagittarius orbit, but we have no possibility to check individual membership, except for the limited test shown in § 2.1. We can provide only a list of possible members ranked according to their distance to the Sagittarius orbit in the (X, Y, Z, V_r) phase space (e.g., Table 1). Hence, the comparison with the above quoted studies can be made only in a broadly general sense.

Dinescu et al. (1999) performed a thorough study of the orbits of the Galactic globulars for which PM estimates are available. In doing this, they identify three metal-poor clusters having orbits typical of the thick disk (instead of the halo, as expected), and they check the hypothesis that the peculiar orbits of these clusters (namely, NGC 6254, NGC 6626, and NGC 6752) could be due to their former membership in the Sgr dSph, concluding that this possibility is unlikely. All these clusters have $R_{GC} < 10$ and are thus are not included in the OHS considered here, and we cannot comment further on the Dinescu et al. (1999) results.

Following the suggestion of Irwin (1999), Dinescu et al. (2000) modeled the (PM based) orbits of the Sgr dSph and of Pal 12 and concluded that the available observations are compatible with the possibility that the cluster was torn from the galaxy $\sim$1.4–1.7 Gyr ago. Our analysis confirms this result.

Siegel at al. (2001) obtained an estimate of the PM of Pal 13 and compared the general characteristics of the integrated orbit of the cluster (total energy, angular momentum, eccentricity, and perigalactic and apogalactic radii) with those of five satellite galaxies of the Milky Way, including Sagittarius. They conclude that a common origin for Pal 13 and Sagittarius is unlikely. However we note that (a) Sagittarius provides (by far) the best match to the orbital parameters of Pal 13 with respect to any other considered galaxy (see Table 8 in Siegel et al.), the maximum discrepancy being $\sim$40% in angular momentum, and (b) the orbital parameters are provided without any uncertainty, as if the adopted PMs were perfectly known. In our view this shortcoming seriously weakens the conclusion by these authors. Here we adopt the same PM estimate obtained by Siegel at al. (2001), reaching the conclusion that Pal 13 is a possible member of the Sagittarius Stream by direct comparison with a model that includes the Sagittarius Stream itself.

PMJ02 performed a global search for structures made of Galactic satellites, adopting the technique of the "orbital poles" originally introduced by Lynden-Bell & Lynden-Bell (1995). In this kind of analysis one searches for intersections among the great circles described by the family of possible poles of the orbit of any given satellite. As stated by PMJ02 "any set of objects having common origin and maintaining a common orbit, no matter how spread out in the sky, will have great circle pole families (GCPFs) that intersect at the same pair of antipodal points on the celestial sphere." Adding the information from PMs, PMJ02 limit the valid pole family of each satellite to an arc of its great circle of orbital poles (arc segment pole family). With this technique they select a set of candidate former members of the Sagittarius galaxy (Ter 7, Ter 8, Arp 2, M54, M53, NGC 5053, Pal 5, M5, Pal 12, and NGC 6356) by requiring that their GCPFs come within 5° from the Sagittarius ACPF and 6 kps $\leq R_{GC} \leq$ 36 kpc. The first four clusters in their list are the well-known present members of the galaxy. They raise doubts about the clear association of each of the other candidate members. For instance, they exclude NGC 5053 and M53 because their metal content is lower than any of the known Sagittarius globulars.[3] With the same arguments

adopted by Siegel at al. (2001) for Pal 13 they argue that Pal 5 and Pal 12 are unlikely members of the family, but they cannot rule out the possibility. Finally, they conclude that despite the counterarguments presented they maintain their original list of candidates, with the exception of NGC 5053. Elsewhere in the paper, they also note that NGC 5466 has energy and angular momentum within 1 σ of those of the Sagittarius galaxy. NGC 6356, M5 and M53 have $R_{GC} < 10$ kpc and hence are not included in our sample. The possible association of NGC 5466 with the Sgr dSph is confirmed by our analysis. The possible association of NGC 5053, Pal 5, and Pal 12 is also confirmed by the present work. PMJ02 also suggested a possible association of NGC 4147 with a group of clusters whose orbits may be related to those of the Magellanic Clouds, but they state that the result is very uncertain. Furthermore we note that on the same basis the possible association of M53 (elsewhere classified as a candidate for association with Sagittarius) with the Small Magellanic Cloud and Ursa Minor is also suggested by PMJ02. We conclude that there is no serious disagreement between the present analysis and the one by PMJ02.

The present contribution, however, *provides the first proof that the orbit of Sagittarius is a preferential subset of phase space for globular clusters inhabiting the outer halo of the Milky Way*, and we place this result on a sound statistical basis, a result not accomplished by any of the previous studies. The success of the present analysis is due to the direct comparison of the positional and kinematical properties of the OHS clusters with a realistic model of the orbit of the Sgr dSph and its relics that has been previously tested against independent observations (Ibata et al. 2001a, 2001b).

Finally, we shall shortly comment on "nonkinematic" criteria that have been used to assess the association of a given cluster with the Sagittarius galaxy. Many authors (see, e.g., Dinescu et al. 1999; PMJ02, and references therein) have discussed the likelihood of the membership of their candidates on the basis of the similarity of their metallicity, horizontal branch (HB) morphology, and/or structural parameters with those of the four known Sagittarius clusters. In our opinion this approach may not be very useful. It is quite clear that Sagittarius was a much larger and complex system in the past and its present status (as well as its present GC system) may not be fully representative of its original range of properties. If, by chance, the cluster Ter 7 had been lost by the Sagittarius galaxy in the previous perigalactic passage, those kinds of criteria would have *erroneously* classified it as a bad candidate for Sagittarius membership, since Ter 7 is much more metal-rich ([Fe/H] $\simeq -0.5$) than any of the other clusters that are still present in the main body of Sgr dSph ([Fe/H] < -1.5). Moreover, the existence of population and/or metallicity gradients may have driven the preferential loss of metal-poor populations (see Alard 2001; Newberg et al. 2002; Bellazzini et al. 2002, and references therein), making the actual low-metallicity limit of the Sagittarius stellar population quite uncertain. The judgment of the likelihood of membership on the basis of the HB morphology is even less justified since it is well known that clusters of different morphologies do actually coexist in real galaxies (see, e.g., Buonanno et al. 1998, and references therein, for the case for Fornax).

A much more reliable discriminant may be provided in the future by the detailed abundance patterns of the clusters. For instance, the behavior of α elements as a function of

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[3] This is not completely true since M53 has the same metallicity as Ter 8, i.e., [Fe/H] $= -1.99$ (see Montegriffo et al. 1998; Da Costa & Armandroff 1995). See also below, for further discussion about nonkinematic criteria of selection of candidate Sagittarius members.

[Fe/H] is determined by the star formation history of the parent galaxy (see McWilliam 1997, and references therein), which was (probably) not the same in the Sgr dSph and in the Galactic halo. In this context it is interesting to note that Pal 12, Ru 106 (Brown, Wallerstein, & Zucker), and Pal 5 (Smith, Sneden, & Kraft 2002) have been found to be less α-enhanced than Galactic halo globulars of similar metallicity.

For the above reasons, we rely only on phase space parameters in our analysis, recalling that by searching the lost relics of the Sagittarius system we are trying to reconstruct its original properties, not the present-day ones.

3. CONCLUSIONS

We have demonstrated that there is a coherent structure in the phase space distribution of the outer halo globular cluster of the Milky Way, strongly correlated with the orbital path of the Sgr dSph galaxy. This correlation cannot have originated by chance, as a random realization of an unstructured halo, if such halo has the same distribution of galactocentric distance and radial velocity as the considered OHS clusters.

Several of the OHS globular clusters have spatial positions and radial velocities compatible with the hypothesis that they are following the same orbit as the Sgr dSph, i.e., they probably belong to the Sagittarius Stream. Furthermore, the spread in phase space around the Sagittarius orbit of such clusters is similar to that predicted for the Sagittarius Stream population, according to the numerical simulations by Ibata et al. (2001b).

We conclude with 95% confidence that *at least four* (*of 32*) *of the OHS clusters are physically associated with the Sagittarius Stream and were former members of the Sgr dSph*. It should be noted, however, that the analysis presented in this contribution is best suited to identify clusters that became unbound relatively recently. In principle, more OHS globular clusters could be associated with the Sagittarius Stream.

In Table 1 we report the list of the selected globulars having $|\Delta V_r| < 60$ km s^{-1} and $D_{\rm orb} < 18$ kpc, in order of increasing $D_{\rm orb}$. The proper motions predicted by the IL98 model are also reported in Table 1. Since the adopted analysis is statistical in nature it is clear that some of the clusters

listed in Table 1 may be just occasional interlopers of the Sagittarius orbit (up to 10 of 14 in the worst case, according to our estimate). The comparison with the available proper motion estimates shown in § 2 does not provide any strong indication in this regard. While the actual membership to the Sagittarius Stream of each individual cluster can be firmly established only with very accurate proper motion measures (as will be achieved by dedicated space missions like GAIA or SIM), it is reasonable to assume that the clusters with the smaller $D_{\rm orb}$ are the ones for which the membership is more likely (see § 2.1). We make the hypothesis that the six clusters more closely associated with the Sagittarius orbital path (i.e., those put in evidence in Figs. 1 and 3) are former members of the Sgr dSph. In this case the number of globular clusters originally in the Sagittarius galaxy is $N_{\rm cl} = 10$. If we adopt for the Sgr dSph the same *globular cluster specific frequency* ($S_N = N_{\rm cl}10^{0.4(M_V+15)}$; Harris & Van den Bergh 1981) of the only other Galactic dSph that has a globular cluster system, i.e., Fornax, with $S_N \simeq 26$, we obtain an estimate of the total absolute magnitude of Sagittarius before the occurrence of any tidal stripping, $M_V \simeq -14$. Newberg et al. (2002) estimated that in the Sagittarius Stream there are as many stars as in the present undisrupted body of the galaxy, thus the ab initio total luminosity of the Sgr dSph was roughly 2 times the present value. Hence the total absolute magnitude at that time was $M_V - \log 2 \simeq -14.1$ (where $M_V = -13.4$ from Mateo 1998). The excellent agreement between the two independent estimates of the initial M_V values fully supports the plausibility of the proposed scenario.

According to the results presented, it emerges that the Sgr dSph was not only an important contributor of halo field stars (Ivezic et al. 2000; Yanny et al. 2000; Newberg et al. 2002), but it also had a significant role in building up the globular clusters system of the Milky Way.

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Note added in proof.—While this paper was in the peer review process, Yoon & Lee found another coherent structure among the most metal-poor Galactic globulars, possibly correlated with the orbit of the Large Megallanic Cloud (S.-J. Yoon & Y.-W. Lee, Science, 297, 578 [2002]).