FIRST GROUND-BASED CHARGE-COUPLED DEVICE PROPER MOTIONS FOR FORNAX. II. FINAL RESULTS*

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ABSTRACT

We present the first entirely ground-based astrometric determination of the proper motion for the Fornax Local Group dwarf spheroidal satellite galaxy of the Milky Way (MW), using charge-coupled device data acquired with the ESO 3.5 m New Technology Telescope at La Silla Observatory in Chile. Our unweighted mean from five quasar fields in the background of Fornax, used as fiducial reference points, leads to \( \mu_\alpha \cos \delta = 0.62 \pm 0.16 \) mas yr\(^{-1}\) and \( \mu_\delta = -0.53 \pm 0.15 \) mas yr\(^{-1}\). A detailed comparison with all previous measurements of this quantity seems to imply that there is still no convincing convergence to a single value, perhaps indicating the existence of unaccounted systematic effects in (some of) these measurements. From all available proper-motion and radial velocity measurements for Fornax, we compute Fornax’s orbital parameters and their uncertainty using a realistic Galactic potential and a Monte Carlo simulation. Properties of the derived orbits are then compared to main star formation episodes in the history of Fornax. All published proper-motion values imply that Fornax has recently (200–300 Myr ago) approached perigalacticon at a distance of \( \sim 150 \) kpc. However, the derived period exhibits a large scatter, as does the apogalacticon. Our orbit, being the most energetic, implies a very large apogalactic distance of \( \sim 950 \) kpc. If this were the case, then Fornax would be a representative of a hypervelocity MW satellite in late infall.

Key words: astrometry – galaxies: individual (Fornax) – galaxies: kinematics and dynamics – Local Group – proper motions – quasars: general

Online-only material: color figures

1. INTRODUCTION

Studying the kinematics of the satellites of the Milky Way (MW) allows us to address various fundamental issues such as the origin and evolution of this satellite system (and the MW itself), the role of tidal interactions in the evolution of the Local Group (LG), and the matter distribution of the latter (including that of the dark matter, thus allowing tests of some cosmological predictions; Shaya et al. 2009). This requires tracing their positions back in time, by integrating their orbits, which, in turn, requires knowing their current positions and their full three-dimensional space velocities. While radial velocities for LG galaxies are known to better than \( \sim 5 \) km s\(^{-1}\), and their distances to \( \sim 10\%\), the biggest source of uncertainty rests on their proper motions (PMs).

In the year 2000 we started a ground-based program aimed at determining the absolute PM of three southern dwarf spheroidal (dSph) galaxies, Carina, Fornax, and Sculptor, with respect to background quasars (QSOs), used as inertial reference points. Three to four epochs of homogeneous charge-coupled device (CCD) data were obtained using a single telescope+detector setup over a period of eight years: ours is the first entirely optical CCD/ground-based PM study of an external galaxy other than the Magellanic Clouds.

In Méndez et al. (2010, hereafter Paper I), we presented a detailed description of our methods, as well as our first results for the PM of Fornax, based on one QSO field (Q10240-3434B). In this paper we present our final PM for Fornax based on measurements from five QSO fields in the background of Fornax. In Section 2 we present a summary description of our observational material, in Section 3 we explain how we obtained our PMs, and, finally, in Section 3.1 we compare our results to previous studies and present our main conclusions.

The Fornax dSph galaxy, at a distance of 147 kpc (e.g., Pietrzyński et al. 2009), is relatively isolated, luminous, and well resolved into individual stars. It seems to be dark matter dominated and has an estimated total mass of \( \sim 10^7 M_\odot \) (e.g., Walker et al. 2007). Unlike other dwarf galaxies, Fornax harbors five globular clusters (Hodge 1961), and it appears to have a complex stellar substructure in the form of shell-like features indicative of recent merger activity (Coleman et al. 2004; Coleman & Da Costa 2005; Olszewski et al. 2006). Furthermore, results by Battaglia et al. (2006) suggest that the ancient stellar population in the center of Fornax is not in equilibrium (apparent as a non-Gaussian, double-peaked velocity distribution), which also points to a relatively recent accretion of external material, such as gas accretion due to the merger with another smaller stellar system.

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6 Another notable exception is the tidally disrupted Sagittarius dwarf which, along with Fornax, is one of the most massive of the MW satellite galaxies after the Large and Small Magellanic Clouds. Sagittarius appears to have globular clusters that are, or were, associated with it (e.g., Law & Majewski 2010).
2. OBSERVATIONS

All observations were carried out with the “Superb Seeing Image,” SuSI2, attached to one of the Nasmyth foci of the ESO 3.5 m New Technology Telescope (NTT) at La Silla Observatory in Chile. The overall characteristics of the detector are fully described in D’Odorico (1998) and D’Odorico et al. (1998). We followed exactly the same observational, reduction, and calibration procedures for all of our QSO fields as described in Paper I. Therefore, in as much as possible, our data set is homogeneous from this point of view (for certain limitations to this statement, see Section 3). SuSI2 is a mosaic of two 2k × 4k EEV 44-82 chips (called No. 45, on the west side, and No. 46, on the east side, for the adopted rotator angle of 0°). As explained in Paper I, we always placed our QSOs at a nominal pixel position near (x, y) = (3000, 2100), close to the middle of chip 46, and only data from this chip were subsequently used for our astrometry.

All of the astrometric observations, including those required to compute the differential chromatic constants (DCR; see Paper I, Section 3.3), were acquired through a Bessel R filter, whereas for the blue frames needed to construct color–magnitude diagrams (CMDs) we used the Bessel B filter, both of which are part of the standard set of filters available for SuSI2.

Our initial list of QSOs in the background of Fornax comprised all 11 distinct QSOs (one, reported in Paper I, forms a gravitational lens pair) reported by Tinney et al. (1997, their Table 5) and Tinney (1999, his Table 1). Unfortunately, several of them proved to be useless for astrometry: deep, good-seeing (FWHM ~ 0.5 arcsec) images taken during the first epoch revealed that they were either too faint for our required astrometric signal-to-noise ratio (S/N > 200 integrated over the point spread function (PSF) fitting radius; see Paper I, Section 3.2 and Figure 4), had a noticeably elongated structure (and therefore had a different, usually more extended, PSF than that of the stars), had a very nearby (usually stellar-like) bright companion, or were definitely blended with field stars. As explained at length in Paper I, any of these features render these targets unsuitable for high-accuracy relative astrometry. These problematic QSOs were dropped from the observing list in subsequent epochs, and we concentrated on “clean” (as far as we could determine with a seeing of ~0.5 arcsec) QSOs. Our final list of five QSOs, from which we were able to determine the PMs of Fornax, is given in Table 1, where we also show the full list of known QSOs behind Fornax from the above-cited references.

In Figure 1 we show the stellar configuration in the immediate surroundings of each of our five selected QSOs. All of these images were acquired on the first epoch, when we consistently had very good seeing (FWHM ~ 0.5 arcsec). The only potentially problematic case was that of QJ0239-3420 which has a faint companion to the northwest (NW), at a distance of ~1.4 arcsec. Fortunately, this nearby source is very dim (with a star/QSO peak brightness ratio smaller than 0.1), and far enough (farther than 1.2 × FWHM, adopted as the PSF fitting radius; see Paper I, Section 3.2 and Figure 4) that, even on our worse frames (with an FWHM of ~1.0 arcsec), it did not pose a problem for the astrometric solution, and so it was fully included in our analysis below.

Table 2 contains a summary of the observational material that was, in the end, used to compute our PMs. We note that more data were acquired for these QSO fields, but proved to be useless on account of bad seeing, poor image quality (deteriorating the astrometric solution), or bad sky transparency. As explained in Paper I, at the start of our program we adjusted the exposure time on the basis of seeing (typical values were between 300 s and 900 s), but later, it was decided to use a fixed integration time of 900 s in all cases for simplicity.

3. PROPER MOTIONS

To determine the PMs we used the same procedure described at length in Paper I. A flow-chart summary of the full process...
Figure 1. Finding charts indicating the configuration and surroundings of our five QSO fields. The QSOs are indicated by an arrow. The field of view is ±250 pixel around the QSO (approximately 40 arcsec on a side), and the FWHM of all images is ~0.5 arcsec. With the exception of QJ0239-3420, all QSOs are well isolated from surrounding sources (see the text). Our tests indicate that the small source to the NW of QJ0239-3420 does not affect the astrometry. To illustrate the effect of seeing, in the bottom right inset, we show a zoom of the area around QJ0239-3420 for the best (top) and worst (bottom) FWHM frames for this field.

Table 2

| QSO ID     | Epoch Range (yr) | No. of Epochs | No. of Astrometric Frames | No. of DCR Frames | DCR HA Range (hr) |
|------------|------------------|---------------|--------------------------|-------------------|-------------------|
| QJ0238-3443| 2000.98–2008.82  | 4             | 09                       | 09                | 0.68 to 2.99      |
| QJ0238-3440| 2000.98–2008.82  | 4             | 19                       | 13                | 0.36 to 3.86      |
| QJ0239-3420| 2000.99–2007.87  | 3             | 14                       | 12                | 0.55 to 3.70      |
| QJ0240-3434B| 2000.61–2007.85  | 3             | 15                       | 13                | −0.65 to −4.03    |
| QJ0240-3438| 2000.61–2008.83  | 4             | 20                       | 10                | −0.74 to −3.62    |

Notes.

a As explained in the text, B-band frames for building up CMDs of each field were also acquired.

b All of these frames satisfy |HA| ≤ 1.5 hr, where HA is hour angle, and FWHM ≤ 1.0 arcsec (as an example, see Table 1 of Paper I).

c Reported in Paper I.

is presented in Figure 2. We refer the reader to Paper I for further details on the methodology and precise meaning of all steps. Even though in our PM solutions we only included frames acquired within ±1.5 hr from the meridian (see Table 2), all of our coordinates were (pre)-corrected for (continuous) atmospheric refraction and DCR as described in Paper I. We also excluded from the PM solution all frames with an FWHM > 1.0 arcsec, as they clearly deteriorated the linear fit of barycentric position versus epoch diagram (see, e.g., Figure 12 in Paper I), where these frames stand out due to their large scatter.

All PM data were treated as homogeneously as possible, including the following constraints.

1. All stars with μ > 2.0 mas yr⁻¹ in our initial local reference system (LRS, basically a set of “high-quality” reference stellar images, eventually bona-fide Fornax stars—see Paper I), indicating that they are either foreground Galactic stars, or that they have a high (pseudo)-PM, possibly due, e.g., to a faint unresolved companion or another problem in the image, were purged from the LRS. The full geometric registration (and PMs) for the remaining LRS stars and the QSO were re-computed in an iterative process.

2. All LRS stars that exhibited a registration residual ≥ 3σ of the formal rms of the two-dimensional geometric registration in the X or Y coordinates in at least four (not necessarily consecutive) frames were eliminated from the LRS. For registration we used a full third-order polynomial fit, which has been justified in Paper I.

3. All LRS stars with σμ > σμc, mas yr⁻¹ were excluded from the LRS. The cut value, σμc, was estimated for each field based on the distribution of PM errors versus magnitude (see Table 3).

4. LRS stars exhibiting a PM error larger than that of the bulk of the LRS stars at a given magnitude (even if they, individually, had σμ < σμc) were eliminated. This cut was done visually, on plots of PM error versus magnitude for each QSO field.

5. Finally, we expunged objects that in the CMD appeared not to belong to Fornax. This photometric cleansing was done by first calibrating our instrumental photometry.
Figure 2. Flow diagram from raw stellar pixel coordinates to final PMs for the QSO and bona-fide Fornax reference stars, based on procedures detailed in Paper I. We note that there is an elaborate previous selection of “suitable” (good S/N, isolated) reference stars (potential members of Fornax) from which precise pixel coordinates are derived through PSF fitting. All these steps occur prior to the entry point in this flow diagram, and are fully explained in Costa et al. (2009) and Paper I.
following the procedure described in Paper I (Section 4), and then by comparing our resulting CMD with that of Stetson (1997), which defines the main features of the Fornax CMD.

In Table 3 we show a summary of what results from applying the above criteria to the initial set of LRS stars for each of our five QSO fields. After applying all previously described cuts, we verified that we ended with a uniform \((X, Y)\) distribution of the LRS stars (see, e.g., Figure 15 in Paper I), and with a reasonable distribution in magnitude and color. The resulting CMDs for the LRS stars and the respective QSO are shown in Figure 3. We note that in Paper I we calibrated our photometry approximately by adopting a color of \((B - R) \sim 1.3\) for the red clump from Stetson (1997) and the QSO blue magnitude from the works by Tinney et al. (1997) and Tinney (1999). However, we noticed that, probably as result of uncertainties in the blue photographic magnitudes for the QSOs (and/or possible QSO variability), the ordinate in these figures had a large zero-point variation from field to field, and hence the red clump did not fall at the same apparent \(R\) magnitude for the five fields, as is expected. We therefore decided to adopt a calibration based on the color of the red clump (as before), but fixing, instead, the magnitude of the red clump at \(R \sim 20.6\), also from the photometry by Stetson (1997, his Figure 7).

In Figures 4 and 5 we show, respectively, the barycentric position versus epoch and the vector-point diagrams for our five fields, for the final LRS stars and the corresponding background QSO.

After processing all of the QSO fields following the protocols described in the previous paragraphs, we computed PMs for the five QSO fields presented in the upper part of Table 1. The results are summarized in Table 4, and are plotted in Figure 6. Table 4 gives the PM in R.A. and decl. as well as the overall rms of the

| QSO ID       | No. of Initial LRS Stars | No. of Final LRS Stars | \(\sigma_{\mu_{\alpha}}\) (mas yr\(^{-1}\)) | PM Error vs. Mag (No. of Stars Purged) | CMD Cleansing (No. of Stars Purged) |
|--------------|--------------------------|------------------------|------------------------------------------|--------------------------------------|-------------------------------------|
| QJ 0238−3443 | 295                      | 226                    | 0.78                                     | 3                                    | 12                                  |
| QJ 0238−3440 | 217                      | 175                    | 0.60                                     | 6                                    | 7                                   |
| QJ 0239−3420 | 337                      | 250                    | 0.60                                     | 12                                   | 11                                  |
| QJ 0240−3434B| 260                      | 217                    | 0.50                                     | 11                                   | 7                                   |
| QJ 0240−3438 | 156                      | 123                    | 0.60                                     | 0                                    | 9                                   |
Figure 4. QSO barycentric position with respect to the (final) LRS stars vs. epoch for our five QSO fields. The lines are (unweighted) fits to the data points, and the negative of the slope of these fits corresponds to the PM of Fornax, whose values are tabulated in Table 4. (A color version of this figure is available in the online journal.)

Unweighted mean 0.62 ± 0.16 0.53 ± 0.15 0.53 ± 0.15

3.1. Comparison to Other Studies

Only two astrometric determinations of the PM for the Fornax dSph galaxy are available, namely that by Dinescu et al. (2004), based on a combination of ground-based plates and Hubble-WFPC data, and that based exclusively on Hubble Space Telescope (HST) data by Piatek et al. (2007, hereafter PI07), who present revised values to those reported earlier (pre-CCD Charge Transfer Inefficiency corrections) in Piatek et al. (2002).

Figure 6 compares our results from individual QSOs, to those obtained by PI07. We have three QSO fields in common with PI07; their values, along with our measurements, are given in Table 5. From this table we see that the differ-
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Figure 5. Vector-point diagrams for our five QSO fields, after having applied the selection criteria described in the text. The QSO is indicated by a solid dot with error bars (1σ uncertainty on the slope of the barycentric position vs. epoch fit). The (pseudo)-PM error of individual LRS stars is similar to that of the QSO, so the mean motion of the bulk of the LRS stars has a very small uncertainty, and our final error is dominated by the PM uncertainty of the QSO itself (see Costa et al. 2011). (A color version of this figure is available in the online journal.)

Figure 6. Individual Fornax PMs determined from our five QSO fields (from Table 4, open squares). Filled squares are the HST PC2+STIS results from four QSOs by Piatek et al. (2007, their Table 3). Three of these QSOs are common to ours (see our Table 5). The PM values published so far, along with our own value, are given in Table 6. More recently, Walker et al. (2008) have used a non-astrometric method called “perspective rotation” which is also included in the table (for details about this method see Paper I), because it provides a completely independent measurement of the transverse motion of Fornax (albeit with a larger error than the more recent astrometric determinations). All of these values are plotted, for comparison, in Figure 7. From the plot and figure we can see that, in general, there is a good agreement between all measurements; indeed, none of them depart by more than 2σ from the straight average of the values in Table 6, with our result being however the most extreme in this sense. Also, averaging the results from all of the authors, we find that the PM in decl. shows a larger scatter (σμδ = 0.16 mas yr\(^{-1}\)) than that in R.A. (σμα cosδ = 0.064 mas yr\(^{-1}\)). This would suggest that (some of) these measurements are affected by unaccounted systematic effects. Of the obvious culprits, we can mention that ground-based astrometric data are affected by

\[ \mu_\delta = -0.360 \pm 0.041 \text{ mas yr}^{-1} \]
DCR. In the case of Fornax data (decl. \(\sim -34\)) acquired from the southern hemisphere, DCR should however mostly affect R.A. PMs (we stress that our data have been corrected for this effect as far as possible; see Paper I).

On the other hand, \(HST\) data, while not affected by DCR, can be affected by “Charge Transfer Inefficiency” (CTI) in the CCD detectors due to the very low sky background which is insufficient to fill in the empty charge traps on the detector. These traps evolve in time because they are produced by in-flight radiation damage, and induce systematic (time dependent) position shifts in the detected sources (for details, see, e.g., Bristow et al. 2006, especially his Figure 10). \(HST\) data have also been corrected for this effect, again, as best as they could (compare, e.g., Table 3 from Piatek et al. 2002 (CTI-uncorrected) and PI07 (CTI-corrected)). We note however that since the \(HST\) cameras were not oriented exactly along decl. in the parallel readout direction, which is the direction mostly affected by CTI (see, e.g., Figures 2, 3, and 4 in PI07), it is difficult to ascribe the decl. scatter to this problem. Also, as mentioned previously, \(HST\) data show a much smaller intrinsic scatter than our measurements (Figure 6), thus suggesting small remaining systematics due to CTI.

4. DISCUSSION AND OUTLOOK

One of the ultimate goals of these studies is the determination of a reliable orbit for Fornax. It is interesting to compare the impact of the different values given in Table 6 on the kinematical and orbital parameters that can be derived from these measurements. Table 7 gives the Heliocentric PMs and the corresponding tangential velocities in Galactic coordinates for the different values reported in Table 6. From this table, it is clear that our PM value will render one of the most energetic orbits yet derived for Fornax.

For illustration purposes, and also as a key ingredient to compute and interpret the orbit of Fornax from the above motions in Galactic coordinates, we have computed velocities in the Heliocentric (HC) and Galactocentric (GC) reference systems. For a detailed description of these various reference systems, and the equations relating them, the reader is referred to Costa et al. (2009). They are shown in Table 8, along with model-independent kinematical and orbital parameters derived from the PM values taken from different studies. Given the large values of \(V_{\rm V0}\) in comparison with the \(V_{\rm GC}\) derived from all PM measurements, it is clear that Fornax must be close to perigalacticon at this time. Also, given the rather small ratio of \(L_z/L\), it is clear that there must be significant excursions of Fornax away from the Galactic plane, regardless of the adopted PM values. We note again that, of all measurements available, our PM measurement yields the most extreme orbit.

### Table 6

| Reference       | \(\mu_\alpha \cos \delta\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | PM (mas yr\(^{-1}\)) | P.A.\(^4\) (deg) | Comments                           |
|-----------------|--------------------------------------------|---------------------------------|----------------------|-----------------|-----------------------------------|
| Dinescu et al.  | 0.59 ± 0.16                               | -0.15 ± 0.16                   | 0.61 ± 0.16          | 104 ± 15        | Plates, 48 galaxies and 8 QSOs    |
| Piatek et al.   | 0.476 ± 0.046                             | -0.360 ± 0.041                | 0.597 ± 0.044        | 127 ± 4         | \(HST\)-PC2+STIS, 4 QSO fields    |
| This work       | 0.62 ± 0.16                               | -0.53 ± 0.15                   | 0.82 ± 0.16          | 125 ± 11        | NTT+SuSI2, 5 QSO fields           |
| Walker et al.   | 0.48 ± 0.15                               | -0.25 ± 0.14                   | 0.54 ± 0.15          | 118 ± 15        | Radial velocities, “perspective rotation” |

**Note.** \(^4\) Position angle measured from north to east.

### Table 7

| Reference       | \(\mu_\alpha\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(V_\alpha\) (km s\(^{-1}\)) | \(V_\delta\) (km s\(^{-1}\)) | \(V_t\) (km s\(^{-1}\)) |
|-----------------|---------------------------------|---------------------------------|-----------------------------|-----------------------------|--------------------------|
| Dinescu et al.  | 0.04 ± 0.16                     | 0.60 ± 0.16                     | 31 ± 112                    | 423 ± 112                   | 424 ± 112                 |
| Piatek et al.   | 0.271 ± 0.041                   | 0.532 ± 0.046                   | 189 ± 31                    | 370 ± 34                    | 416 ± 33                  |
| This work       | 0.41 ± 0.15                     | 0.70 ± 0.16                     | 288 ± 107                   | 490 ± 113                   | 568 ± 112                 |
| Walker et al.   | 0.16 ± 0.14                     | 0.52 ± 0.15                     | 113 ± 98                    | 360 ± 105                   | 377 ± 104                 |

**Notes.**

\(^4\) To derive Galactic motions from the J2000 \(\mu_\alpha \cos \delta\) and \(\mu_\delta\) PMs, we have adopted a position for the J2000 Galactic pole of (R.A. = \(12:51:26.2754, \text{decl.} = +27:07:41.705\)) following Miyamoto & Soma (1993; see, especially, their Equation (29)).

\(^b\) To derive the tangential velocities \(V_\alpha\) and \(V_\delta\), we have adopted a distance modulus for Fornax of \((m - M)_0 = 20.84 ± 0.15\) from the “Araucaria distance scale project” (Pietrzyński et al. 2009). The velocity values above include a full statistical propagation of PM and distance (taken to be \(d = 147 ± 10\) kpc) errors. \(V_t\) is the total Heliocentric tangential velocity, and its error.
### Table 8

Fornax Current Heliocentric and Galactocentric Velocities and Specific Orbital Kinematical Parameters from Values of Different Authors

| Reference            | \(U_{\text{HC}}\) (km s\(^{-1}\)) | \(V_{\text{HC}}\) (km s\(^{-1}\)) | \(W_{\text{HC}}\) (km s\(^{-1}\)) | \(V_{\text{GC}}\) (km s\(^{-1}\)) | \(V_{\text{GC}}\) (km s\(^{-1}\)) | \(K/m^c\) (km s\(^{-1}\))^2 \(\times 10^3\) | \(L/m^d\) (kpc km s\(^{-1}\))^2 \(\times 10^3\) | \(L_z/m^d\) (kpc km s\(^{-1}\))^2 \(\times 10^3\) |
|----------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Dinescu et al. (2004)| -195 ± 109                        | -359 ± 105                        | 126 ± 46                          | -23 ± 62                          | 59 ± 107                          | 257 ± 98                                    | 263 ± 98                                      | 35                                            | 8                                             |
| Piatek et al. (2007) | -36 ± 31                           | -404 ± 31                         | 104 ± 15                          | -32 ± 19                          | -93 ± 32                          | 189 ± 29                                    | 210 ± 30                                      | 23                                            | 31                                           |
| This work            | -13 ± 106                          | -550 ± 104                        | 154 ± 47                          | -33 ± 62                          | -203 ± 105                        | 298 ± 96                                    | 361 ± 99                                      | 66                                            | 53                                           |
| Walker et al. (2008) | -95 ± 97                           | -355 ± 96                         | 100 ± 43                          | -28 ± 58                          | -16 ± 97                          | 186 ± 89                                    | 186 ± 89                                      | 18                                            | 27                                           |

**Notes.**

a Heliocentric velocities have been computed using the adopted J2000 R.A. and decl. coordinates for the Fornax center (see Table 7), which correspond to Galactic coordinates \((l, b) = (237.10, -65.65)\). The errors correspond to the statistical propagation of all observational errors. The \((U, V, W)\) is a right-handed system that points to the Galactic center, Galactic rotation, and north Galactic pole, respectively.

b Galactocentric velocities have been computed adopting a solar peculiar velocity of \((u_\odot, v_\odot, w_\odot) = (10.00 \pm 0.36, 5.25 \pm 0.62, 7.17 \pm 0.38)\) km s\(^{-1}\) from Dehnen & Binney (1998), a local standard of rest (LSR) speed of 220 ± 5 km s\(^{-1}\), and \(R_\odot = 8.5 \pm 0.5\) kpc. The errors correspond to the statistical propagation of all observational errors. While these are commonly used values, we note that recent studies seem to suggest a larger V component of the solar motion with respect to the LSR, ~13 km s\(^{-1}\) (e.g., Coşkunolu et al. 2011). However, given the current PM uncertainties, this change will have little effect on the calculated motion of Fornax. Also, note that our uncertainty for the LSR speed is rather optimistic; for example, Bovy et al. (2009) quote \(V_{\text{LSR}} = 244 \pm 13\) km s\(^{-1}\), while Brunthaler et al. (2011) argue for \(V_{\text{LSR}} = 239 \pm 7\) km s\(^{-1}\).

c Kinetic energy per unit mass, as seen from a point at rest with respect to the Galactic center.

d Total \(= \sqrt{L_x^2 + L_y^2 + L_z^2}\) and \(z\)-component of the angular momentum per unit mass, with respect to the Galactic center, in our right-handed system.
Figure 8. X–Y and X–Z projections of the orbit for Fornax from PM values by different authors: dashed line is for Dinescu et al. (2004), dot-dashed line for Piatek et al. (2007), solid line for Walker et al. (2008), and dotted line for this work. The filled dot at \((X, Y, Z) = (-41.4, -50.9, -133.9)\) kpc indicates the current position of Fornax.

Table 9
Fornax Orbital Parameters from PM Values of Different Authors

| Reference          | Orbital Period (Gyr) | Apogalactic Distance (kpc) | Perigalactic Distance (kpc) | \(Z_{\text{max}}\) (kpc) | \(Z_{\text{min}}\) (kpc) | Eccentricity | Inclination (deg) | \(V_Z\) (km s\(^{-1}\)) | \(V_p\) (km s\(^{-1}\)) |
|--------------------|----------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------|-------------------|--------------------------|--------------------------|
| Dinescu et al. (2004) | 8 ± 4               | 328 ± 226                   | 148 ± 10                    | 223 ± 84                 | -238 ± 108               | 0.38 ± 0.21  | 68 ± 8            | 189 ± 9                  | 265 ± 51                 |
| Piatek et al. (2007)   | 6 ± 1               | 197 ± 58                    | 142 ± 14                    | 163 ± 35                 | -166 ± 37               | 0.16 ± 0.09  | 76 ± 4            | 186 ± 2                  | 221 ± 17                 |
| This work            | 21 ± 8              | 956 ± 376                   | 148 ± 8                     | 498 ± 191                | -411 ± 172              | 0.73 ± 0.18  | 41 ± 8            | 181 ± 19                 | 363 ± 51                 |
| Walker et al. (2008)  | 5 ± 3               | 164 ± 109                   | 131 ± 30                    | 147 ± 73                 | -148 ± 66               | 0.11 ± 0.18  | 83 ± 7            | 191 ± 8                  | 212 ± 41                 |

Note. The errors were computed as the inner 50% interquartile range derived from 1000 simulations with uncertainties drawn from Gaussian distributions of the errors in PMs, \(V_r\), and distance. The integration period was chosen to be large enough (50 Gyr) so that the longest orbital period solution completed at least two full orbital cycles.

We have computed Galactic orbits for Fornax by integrating back in time the equation of motion under a realistic three-component (disk, halo, and spheroid) model Galactic potential (Johnston et al. 1995), and using the current position and velocity (and their uncertainties, in a Monte Carlo scheme) as initial conditions. Details of the integrator, and the Monte Carlo simulations, are discussed in Dinescu et al. (2004). A particularly important feature of the integrator used is its care to conserve energy and total angular momentum, obvious features that are however sometimes tricky to achieve over the full orbit, particularly when the number of integration steps (~several thousands in our case) is large. The adopted gravitational potential is strictly axisymmetric, and it does not include the Galactic bar or the MW spiral pattern. Recent numerical simulations by Allen et al. (2008), which include these non-axisymmetric components, indicate however that their effect, in particular in the orbits of Galactic globular clusters (and therefore also in the case of the more external satellite galaxies), is minimal, and it should not alter our conclusions importantly. The results of these integrations are shown in Table 9 and in Figure 8. In Table 9 the meaning of the different columns is rather obvious, except perhaps for the last two columns that correspond to the crossing (vertical) velocity of Fornax through the Galactic plane (\(V_z\)) and the total speed at perigalacticon (\(V_p\)). As can be seen, regardless of what PM values one adopts, comparing the \(V_p\) values to the \(V_{\text{per}}\) in Table 8 confirms that the current Fornax position lies indeed near perigalacticon (see also Figure 9, top panel). Actually, all PMs indicate that the minimum distance, projected into the Galactic plane, happened 200–300 Myr ago (Figure 9, bottom panel). This is a very interesting quantity because Battaglia et al. (2006) have found evidence of at least three distinct stellar components in Fornax: a young population (few 100 Myr old) concentrated in the center of the galaxy, visible as a main sequence in the CMD; an
Figure 9. Fornax distance (log scale) as a function of age from our orbit integrations, for PM values from different authors. Top panel is for the Galactocentric distance, bottom panel is for the distance projected on the plane of the MW. Both panels: dot-dashed line is for Dinescu et al. (2004), dashed line for Piatek et al. (2007), double dot-dashed line for Walker et al. (2008), and dotted line for this work.

intermediate age population (2–8 Gyr old, possibly related to a shell structure in Fornax, described in the next paragraph); and an ancient population (>10 Gyr). More recently, Kirby et al. (2011) have also found (see, e.g., their Figure 2) evidence of enhanced star formation in the range 200–300 Myr. One could therefore conclude that the latest episode of star formation on Fornax may have been indeed triggered by its perigalacticon passage.

When tracing the galaxy back in time, the uncertainty in the computed position increases as time goes on, for a given uncertainty in the initial conditions, and, as we extrapolate further back in time, different PM values lead to quite different orbits. This is clearly shown in Figure 9, which shows the distance of Fornax from the Galactic center ($d_{GC}$, top panel) and the same distance projected onto the Galactic plane ($R_{pl}$, bottom panel) as a function of time from now. Initially, all PM values produce a similar $d_{GC}$, $R_{pl}$ versus time, but the solutions diverge afterward. As mentioned before, our value renders the most extreme solution, basically indicating that in a Hubble time Fornax has not completed an orbit yet. This is at odds with all of the other solutions which, while differing among themselves, do indicate nevertheless several perigalacticon passages in the last 10 Gyr. If, as argued before, perigalacticon has had an influence on enhancing star formation, the stellar population results by Battaglia et al. (2006) favor a rather long orbital period, thus

supporting our solution. We note here that the 2 Gyr population belonging to the shell structure found by Coleman et al. (2004), Coleman & Da Costa (2005), and Olszewski et al. (2006) has been interpreted by these authors as the product of a merger with a smaller, gas-rich system, and may not bear any relation to the interaction between Fornax and the MW. We are thus seemingly left with two significant star formation episodes, one at (200–300 Myr), close to perigalacticon, and another one at age >10 Gyr, which again argues for a longer orbital period (interestingly, from Figure 9 we see that ~2 Gyr marks the most recent apogalactic position for Fornax for the PI07 and Walker et al. 2008 orbits). Our extended orbit implies that Fornax would belong to one of the “hypervelocity” satellites of the MW, as argued by Kallivayalil et al. (2006), Besla et al. (2007), and Piatek et al. (2008) (all results based on the same HST data set). One could perhaps wonder whether the late infall nature of Fornax’s orbits (assuming our PMs) is possibly related to the fact that it is the only satellite dwarf galaxy of the MW (Mateo 1998), along with the spatially dissipated Sagittarius dwarf (Law & Majewski 2010), that harbor a globular cluster population.

A final word of caution regarding the above discussion: from Table 9, we see that current PM measurements for Fornax imply that the range of derived orbital parameters is quite broad, and it seems adventurous to extract strong conclusions from them. As already mentioned, of particular
concern is the possible existence of yet unaccounted systematic effects in the PM measurements. Only high-accuracy future astrometric satellite measurements, like Global Astrometric Interferometer for Astrophysics, with expected uncertainties of a few microarcseconds (average over many stars) could help resolve this issue.

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