SPACE VELOCITIES OF SOUTHERN GLOBULAR CLUSTERS. V. A LOW GALACTIC LATITUDE SAMPLE

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Received 2007 March 15; accepted 2007 March 28

ABSTRACT

We have measured the absolute proper motions of globular clusters NGC 2808, 3201, 4372, 4833, 5927, and 5986. The proper motions are on the Hipparcos system, and they are the first determinations ever made for these low Galactic latitude clusters. The proper-motion uncertainties range from 0.3 to 0.5 mas yr⁻¹. The inferred orbits indicate that (1) the single metal-rich cluster in our sample, NGC 5927, dynamically belongs to the thick disk; (2) the remaining metal-poor clusters have rather low-energy orbits of high eccentricity, and among these there appear to be two “pairs” of dynamically associated clusters; (3) the most energetic cluster in our sample, NGC 3201, is on a highly retrograde orbit—which had already been surmised from radial velocity alone—with an apocentric distance of 22 kpc; and (4) none of the metal-poor clusters appear to be associated with the recently detected SDSS streams or with the Monoceros structure. These are the first results of the Southern Proper Motion program where the second-epoch observations are taken with the recent CCD camera system installed on the double astrograph at El Leoncito, Argentina.

Key words: astrometry — globular clusters: individual (NGC 2808, NGC 3201, NGC 4372, NGC 4833, NGC 5927, NGC 5986) — surveys

1. INTRODUCTION

In the past decade considerable progress has been made in understanding our Galaxy’s globular cluster (GC) system. This is in large part due to dedicated programs that aim to homogeneously characterize properties of clusters including chemical abundance patterns, ages, horizontal-branch (HB) morphology, structural parameters, and orbits. Studies have combined the various recently acquired observational databases to search for correlations that can point to a realistic picture of the GC system (see, e.g., Carretta 2006; Recio-Blanco et al. 2006; Pritzl et al. 2005; Mackey & Gilmore 2004). Briefly, the present picture points to an accreted origin for the outer halo clusters (r_{GC} ≥ 10 kpc), while a combination of dissipational collapse and some accretion can best explain the current properties of inner GCs. However, details of these pictures are by no means understood, as there appears to be a series of “noncanonical” observations. For instance, there are metal-poor ([Fe/H] < −1.0) clusters with disklike kinematics (Dinescu et al. 1999a, hereafter Paper III, and references therein; Dinescu et al. 2003, hereafter Paper IV), there are metal-rich clusters ([Fe/H] > −0.8) with unusually blue extended HBs that appear to reside within the bulge (e.g., Rich et al. 1997), and (for the data currently available) the orbits of the most energetic clusters appear to be on average more eccentric than those of present-day dwarf spheroidal satellites (Dinescu et al. 2001). Also, these clusters are not dynamically associated with any of the current streams found in the SDSS (Belokurov et al. 2007; Grillmair & Dionatos 2006; see also our §5). There is only one exception to this latter point: cluster Pal 12 and its association with the Sagittarius dwarf galaxy (Sgr; Dinescu et al. 2000; Martínez-Delgado et al. 2002; Cohen 2004). Therefore, questions such as how much accretion took place in the past to build up the inner halo, can it really be traced and separated from the features of a dissipational collapse, and how different was it from the ongoing/recent accretion seen in surveys such as SDSS, remain to be explored.

With these questions in mind, we continue our program to determine the absolute proper motions of GCs, especially in the inner halo, and thus contribute new orbit information to the overall picture of the formation of the Milky Way GC system. Previous results from our program (Dinescu et al. 1997, hereafter Paper I; Dinescu et al. 1999b, hereafter Paper II; Paper III; Paper IV) were based on photographic plates alone. The current results are based on CCD data for the second epoch. A CCD system with two cameras was mounted in 2003 on the double astrograph at El Leoncito, Argentina, where our observations are based. Here we show the first astrometric results that make use of the new CCD system.

In §2 we describe the observations and reductions, including those of the CCD system recently mounted on the astrograph. In §3 we describe the proper-motion derivations. Section 4 presents the velocity and orbit results, and finally, a discussion of the results is given in §5.

2. OBSERVATIONS AND MEASUREMENTS

This work is part of the continuation of the Southern Proper Motion (SPM) program (Platais et al. 1998; Girard et al. 1998, 2004), a survey that aims to produce absolute proper motions and V, B photometry for ∼100 million stars in the southern sky, down to V ∼ 17.5. A recent release of this program based on photographic material alone includes 10 million objects (Girard et al. 2004). The photographic plate material used in this work is described in Table 1.

The remaining area for the second-epoch observations is being mapped with a two-camera CCD system installed on the 51 cm double astrograph at Cesco Observatory, El Leoncito, Argentina.
The earliest observations included in the SPM program started in 2003 June. This system’s properties and performances are briefly described below, while a more detailed description will be given in a future SPM general program update.

The program clusters are a low-latitude sample that supplements our previous work for 15 high-latitude clusters (Papers I and II). Thus, in the current work, the proper motions are tied to inertial reference system via Hipparcos stars rather than galaxies. The first results for this low-latitude sample were presented for four bulge clusters ($l = 350°–360°$) in Paper IV. The current sample is located in the fourth Galactic quadrant (Table 2). Other limitations on the sample are imposed by the SPM first-epoch plate material; i.e., clusters are south of 5927° and within ~10 kpc from the Sun. The novelty of the current work lies in rounding each plate into another, as well as CCD positions into the photographic material, (2) are mainly due to the nonlinear magnitude-dependent systematics that affect both positions and magnitudes. A comparison between the absolute proper motion of NGC 6121 (M4) as determined from the SPM material and calibrated via Hipparcos stars (Paper II) and that determined from HST data and calibrated to extragalactic objects (one QSO, Bedin et al. 2003; 11 galaxies, Kalirai et al. 2004) indicates excellent agreement within the quoted uncertainties of ~0.4 mas yr$^{-1}$.

The target clusters and the properties of the SPM fields and plates in which they were measured are listed in Table 1. The photographic plates were scanned with the Yale PDS microdensitometer in object-by-object mode, with a pixel size of 12.7 µm. On each SPM field, we measure a preselected set of stars (see also Paper IV). This set consists of all Hipparcos and Tycho-2 stars (Perryman et al. 1997), ~200 Guide Star Catalog 1.1 (GSC; Lasker et al. 1990) stars, ~3000 faint field stars selected from the USNO-A2.0 catalog (Monet et al. 1998) in the magnitude range 15–17, and cluster stars. For bright stars ($V < 14$) we measure both exposures and diffraction images. Hipparcos stars provide the correction to absolute proper motion, while Tycho-2 and GSC stars assure an appropriate magnitude range of various diffraction orders with which to model magnitude-dependent systematics. The faint stars serve as reference stars, i.e., are used to map one plate into another, as well as CCD positions into the photographic objects. Spatially, they are distributed around each Hipparcos star and in a ring around the cluster. This special configuration was chosen to minimize modeling uncertainties when plate positions are transformed into one another (see Paper I). For each SPM field we measure ~100 Hipparcos stars; there are 20 faint stars surrounding each Hipparcos star and ~2000 faint stars within the ring surrounding the cluster. The list of cluster stars to be measured on the plate is determined from a CCD frame (see below) centered on the cluster. The input positions for these stars are determined from the CCD frame and the software package SExtractor (Bertin & Arnouts 1996). Cluster stars are selected to cover a region of a few times the half-light radius, as taken from the 2003 update of Harris (1996, hereafter H96). The radius of this region varies between $4'$ and $9'$ for the various clusters, with the central $1'–2'$ being unusable because of crowding.

### Table 1

| NGC  | Field No. | R.A.  | Decl. | Plate No. (Epoch) |
|------|-----------|------|-------|------------------|
| 2808 | 096       | 09.2 | -65   | 401BY (1969.04)  |
| 3201 | 289       | 10.2 | -45   | 095BY (1967.05)  |
| 4372 | 068       | 12.4 | -70   | 794BY (1972.22)  |
| 4833 | 068       | 12.4 | -70   | 794BY (1972.22)  |
| 5927 | 241       | 15.1 | -50   | 295BY (1968.33)  |
| 5986 | 362       | 15.3 | -40   | 300BY (1968.33)  |

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### Table 2

| NGC  | $l$ (deg) | $b$ (deg) | $d_0$ (kpc) | $V_{rad}$ (km s$^{-1}$) | [Fe/H] | $M_V$ | $\mu_\alpha\cos\delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) |
|------|-----------|-----------|-------------|------------------------|--------|------|-------------------------------|-------------------------------|
| 2808 | 282.2     | -11.3     | 9.6         | 93.6                   | -1.15  | -9.39| 0.58 ± 0.45                   | 2.06 ± 0.46                   |
| 3201 | 277.2     | 8.6       | 5.0         | 494.0                  | -1.58  | -7.46| 5.28 ± 0.32                   | -0.99 ± 0.33                  |
| 4372 | 301.0     | -9.9      | 5.8         | 72.3                   | -2.09  | -7.77| -6.49 ± 0.33                  | 3.71 ± 0.32                   |
| 4833 | 303.6     | -8.0      | 6.5         | 200.2                  | -1.80  | -8.16| -8.11 ± 0.35                  | -0.96 ± 0.34                  |
| 5927 | 326.6     | 4.9       | 7.6         | -107.5                 | -0.37  | -7.80| -5.72 ± 0.39                  | -2.61 ± 0.40                  |
| 5986 | 337.0     | 13.3      | 10.4        | 88.9                   | -1.58  | -8.44| -3.81 ± 0.45                  | -2.99 ± 0.37                  |
front-illuminated Loral chip with a total area of 0.94" × 0.94". The pixel size of 0.83" is well matched to our site, where the seeing is typically between 2" and 3", corresponding to 3–4 pixels per FWHM. With a 2 minute exposure in reasonable seeing conditions, a magnitude limit of \( V \sim 18 \) is reached. The original blue camera was an Apogee AP-8 CCD with a 1K × 1K SITe back-illuminated chip, covering 0.38" × 0.38" at 1.32" pixel\(^{-1}\). In 2005 May this camera was replaced by an Apogee Alta E42 2K × 2K camera with a field of view of 0.42" × 0.42" at 0.74" pixel\(^{-1}\). The observations are taken with the diffraction grating oriented at 45°. Thus, the entire CCD dynamical range covered is 10 mag, i.e., 6 inherently from the CCD plus 4 provided by the grating.

For the SPM program, the PixelVision camera is the primary astrometry instrument and \( V \)-band photometer, while the Apogee cameras provide \( B \) photometry and possibly astrometry over a fraction of the survey. For the cluster work presented here, we make use only of the PixelVision astrometric data. The planned twofold overlap coverage with CCD frames requires some 90 frames over an isolated 6.3" × 6.3" SPm field. In addition, six or more frames are taken centered on each program cluster; each set of three frames has exposures of 30, 60, and 120 s. The CCD preprocessing pipeline includes calibrations using biases and flats for the PixelVision frames. Detections and aperture photometry are derived with SExtractor software. The positions from SExtractor, which are intensity-weighted centroids, are then used as initial positions in our refined centering routine that fits a two-dimensional elliptical Gaussian to the image profile. These later positions have a centering precision of ~20 mas per single image for well-measured objects (\( V = 7–15 \)).

Before attempting to derive proper motions based on the PixelVision CCD positions, two separate precorrections are performed. First, a correction for the optical field angle distortion (OFAD) of the field of view is determined and applied. Second, positions from the grating-order images must be placed on a common system with those of the deeper, central-order images. This latter step is necessary to provide a reliable means of linking the faint cluster members with the bright \textit{Hipparcos} stars that will be used to determine the correction to absolute proper motions.

The OFAD of the PixelVision frames, to the extent that it is constant and stable, can be determined by averaging the residuals between our CCD positions and those of an external catalog over many frames. General quadratic polynomial transformations between UCAC2 (Zacharias et al. 2000) coordinates and the (central-order) positions from the PixelVision frames provide residuals adequate for this task. As the telescope pointings used to create the UCAC2 catalog are distributed randomly across the PixelVision field of view, any resulting systematic patterns revealed can be attributed to the combined PixelVision/astromograph effective OFAD. We have averaged a minimum of ~200,000 residuals from at least 94 frames reduced into the UCAC2 using a quadratic transformation for each SPm field in this study. For each field, an empirical correction mask is derived on a 21 × 21 grid across the 4K × 4K pixel field. This mask is applied to the positions from each PixelVision frame, using bilinear interpolation within the mask grid. Typical amplitudes of the position corrections are 10–15 mas.

The second crucial step in the processing of PixelVision positions is the unification of the various diffraction-order coordinate systems. Given perfect optics and detector, and ignoring the possible effects of differential color refraction, the average position of the two first-order image centers should coincide exactly with the position of the central-order image. Likewise, the average of the positions of the two second-order images should also be coincident with the central-order image. An offset can indicate the presence of magnitude equation, the magnitude-dependent bias in stellar image positions often seen in photographic material but also expected to a lesser degree in CCD data because of imperfect charge transfer efficiency (CTE). With the first-order images being effectively 4 mag fainter than the corresponding central-order image, the presence of any magnitude-dependent bias would directly lead to a nonzero offset. In fact, these positional offsets are used to determine and then correct the magnitude equation present in the SPm photographic plates (see Girard et al. 1998).

In the case of the PixelVision data, our hope was to use the offsets between central and diffraction-grating images to measure any CTE-induced magnitude equation and correct for it. Indeed, substantial offsets on the order of 0.05 pixels (0.04") are seen; however, these do not appear to be CTE-related, i.e., caused by inherent magnitude equation. The offsets of the average of the first-order images relative to the central image, \( \Delta_{xy} \), vary from 0.0 to 0.1 pixels. These offsets are well correlated with the corresponding offsets of the average of the second-order image pairs relative to that of the central image, \( \Delta_{2y} \), within any given frame. Empirically, we find \( \Delta_{2y} = 2.0 \Delta_{xy} \). This is most certainly not the behavior to be expected if the offsets were due to magnitude equation. The second-order images are only marginally fainter than the first-order images, while both are substantially fainter than the central order. The magnitude differences between grating order and central order are 4.00 and 4.66 for the first and second orders, respectively. Obviously, the observed positional offsets, \( \Delta_{10} \) and \( \Delta_{20} \), are not proportional to the magnitude offsets.

A search for possible dependencies between the size of a particular frame’s offsets and hour angle, grating orientation angle, and seeing have all failed to reveal any underlying cause of the observed offsets. Noting that the ratio of the first- and second-order offsets, 2.0, matches the ratio of the actual separation of these diffraction images on the frame, we have decided to interpret the offsets as geometric in nature. That is, the bias in position is postulated to be proportional to the separation from the central-order image. Thus, we have adopted a scheme for transformation from grating-order coordinate system to central-order system that is a uniform \( \Delta X_{10}, \Delta Y_{10} \) to be applied to the positions of all first-order image pairs and \( \Delta X_{20}, \Delta Y_{20} \) that is applied to the second-order positions. The values of \( \Delta X_{10}, \Delta Y_{10}, \Delta X_{20}, \) and \( \Delta Y_{20} \) are calculated separately for each PixelVision frame, using probability plots (Hamaker 1978) of the inner 80% of all measurable grating-pair/central-image triads that also meet conservative photometric criteria to ensure the exclusion of saturated central-order images.

Further details of our analysis that led to the development of both the positional correction mask and the grating-order offsets that are applied to the PixelVision positions will accompany the publication of the next SPM catalog, expected later this year. For the present study, comparisons of the final proper motions determined using the first- and second-order images separately will serve as a check on the latter, and less certain, of these two corrections. All CCD observations were taken between 2003 and 2005, thus ensuring a baseline of 30–38 yr (see Table 2).

3. PROPER MOTIONS

After all the precorrections are applied to the photographic plate positions (i.e., refraction, magnitude systematic correction, etc.; see Girard et al. 1998) and CCD positions (see above), we proceed to calculate proper motions using the central-plate overlap method (e.g., Girard et al. 1989). All measurements are transformed into the system of one photographic plate that is used as a
master plate. We choose a first-epoch visual plate to serve as the master. The remaining first-epoch plates are transformed into the master plate using a polynomial of up to fourth order. The reference stars used for these transformations have a magnitude range between $V = 10$ and 18; however, the input list is such that stars with $V \sim 16$ dominate the reference frame. Therefore, it is the central-order image that is used in these transformations. Between 5000 and 6800 stars are used in these plate transformations, and the derived positional precision per single measurement for these stars is between 70 and 85 mas. The central-order transformation from one plate into another is then applied to the remaining orders as well.

The CCD positions are also mapped into the system of the photographic master plate. This is done individually for each CCD frame. For these transformations, only second-order polynomials are necessary. Typically, for each CCD frame, there are 100 stars that model this transformation (see the selection of the input list in § 2.1), and, as with the plates, only the central-order image is used. For the first- and second-order images, we apply the transformation defined by the central order. For frames that include a cluster, there are between 100 and 1800 faint reference stars that map this transformation; cluster stars (i.e., those selected within a few half-light radii of the cluster) are not used in this transformation. The scatter in this transformation’s residuals is due to both measurement errors and cosmic proper-motion dispersion. Proper motions are then determined by treating each image order as an independent set of positions for both photographic plates and CCD frames. Thus, we have the ability to test determinations based on various image orders and plates. A linear least-squares fit of positions as a function of time gives the proper motion for each object. Measurements that differ by more than 0.2" from the best-fit line are considered outliers and are excluded; the formal proper-motion uncertainty is given by the scatter about the best-fit line. These proper motions are thus relative to a reference frame that is dominated by 16th magnitude stars. By treating each CCD frame individually, we make the implicit assumption that the mean motion of the reference system does not vary over a 6" $\times$ 6" field. However, this is not necessarily true; in fact, we have found linear spatial gradients across the SPM fields that must be considered when the final cluster proper motion is determined (see below).

3.1. Correction to Absolute Proper Motions

The correction from a relative reference frame defined by 16th magnitude stars to an inertial reference frame is determined from straight differences between the Hipparcos proper motions and our relative proper motions. In Figure 1 we show these differences for all five SPM fields. The left panels show the vector-point diagram (VPD), while the middle and right panels show the differences in each coordinate as a function of magnitude. Units of proper motion are mas yr$^{-1}$ throughout the paper, and $\mu_{\alpha}^* = \mu_{\alpha} \cos \delta$. The offset defined by these differences is the correction to absolute proper motion. In Figure 1 we have applied these offsets so that a similar proper-motion range is displayed for all fields. The offsets are determined using probability plots (Hamaker 1978) trimmed at 10% at each edge. Other estimators, such as simple average and median, have also been tested; they all give consistent results within the estimated uncertainty.

We obtain a scatter of between 2 and 3 mas yr$^{-1}$ and, consequently, formal uncertainties in the absolute proper-motion correction of between 0.2 and 0.3 mas yr$^{-1}$. The proper motions shown are constructed from all image orders on the photographic plates and only the first and second orders on the CCD frames.

Central-order images for Hipparcos stars on the CCD frames are saturated and unusable. For each SPM field, we have also made separate determinations of the correction using only blue plates and only yellow plates or only CCD first-order or second-order images to check for possible systematics. The results indicate that differences between different determinations are within the estimated uncertainties. The sole variation found is the variation of the proper-motion differences across the field. The size of the gradients is $\lesssim$0.01 mas yr$^{-1}$ mm$^{-1}$, which will amount to a significant deviation, when compared to formal uncertainties, for clusters that lie far from the center of the spatial distribution of the Hipparcos stars. We have therefore applied adjustments to the absolute proper-motion correction that account for these gradients for each cluster. We have also verified that these spatial gradients are of the magnitude expected for the change in the mean motion of the reference system across the field. We have used the Besançon Galactic model (Robin et al. 2003, 2004) to predict the mean proper-motion gradient across SPM field 068 and confirm the variation seen in our measures.

3.2. Cluster Proper Motions

The mean motion of the cluster with respect to field stars is determined from the stars measured in the cluster region and trimmed in the color-magnitude diagram (CMD) for clusters NGC 2808, 4833, 5927, and 5986. For the remaining clusters, NGC 3201 and 4372, we have applied a two-component Gaussian fitting procedure for the proper-motion distributions, as the field contribution is considerable, even after being trimmed via the CMD. In the cases of NGC 2808, 5927, and 5986 we have used 2MASS (Cutri et al. 2003) $J$ and $K$ photometry to select cluster stars in the CMD. For NGC 4833 we have used $B$ and $V$ photometry from the study of Melbourne et al. (2000), which covers the entire area of our measured cluster stars (a circle with 6.8" radius). In Figures 2 and 3 we show the CMDs and the proper-motion distributions for each cluster. The open circles represent all stars measured in the cluster area, while the filled circles represent those selected from the CMD to be likely cluster members. The left panels show the CMDs, the middle panels show the VPDs of all the stars in the cluster area, and the right panels show the VPDs of the stars selected from the corresponding CMD. The histograms show the marginal distributions of the proper motions. The cross shows the adopted mean relative proper motion of the cluster. For clusters NGC 2808, 4833, 5927, and 5986 we have determined this mean with probability plots trimmed at 10% of the CMD-selected stars within a radius of 20 mas yr$^{-1}$ from the approximate centroid of the cluster proper-motion distribution. Thus, stars outside this proper-motion range are considered outliers. The remaining field contribution after the CMD selection is assumed to be small and therefore eliminated by the 10% cut in the probability-plot determination.

This was not the case, however, for NGC 4372 and 3201. Since the area where cluster stars were measured for these two clusters is larger than that of the other four clusters, as they are more extended, it is likely that more field contamination contributes to the cluster sample, even when a CMD selection is applied. That this is the case for NGC 4372 can be seen in the $\mu_{\alpha}$ marginal distribution (Fig. 2, middle right panel), which is visibly skewed. Therefore, we choose to fit the proper-motion distribution of all of the stars in the cluster area (i.e., no selection using the CMD) with a model consisting of the sum of two Gaussians, one representing NGC 4372 and the other the field. This is done separately for each coordinate, and the “observed” proper-motion distribution is constructed from the data smoothed...
with the individual proper-motion errors. Details of this procedure can be found in, for instance, Girard et al. (1989). The mean and width of the fitted Gaussian to the cluster sample represent the mean proper motion and proper-motion uncertainty of the cluster.

A similar procedure was applied to the field of NGC 3201. This is illustrated in Figure 4. The top left panel of Figure 4 shows the proper-motion distribution of all stars measured in the cluster area. The dotted lines show the rotated system in which the Gaussian fit is made, aligning the x-axis with the elongated shape of the field proper-motion distribution. In the top right panel we show the radial velocity selected sample of cluster stars. The radial velocities are from Côte et al. (1995); with a mean of 494 km s\(^{-1}\), they are thus very distinct from the field radial velocity distribution. The cross marks the mean proper motion as determined from the Gaussian fit. This fit is shown in the bottom panels of Figure 4. The fit is applied to the entire sample of stars measured in the cluster area; the circles show the observed proper-motion distribution, and the solid line shows the fit. We have also calculated the mean motion of the cluster by using only the radial velocity–selected stars and the probability plot estimator with no trimming. Only stars lying outside a 20 mas yr\(^{-1}\) radius from the proper-motion centroid are excluded as measurement outliers. From this determination we obtain \((\mu_\alpha^*, \mu_\delta) = (13.32 \pm 0.35, -3.72 \pm 0.33)\) mas yr\(^{-1}\). The Gaussian fit gives \((\mu_\alpha^*, \mu_\delta) = (12.93 \pm 0.22, -3.99 \pm 0.18)\) mas yr\(^{-1}\). Since the results agree very well, we are convinced that the field contamination is well modeled and appropriately accounted for in the Gaussian fit. Therefore, we adopt this value.

Fig. 1.—Differences between Hipparcos and our proper motions for the five SPM fields. The average value of the differences, i.e., the correction to absolute proper motion, has already been applied as an offset such that the proper-motion range is the same for all fields.
The number of cluster stars that enter into each determination varies between 260 and 400. As in the case of correction to absolute proper motions, we have searched for possible systematics by performing separate solutions for the blue and visual plates. In the case of NGC 4833, since the sample allowed it, we have also looked at the mean proper motion as determined from the blue HB stars and the red giant stars. We have found that the results agreed within estimated uncertainties in all cases except that of NGC 4372. Here the blue plate solution proved different from that of the visual plate, with the blue plate solution showing a large scatter in the cluster star proper motions. Since NGC 4372 lies in the corner of the SPM field, it is likely that this area of the first-epoch blue plate is damaged. This was not seen, however, in the field of NGC 4833, which lies on the same SPM field (Table 1) but near the center of the plate. We have therefore eliminated the blue plate measurements from NGC 4372’s proper-motion determination.

The final absolute proper motions are listed in Table 2, along with other cluster parameters taken from H96. Our proper-motion uncertainties, which include contributions from both the absolute correction and the cluster mean relative motion, are between 0.3 and 0.5 mas yr$^{-1}$.

4. VELOCITIES AND ORBITAL PARAMETERS

Velocities are calculated assuming the solar circle radius $R_0 = 8.0$ kpc and the rotation velocity of the local standard of rest (LSR) $\Theta_0 = 220$ km s$^{-1}$. The adopted solar peculiar motion is $(U_\odot, V_\odot, W_\odot) = (-10.00, 5.25, 7.17)$ km s$^{-1}$ (Dehnen & Binney 1998); $U$ is positive outward from the Galactic center. In Table 3 we list the current location of each cluster and its velocity.
components in a cylindrical coordinate system. Uncertainties in the velocity components include uncertainties in the proper motion and radial velocity and an adopted 10% error in the distance; in Table 3 they are the numbers in parentheses. Also, in Table 3 $z$ is the displacement perpendicular to the Galactic plane, and $R_{GC}$ is the distance from the Galactic center projected onto the Galactic plane. Of the six clusters, the most straightforward cases of kinematical classification as inferred solely from the velocities and current Galactic locations are NGC 5927 and 3201. NGC 5927, a metal-rich cluster (Table 2), has kinematics consistent with membership in the thick disk of the Galaxy, while NGC 3201 has a strongly retrograde orbit, as originally suspected from its radial velocity alone (e.g., Gonzalez & Wallerstein 1998).

Orbital parameters have been calculated as in Paper III. We have used the Johnston et al. (1995, hereafter JSH95) potential model to integrate the orbits. This model includes a bulge, disk, and spherical dark halo and is widely used as a tool to investigate orbits in a simple, analytical form for the Galactic potential. The orbital parameters are averages over a 10 Gyr time interval. Uncertainties were derived from the width of the distributions of

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**TABLE 3**

| NGC   | $R_{GC}$ | $z$  | $v$  | $\Theta$ | $W$  |
|-------|----------|------|------|----------|------|
| 2808  | 11.0     | −1.9 | −82 (13) | 74 (18)  | 70 (22) |
| 3201  | 8.9      | −0.8 | −24 (12) | −301 (08) | 131 (09) |
| 4372  | 7.0      | −1.0 | 39 (15)  | 114 (14) | 77 (12) |
| 4833  | 7.0      | −0.9 | 116 (20) | 22 (22)  | −43 (11) |
| 5927  | 4.5      | 0.6  | −16 (22) | 227 (17) | 35 (15) |
| 5986  | 4.2      | 2.4  | 25 (27)  | 13 (15)  | 31 (19) |
orbital parameters over repeated integrations with different initial positions and velocities. The estimate of the uncertainty is taken to be half of the interquartile range, which is defined as the inner 50% of the data. Orbital integrations were repeated in a Monte Carlo fashion based on the uncertainties in the observed quantities: proper motions, distance, and radial velocity. Naturally, these derived orbital parameter uncertainties do not reflect uncertainties in the potential model or the LSR properties.

The results of the orbit integrations are presented in Tables 4 and 5, where the uncertainties are the values in parentheses. The integrals of motion and orbital periods are listed in Table 4, while the pericenter, apocenter radii, maximum distance from the plane, eccentricity, and orbital inclinations are presented in Table 5. We derive two orbital periods, the azimuthal and the radial. The radial period characterizes the interval between pericenter (or apocenter) passages and is smaller than the azimuthal period because of the precession of the orbit. Uncertainties in the radial period are similar to those in the azimuthal period; therefore, we have not added them to column (6) of Table 4. We also include the total angular momentum $L_z$ which is not a strictly conserved quantity for the JSH95 potential. However, it does provide some insight into the orbits, since it can be thought of as a third integral of motion. The value of $L_z$ in Table 4 is the average over one orbital integration. As with the other orbital parameters, the uncertainty in $\langle L_z \rangle$ is determined from multiple orbital integrations as the initial conditions are varied according to the uncertainties in the measured quantities.

Improved potential models that more accurately describe the inner region of the Galaxy have been used in other studies. A recent example is the work of Allen et al. (2006), who find that orbits do not differ considerably between a bar model and an axisymmetric model for clusters that do not reside within the bar region of our Galaxy. The cluster orbits that are affected by the bar tend to have larger radial and vertical excursions than in the axisymmetric case. For the clusters presented here, the one perhaps most prone to the bar potential is NGC 5986. Since its orbit is already highly eccentric, the effect of the bar will not change the overall shape of the orbit.

5. DISCUSSION

As inferred from the velocities, NGC 5927’s orbital parameters confirm its membership in a rotationally supported system, the thick disk. This is not surprising considering its high metallicity (Armandroff 1988). The remaining clusters that have metallicities consistent with membership in the halo (Zinn 1985) have orbits that generally confirm this membership. These orbits have moderate-to-high orbital eccentricities and a broad range in orbital angular momentum. It is somewhat intriguing that the orbital inclinations for all five of the metal-poor clusters are rather low (Table 5), while the average value is $\Psi_r \sim 37^\circ$ for the entire sample of 43 clusters with $\mathrm{[Fe/H]} < -1.0$ (Paper III and recent updates).

With the exception of NGC 2808 and 3201, all the clusters spend their time within the solar circle; however, NGC 2808 does penetrate the inner Galaxy region. NGC 3201 is the most energetic cluster in the sample. We have therefore checked whether its orbit projected onto the sky matches the two recent streams found in the SDSS: (1) the $63^\circ$ long narrow stream reported by Grillmair & Dionatos (2006) and (2) the “orphan stream” found by Belokurov et al. (2007) and Grillmair (2006). The orbit of NGC 3201 does not match either of the paths of these two streams. In fact, the maximum distance from the Galactic plane reached by NGC 3201 (Table 5) is less than the current distance from the plane of both of these two streams: 8 kpc for the $63^\circ$ long stream and 16 kpc for the orphan stream.

Two recent papers (Fringachloy et al. 2004; Martin et al. 2004) have suggested that a number of globular and open clusters may be associated with the ringlike Monoceros structure (SDSS; Newberg et al. 2002) and the Canis Major overdensity (Martin et al. 2004). These suggestions were based on the Galactic location and radial velocity of the clusters. Among these clusters, NGC 2808 was a candidate. However, our data rule out this association, given the very eccentric orbit of NGC 2808 (Table 5) and the thick-disk-like orbit of the Monoceros structure (Periarrubia et al. 2005). In fact, none of the metal-poor clusters in our sample can be associated with the Monoceros and/or Canis Major structures, on account of their highly eccentric or retrograde orbits.

NGC 2808 is a massive cluster with a well-documented extended blue HB (e.g., Bedin et al. 2000; D’Antona et al. 2004 and references therein). In fact, D’Antona et al. (2005) demonstrate that NGC 2808’s main sequence has a spread blueward of the fiducial main sequence which can be explained by a He-enhanced population ($Y \sim 0.4$ for 20% of the population). HB models with an enhanced He population also reproduce the peculiar HB morphology of this cluster (D’Antona et al. 2005). This is the second

TABLE 4
INTEGRALS OF MOTION AND ORBITAL PERIODS

| NGC   | $E_{\text{orb}}$ $(10^4 \text{ km}^2 \text{ s}^{-2})$ | $L_z$ $(\text{kpc km s}^{-1})$ | $\langle L_z \rangle$ $(\text{kpc km s}^{-1})$ | $P_r$ $(10^5 \text{ yr})$ | $P_e$ $(10^5 \text{ yr})$ |
|-------|----------------------|-----------------|----------------------|----------------|----------------|
| 2808  | -7.7 (0.3)           | 813 (103)       | 978 (105)            | 240 (14)      | 154            |
| 3201  | -4.3 (0.3)           | -2668 (079)     | 2891 (099)           | 461 (26)      | 315            |
| 4372  | -9.7 (0.2)           | 807 (041)       | 917 (054)            | 156 (10)      | 106            |
| 4833  | -10.0 (0.3)          | 150 (092)       | 463 (054)            | 154 (09)      | 91             |
| 5927  | -10.2 (0.2)          | 1030 (027)      | 1063 (032)           | 147 (05)      | 99             |
| 5986  | -11.9 (0.4)          | 54 (068)        | 199 (044)            | 107 (10)      | 62             |

TABLE 5
ORBITAL PARAMETERS

| NGC   | $r_p$ (kpc) | $r_a$ (kpc) | $z_{\text{max}}$ (kpc) | Ecc. | $\Psi_r$ (deg) |
|-------|-------------|-------------|------------------------|------|---------------|
| 2808  | 2.6 (0.4)   | 12.3 (0.7)  | 3.8 (0.3)              | 0.65 (0.05) | 18 (1) |
| 3201  | 9.0 (0.2)   | 22.1 (1.4)  | 5.1 (0.5)              | 0.42 (0.02) | 18 (1) |
| 4372  | 2.8 (0.2)   | 7.4 (0.2)   | 1.6 (0.2)              | 0.45 (0.04) | 18 (2) |
| 4833  | 0.7 (0.2)   | 7.7 (0.7)   | 1.8 (0.4)              | 0.84 (0.03) | 20 (5) |
| 5927  | 4.5 (0.1)   | 5.5 (0.3)   | 0.7 (0.1)              | 0.10 (0.03) | 9 (1)  |
| 5986  | 0.6 (0.2)   | 5.0 (0.5)   | 1.9 (0.3)              | 0.79 (0.04) | 29 (5) |
case of a GC where the main sequence indicates He enhancement, the first case being the remarkable ω Cen (Bedin et al. 2004; Norris 2004; Piotto et al. 2005), the most massive cluster of our Galaxy. The very extended blue HB of ω Cen also can be well explained in the framework of He enhancement (Lee et al. 2005). Unlike ω Cen, very little to no metallicity spread is found in NGC 2808 (Carretta et al. 2006). It is now widely believed that ω Cen is the nucleus of a satellite galaxy that was captured and destroyed by the gravitational field of the Milky Way, mainly on account of its chemical abundance patterns that indicate strong self-enrichment and multiple episodes of star formation (e.g., Smith 2004). More recently, a new picture has emerged for all GCs with extended blue HBs. Since the He enhancement appears to explain well the peculiar HB morphology (see also the case of NGC 6441; Caloi & D’Antona 2007), and since most theoretical studies point to self-enrichment from a previous generation of massive stars in their AGB phase as the source of the high He abundance (e.g., Karakas et al. 2006 and references therein), it has been suggested that all clusters with extended HBs may have been cores of disrupted dwarf galaxies (Lee et al. 2007). Lee et al. (2007) also show that these extended HB clusters are the most massive in our Galaxy. Recent models of He enrichment from a previous generation of massive stars within a GC-size system are, however, unable to reproduce the very high He abundance (Y ≈ 0.4) inferred in NGC 2808 and ω Cen (e.g., Karakas et al. 2006; Bekki & Norris 2006). This too has prompted the hypothesis that such systems are born early on at the bottom of the potential well of a more massive system (M ≈ 10^7−10^8 M_⊙; Bekki & Norris 2006) than they currently retain; and subsequently the halos of these systems are disrupted and destroyed by the Galactic tidal field. However, none of the current models are able to explain both the amount of He enrichment and the particular abundance patterns seen in these GCs (e.g., the Na-O anticorrelation and the C+N+O constancy; Karakas et al. 2006; Bekki et al. 2007; Romano et al. 2007).

Regardless of the difficulties of models reproducing these abundance patterns in detail, the suggestion that these clusters may have originated in rather massive satellite systems has prompted a closer look at the properties of their orbits. Thus, according to the newly emerged picture, the orbits of the progenitors of these extended HB clusters should have been particularly prone to orbital decay, because they were massive and underwent dynamical friction and disruption as they reached the denser inner regions of our Galaxy. Models of the disruption of the host system of ω Cen by Tsuchiya et al. (2003, 2004) that aim to reproduce its present orbit and mass indicate that the original system started with an orbital eccentricity of 0.90 and an apocenter radius of 58 kpc, while the current values are ~0.6 and ~6 kpc (Paper III; Allen et al. 2006). Along this line of reasoning, NGC 2808 may be analogous. It has a relatively high orbital eccentricity (0.65) and does not move farther than ~12 kpc from the Galactic center (Table 5). In our sample, besides NGC 2808, cluster NGC 5986 may also belong to this category of systems with extended HBs (Alves et al. 2001; Rosenberg et al. 2000). It is also a rather massive cluster (Table 2). Its orbit is highly eccentric, practically plunging, and confined to within the inner 5 kpc of the Galactic center.

A rather unexpected result from the orbits derived for the metal-poor clusters is that there are two pairs of clusters that have very similar orbital parameters. The first pair consists of NGC 5986 and 4833 (Tables 4 and 5), and the second pairing is NGC 2808 and 4372. Clearly, orbit angular momenta L_z, pericentric radii, eccentricities, and orbit inclinations agree very well (within 1 σ) for the pair NGC 5986/4833 and moderately well for the pair NGC 2808/4372. The most significant difference is the total orbital energy difference between the two clusters in either pair, which implicitly affects the apocenter radii, the maximum distance from the Galactic plane, and, to some extent, the eccentricity. The orbital energy difference between the two clusters of either pair is ΔE_{orb} ≈ 2 × 10^4 km^2 s^{-2}. For reference, we take the example of Sgr and cluster Pal 12, which is now believed to have been torn from Sgr. An initial argument supporting this picture was the analysis of their orbits (Dinescu et al. 2000). However, other evidence later strengthened this view: the chemical abundance pattern of Pal 12 matches that of the stars in Sgr (Sbordone et al. 2007; Cohen 2004), and the cluster is embedded in Sgr tidal debris (Martínez-Delgado et al. 2002).

Assuming that Pal 12 was indeed torn from Sgr, we have calculated orbits for these two systems using the proper motion from Dinescu et al. (2000) for Pal 12 and the proper motion of Sgr given by Dinescu et al. (2005), both in the JSH95 potential. We obtain a difference between the orbital energy of Pal 12 and Sgr of 2.5 × 10^4 km^2 s^{-2}. This simple exercise leads to the suggestion that the clusters in each pair may be dynamically associated and therefore have a common origin in satellites of the size of Sgr. From the theoretical point of view, the disruption events of satellite galaxies described by Helmi & de Zeeuw (2000) in the E_{orb}-L_z and L-z planes (e.g., their Fig. 4) show ranges in E_{orb} and L compatible with the ranges of our two pairs of clusters. For a given satellite, it is L_z that has the narrowest range in the Helmi & de Zeeuw simulations, and indeed these values agree within the errors for our two pairs of clusters. If the clusters in each pair are indeed dynamically associated, this reinforces the hypothesis that each pair was born in a massive satellite system that was subsequently destroyed.

Alternatively, another simple exercise is to estimate the chance of obtaining two apparent “pairs” of dynamically associated clusters, drawn from a system which has velocities distributed randomly according to the velocity ellipsoid of the halo. We have therefore assigned velocities drawn randomly from a velocity ellipsoid with dispersions (σ_1, σ_2, σ_3) = (138, 104, 111) km s^{-1} and averages equal to zero in each velocity component. The velocity dispersions are taken from Paper III for the metal-poor halo sample ([Fe/H] < −0.8). We have thus generated a set of 100 such random representations for the five metal-poor clusters in our sample. The integrals of motion were calculated for each generated representation, and then we searched for “pairs” of clusters within a given volume in the integrals-of-motion space. The search box in this space is based on the observed separations and uncertainties of our actual measures for the two proposed cluster pairs in our sample. For example, the L_z side of the box is calculated from the quadrature sum of the difference between L_z for one of our tentative cluster pairs and the uncertainty in this difference as given by the values in parentheses in Table 4. Thus, for the pair NGC 2808/4372 the search box is (ΔL_z, ΔE, ΔL) = (111.2 ± 10^4, 133, and for NGC 5986/4833 it is (ΔL_z, ΔE, ΔL) = (149, 1.96 × 10^4, 273) (the units are those in Table 4). For the NGC 2808/4372 pair we obtain a 23% chance of finding an apparent dynamically associated pair from a system that has velocities randomly distributed according to the known velocity ellipsoid of the halo, while for the NGC 5986/4833 pair we obtain a 30% chance. Taken together, the chance that both of these cluster pairings are mere coincidence is 7%.

To this extent, we have shown that in a sample of five metal-poor clusters there appears to be clumping in the integrals-of-motion space that is not likely due to chance occurrence. This clumpiness should be further tested and quantified by analyzing
the entire sample of GCs with three-dimensional velocities and by comparing the data with more realistic models of the formation of the GC system, such as those in Prieto & Gnedin (2006). We hope to be able to address this in a future paper.

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This work was supported by NSF grants AST 04-07292 and AST 04-07293. We thank the referee, who suggested the exercise concerning the chance occurrence of pairs of dynamically associated clusters.