A FIRST MEASUREMENT OF THE PROPER MOTION OF THE LEO II DWARF SPHEROIDAL GALAXY*

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ABSTRACT

We use 14 year baseline images obtained with the Wide Field and Planetary Camera 2 on board the Hubble Space Telescope (HST) to derive a proper motion for one of the Milky Way’s most distant dwarf spheroidal companions, Leo II, relative to an extragalactic background reference frame. Astrometric measurements are performed in the effective point-spread function formalism using our own developed code. An astrometric reference grid is defined using 3224 stars that are members of Leo II and brighter than a magnitude of 25 in the F814W band. We identify 17 compact extragalactic sources, for which we measure a systemic proper motion relative to this stellar reference grid. We derive a proper motion \([\mu_\alpha, \mu_\delta] = (+104\pm11.3, -33\pm15.1)\) mas yr\(^{-1}\) for Leo II in the heliocentric reference frame. Though marginally detected, the proper motion yields constraints on the orbit of Leo II. Given a distance of \(d \simeq 230\) kpc and a heliocentric radial velocity \(v_r = +79\) km s\(^{-1}\), and after subtraction of the solar motion, our measurement indicates a total orbital motion \(v_G = 266.1\pm128.7\) km s\(^{-1}\) in the Galactocentric reference frame, with a radial component \(v_{r,0} = 21.5\pm4.3\) km s\(^{-1}\) and tangential component \(v_{\theta,0} = 265.2\pm129.4\) km s\(^{-1}\). The small radial component indicates that Leo II either has a low-eccentricity orbit or is currently close to perigalacticon or apogalacticon distance. We see evidence for systematic errors in the astrometry of the extragalactic sources which, while close to being point sources, are slightly resolved in the HST images. We argue that more extensive observations at later epochs will be necessary to better constrain the proper motion of Leo II. We provide a detailed catalog of the stellar and extragalactic sources identified in the HST data which should provide a solid early-epoch reference for future astrometric measurements.

Key words: galaxies: dwarf – galaxies: individual (Leo II) – Galaxy: halo – Local Group – proper motions

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Leo II dwarf spheroidal (dSph) galaxy was originally discovered in the course of the Palomar Sky Survey (Harrington & Wilson 1950). Its great distance from the Milky Way (MW) marked it as being significant, so it was the target of early studies (e.g., Hodge 1962). Vogt et al. (1995) found evidence for dark matter from its 11 km s\(^{-1}\) velocity dispersion, while Mighell & Rich (1996) obtained the first Hubble Space Telescope (HST)-based color–magnitude diagram (CMD) from Wide Field and Planetary Camera 2 (WFPC2) photometry, deriving an age of 9 ± 1 Gyr for its intermediate age population. The most recent distance estimates, measured from the tip of the red giant branch, place Leo II at 233 ± 15 kpc (Bellazzini et al. 2005) from the MW, and it remains as one of the most distant known MW satellites that are candidates to be bound to the Galaxy. A recent analysis of 171 stellar radial velocities by Koch et al. (2007b) finds no evidence that the galaxy is experiencing the effects of tidal disruption and indicates a mass-to-light ratio of 25–50 \((M/L)_c\). The Leo II dwarf galaxy is of great interest not only as a distant companion that offers a constraint on the mass of the MW (e.g., Watkins et al. 2010), but also as one of the nearest galaxies that might have conceivably undergone evolution in isolation from the effect of the MW. Furthermore, its orbital path provides an important feature of the evolutionary history of the Leo II dwarf.

Proper motions of other nearby dSphs have been detected and estimated using images from the HST. A proper motion was determined for the Fornax dSph \((d \approx 140\) kpc) by Dinescu et al. (2004) and Piatek et al. (2002, 2007), for Ursa Minor \((d \approx 66\) kpc) by Piatek et al. (2005), Sculptor \((d \approx 79\) kpc) by Piatek et al. (2006), Carina \((d \approx 100\) kpc) by Piatek et al. (2003), and the Small Magellanic Cloud \((d \approx 58\) kpc) by Kallivayalil et al. (2006). In all cases, the orbital integration based on current Galactic mass models yields bound orbits, with apogalactic distances not exceeding ~150 kpc, although including the proper motion uncertainties, one cannot rule out apogalactic distances as high as 300 kpc for Sculptor at the 95% confidence level (Piatek et al. 2006). However, recent proper motion measurements of the Large and Small Magellanic Clouds yield space velocities larger than expected, which suggests that the two objects may be only marginally bound to the Galaxy (Kallivayalil et al. 2009).

Due to their relatively large distances, the proper motions of dSphs are at the sub-pixel level over the baselines typically available from HST archival images (~20 years). For example, at a distance of 100 kpc, a 100 km s\(^{-1}\) velocity translates into a proper motion of only 0.211 mas yr\(^{-1}\), which yields a net motion of only 0.03 pixels on the WFPC2 camera over a period of 15 years. Due to the undersampling of the point-spread function (PSF) in HST images, the detection of such a small astrometric
motion requires a special astrometric reduction procedure. The effective point-spread function (ePSF) method, pioneered by Anderson & King (2000) and Piatek et al. (2002), is well suited to the task.

We have developed our own reduction software, based on the ePSF method, in order to detect and calculate the proper motion of Leo II. This paper presents initial results from this analysis, which allows us for the first time to investigate whether this remote dSph is an actual, bound satellite to the MW and, if so, to study in detail its orbital characteristics. The archival HST data sets used in our study are described in Section 2. The astrometric reduction is summarized in Section 3. The identification of extragalactic sources, critical in establishing an astrometric reference frame, is described in Section 4. The proper motion of Leo II is calculated in Section 5. The inferred space motion and orbit of Leo II are discussed in Section 6.

2. HST OBSERVATIONS AND ARCHIVAL DATA

The dSph Leo II was first observed with the WFPC2 on 1994 May 15. In addition to a pair of shallow 80 s exposures in the F555W band, a total of eight deep exposures (600 s each) were obtained in each of the F555W and F814W bands. Dithering patterns were not generally used at the time, and the 1994 frames have no significant offsets between them.

Leo II was reobserved on 2004 March 19. This time, only eight exposures in the F814W band were obtained, 500–700 s each. The 2004 fields are aligned with the 1994 fields to within ≈3" and with the same field orientation. The 2004 exposures followed a four-point dithering pattern. Frames 1 and 2 constitute a pair with no offset between each other, as are the pairs consisting of frames 3–4, 5–6, and 7–8. The four-point dithering pattern occurs between each of the pairs.

Leo II was observed again on 2008 March 25, yielding eight exposures of 1100 s in each of the F555W and F814W bands. This time an eight-point dithering pattern was used, so no two images are perfectly aligned, and display small offsets between each other. The 2008 frames have the same orientation as the 1994 and 2004 frames, but are offset by 20" in the direction of right ascension (R.A.). This means that on one side of each Wide-Field (WF) camera frame from 1994/2004, there is a band ≈200 pixels wide which is not covered by the 2008 exposures. This leaves an area of approximately 4 arcmin² or 75% of the field of view of the WF camera chips, which was imaged at all three epochs. The center of the WFPC2 field of view was offset only ≈1" from the center of the dSph. With Leo II having a core radius of 2.64 (Coleman et al. 2007), the HST observations thus cover ~22% of the area within the core radius of Leo II.

3. ASTROMETRIC ANALYSIS

The positions of all sources on the frames were recalculated in the ePSF formalism, using a method analogous to the one introduced and developed by Anderson & King (2000, hereafter AK) and Piatek et al. (2002). The method consists of fitting the pixel profile of a source \[ P_k(i, j) \] with a local representation of the response of the camera to a point source \[ \Psi_k = \Psi(i - x_k, j - y_k) \], where \((x_k, y_k)\) denote the hypothetical location of the point source in the \((i, j)\) pixel grid. Instead of being modeled by a mathematical function, the functional form of \(\Psi\), the ePSF, is extracted from the data using the multiple samplings provided by the large number of point sources in the field because each of the \(k\) sources provides samplings of \(\Psi\) at the locations \((i - x_k, j - y_k)\). Because the hypothetical locations of the point sources \((x_k, y_k)\) are not known a priori, the functional form of \(\Psi\) must be determined using an iterative procedure, where the \((x_k, y_k)\) are recalculated and the functional form of \(\Psi\) re-evaluated after each iteration, as described in Anderson & King (2000). We have developed our own reduction software, which determines the ePSF directly out of the data, using an iteration procedure, exactly as prescribed in AK. Our ePSF is determined separately for each of the three epochs and independently for each band. An ePSF is also calculated separately for each of the WF camera frames (WF2, WF3, WF4), and the ePSF is allowed to vary continuously across the frame, following its separate determination in each of nine sectors across the chip. Since our general procedure is in most points identical to the one described in Anderson & King (2000), we do not repeat the details here.

Once a satisfactory ePSF is determined, an algorithm is used to converge the centroid \((x_k, y_k)\) of each source. The algorithm differs from a least-square fit in that it uses a weighting of all the pixels proportional to the local first derivative of the ePSF profile, which gives more weight to the profile edges than to the central pixel which often yields little positional information. The flux \(f_k\) of the source is re-evaluated after each iteration from an ePSF fit of the stellar profile calculated for the current \((x_k, y_k)\) estimate. Convergence is attained after 5–10 iterations. A \(\chi^2\) test is then used to evaluate the goodness of fit; sources that differ significantly from the ePSF—such as camera artifacts, cosmic ray events, and very extended sources (e.g., galaxies)—are rejected. The first moments of the residuals \(\Gamma_k\) are calculated as

\[
\Gamma_k = \sum_{i,j} (P_{k,i,j} - f_k \Psi(i - x_k, j - y_k)),
\]

and should be ≈0 assuming \(f_k\) is a close estimate of the flux. Second moments of the distribution \(\Lambda_k\) are then calculated, which offer a quantification of how much intrinsic “spread” there is in the source compared to the local ePSF:

\[
\Lambda_k = \sum_{i,j} \sqrt{(i - x_k)^2 + (j - y_k)^2} \times \left(\left|P_{k,i,j} - f_k \Psi(i - x_k, j - y_k)\right|^2\right).
\]

The second moment is expected to be ≈0 only if the source has approximately the same spread as the local ePSF—i.e., it is unresolved by the camera. But if the source has a profile different from the ePSF, then \(\Lambda_k\) could be significantly different from 0. This value \(\Lambda_k\) thus works like a “sharpness parameter,” distinguishing between resolved and unresolved sources. We find that the vast majority of the stars in the Leo II field have \(-0.4 < \Lambda_k < 0.4\), which determines the range over which sources can be considered point-like; we use those sources to define the local astrometric grid. Sources with a second moment \(\Lambda_k > 0.4\) have a significantly larger spread than expected from the local ePSF, and are effectively resolved by the camera. This is clear in Figure 1 where we see a tail of sources with larger \(\Lambda_k\) values. Visual examination of sources with large measured values of \(\Lambda_k\) indeed reveals the sources to be noticeably extended compared with most other sources in the field. Sources with a very large sharpness factor (\(\Lambda > 3\)) are so broadened compared to the ePSF that they generally fail the \(\chi^2\) test and are rejected by the code; hence the sources that are detected by the code but flagged as “resolved” are still relatively compact objects.

The “unresolved” sources are used to build a relative astrometric frame. Astrometric corrections are performed in multiple
local ePSF, which means it is unresolved by the camera. The distribution shows the camera. A value of $\Lambda$ ("sharpness parameter") for sources detected in the Leo II field by the WFPC2 steps, in order to bring the positions measured in all exposures/epochs into a single common reference grid. Each unresolved source is used in defining the grid with a weight proportional to its estimated astrometric uncertainty; in effect this yields a larger weight on the brighter sources. Corrections are first performed on individual frames of a given epoch/band; these correct for small offsets, rotations, or dilations between successive images, notably the offsets from the dithering patterns and also changes in the field scale due to thermal dilation in $HST$ and the WFPC2. Average positions are then recalculated for each epoch/band using the mean position of all the measurements from that particular set. Additional corrections are then performed to bring the calculated mean positions from all seven epochs/epochs into a common master grid. Finally, proper motions are calculated for each individual source by a linear regression of the mean position of the source as a function of epoch.

Astrometric and photometric data for all of the unresolved (point-like) sources are provided in Table 1. The table lists the measured positions ($\alpha$, $\delta$) and relative proper motions ($\mu_\alpha, \mu_\delta$) of the 3224 sources, along with F555W and F814W magnitudes. We also list the second moments of objects are detected on or near the main-sequence locus.

### Table 1

| $\alpha$ (12000) | $\delta$ (12000) | $\mu_\alpha$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | F555W (mag) | F814W (mag) | F555W–F814W (mag) | $\Lambda$ | camera |
|-----------------|-----------------|-------------------------|-------------------------|-------------|-------------|-------------------|---------|--------|
| 168.3551962 ± 0.0000007 | +22.1485758 ± 0.0000007 | −0.34 ± 0.36 | 0.97 ± 0.37 | 25.90 | 25.26 | 0.63 | 0.17 | 2 |
| 168.3552438 ± 0.0000009 | +22.1480854 ± 0.0000009 | 0.51 ± 0.36 | 0.12 ± 0.49 | 25.98 | 25.41 | 0.56 | −0.29 | 2 |
| 168.3553641 ± 0.0000001 | +22.1512710 ± 0.0000002 | 0.07 ± 0.06 | 0.05 ± 0.10 | 22.84 | 21.93 | 0.91 | 0.09 | 2 |
| 168.3553896 ± 0.0000006 | +22.1492520 ± 0.0000006 | 0.71 ± 0.26 | −0.79 ± 0.33 | 26.02 | 25.59 | 0.43 | 0.01 | 2 |
| 168.3553999 ± 0.0000002 | +22.1519683 ± 0.0000004 | 0.47 ± 0.14 | 0.07 ± 0.22 | 25.17 | 24.71 | 0.46 | 0.14 | 2 |
| 168.3554060 ± 0.0000003 | +22.1473196 ± 0.0000002 | 0.11 ± 0.10 | 0.01 ± 0.10 | 24.52 | 23.73 | 0.80 | 0.05 | 2 |
| 168.3554769 ± 0.0000006 | +22.1465200 ± 0.0000004 | −0.03 ± 0.21 | 0.34 ± 0.21 | 25.38 | 24.84 | 0.55 | 0.20 | 2 |
| 168.3555478 ± 0.0000007 | +22.1454925 ± 0.0000005 | 0.01 ± 0.29 | 0.52 ± 0.24 | 25.39 | 24.77 | 0.63 | 0.08 | 2 |
| 168.3555627 ± 0.0000005 | +22.1502803 ± 0.0000006 | −0.41 ± 0.22 | 0.26 ± 0.29 | 25.45 | 24.83 | 0.62 | 0.02 | 2 |
| 168.3555798 ± 0.0000009 | +22.1513628 ± 0.0000005 | 1.03 ± 0.33 | 0.69 ± 0.28 | 25.80 | 25.20 | 0.60 | 0.03 | 2 |
| 168.3556039 ± 0.0000003 | +22.1465930 ± 0.0000006 | 0.14 ± 0.10 | −0.12 ± 0.11 | 23.88 | 23.05 | 0.82 | 0.19 | 2 |
| 168.3556903 ± 0.0000008 | +22.1532404 ± 0.0000004 | 0.30 ± 0.22 | 0.08 ± 0.17 | 25.84 | 25.30 | 0.54 | −0.13 | 2 |
| 168.3556196 ± 0.0000009 | +22.1484238 ± 0.0000004 | 0.48 ± 0.29 | −0.13 ± 0.23 | 25.08 | 24.55 | 0.53 | 0.16 | 2 |
| 168.3556291 ± 0.0000003 | +22.1536420 ± 0.0000005 | 0.01 ± 0.15 | −1.01 ± 0.24 | 25.61 | 25.06 | 0.56 | 0.10 | 2 |
| 168.3557186 ± 0.0000010 | +22.1485511 ± 0.0000008 | −0.29 ± 0.44 | −0.75 ± 0.38 | 25.79 | 25.15 | 0.64 | 0.26 | 2 |
| 168.3557224 ± 0.0000005 | +22.1542072 ± 0.0000004 | −0.21 ± 0.23 | −0.40 ± 0.22 | 25.79 | 25.32 | 0.47 | 0.20 | 2 |
| 168.3557244 ± 0.0000002 | +22.1532839 ± 0.0000006 | 0.41 ± 0.13 | −0.41 ± 0.30 | 25.26 | 24.75 | 0.51 | 0.09 | 2 |
| 168.3557257 ± 0.0000005 | +22.1510173 ± 0.0000005 | −0.34 ± 0.20 | 0.59 ± 0.25 | 25.83 | 25.15 | 0.68 | −0.07 | 2 |
| 168.3557225 ± 0.0000003 | +22.1573483 ± 0.0000005 | 0.67 ± 0.14 | 0.08 ± 0.28 | 25.96 | 25.49 | 0.47 | 0.18 | 2 |
| 168.3557424 ± 0.00000049 | +22.1482409 ± 0.0000009 | 0.18 ± 0.82 | −0.24 ± 0.62 | 26.31 | 25.93 | 0.38 | 0.14 | 2 |

Note. $^*$ Relative proper motions in the defined Leo II stellar grid.

(A this table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

4. Identification of Extragalactic Reference Sources

A CMD of all of the sources in the combined Leo II field is shown in Figure 2. Distinct plots are presented for the resolved (bottom panel) and unresolved (top panel) sources, as defined in Figure 1. The CMD for the unresolved sources clearly displays the asymptotic giant branch, horizontal branch, red giant sequence, and main sequence expected for the dSph (see also Mighell & Rich1996; Coleman et al.2007; Komiyama et al. 2007). A distinct population of blue stragglers is also detected. The CMD of the resolved sources tells another story. The giant sequences are indistinguishable. However, a significant number of objects are detected on or near the main-sequence locus. Because their colors and magnitudes are consistent with main-sequence stars, we conclude that these "resolved" sources are most likely visual binaries, probably due to crowding in the dense Leo II field.

The CMD of unresolved sources also displays a distinct population of very red objects (F555W − F814W > 1.4 mag). Many of these are moderately bright and within the range ($V < 23.5$) from which we can expect accurate astrometry.
extragalactic objects should fall off the stellar locus. Distant from extragalactic background sources. The idea is that most (Figure 3).

A close examination of the sources confirms this impression main stellar locus, suggests that they are background galaxies. combined with the fact that they are found significantly off the population, we conclude that these are, in fact, extended objects, with PSFs that are locally wider that the fiducial ePSF. This, with a dispersion (σμx, σμy) = (2.54, 2.60) millipixels yr⁻¹. The low mean values are consistent with these brighter sources being part of the astrometric reference grid (of which they are a subset). The dispersion values yield an estimate of the intrinsic uncertainty in the proper motion measurement for individual point sources, which is thus on the order of ±0.0025 pixels yr⁻¹ along both lines (X) and columns (Y) on the WFC3 frames. The fact that the scatter values are very nearly identical in X and Y suggests that galaxies in particular should be redder than stellar members as a result of their intrinsically red populations and redshift. To help in the identification of an extragalactic reference set, we particularly consider the distribution of resolved sources, which are likely to include most of the background galaxies (see above). The distribution of resolved source in Figure 2 is unambiguous. A significant number of resolved objects define a locus well to the red of the fiducial stellar locus of Leo II members. Sources with F555W–F814W > 1.3 and F555W < 25.0 are indeed very unlikely to be stellar members of Leo II. The brightest and reddest of these sources (see empirical box in Figure 2 are formally identified as extra-galactic reference objects; one source affected by a large astrometric uncertainty is, however, excluded.

The resolved (Leo II) sources, which define the local astrometric grid, and the extragalactic sources, which are used as background astrometric reference, are all plotted in Figure 4 as a function of R.A. and declination (decl.). Extragalactic reference objects are distributed over all three independent camera frames. The extragalactic sources are also relatively spread out and sample both the centers and edges of each field.

Astrometric and photometric data for the extragalactic reference objects are provided in Table 2. The table lists the measured positions (α,δ) and proper motions (μα,μδ) of the 17 sources, along with F555W and F814W magnitudes. We also list the second moments Λ of the source profiles (see Section 3 above), which measure how the profiles compare to a point source. The WF camera frame (2–4) in which the source was detected is also listed.

5. RELATIVE PROPER MOTION OF LEO II MEMBERS

The identification of a set of extragalactic sources makes it possible, in principle, to estimate a proper motion for Leo II by measuring the systemic proper motion of these extragalactic sources relative to the astrometric reference frame defined by the stellar members of Leo II. The absolute proper motion of Leo II with respect to the extragalactic rest frame is then simply the vector opposite to this relative proper motion of extragalactic sources. As this represents the proper motion measured from the heliocentric rest frame, the component of the solar motion around the Galaxy must then be taken into account to determine an absolute proper motion relative to a reference frame at rest relative to the Galactic barycenter, from which the orbit of Leo II can be calculated.

First we examine the proper motion in the direction of the X and Y pixel positions (μx, μy). These are different from the R.A. and decl. because each of the three WF2, WF3, and WF4 cameras has its X–Y axis oriented differently. The X and Y positional accuracy is thus more sensitive to instrumental effects (systematic errors in particular) and better sets the astrometric accuracy of our measurements. The proper motion distribution is plotted in Figure 5 (left panels) as a function of magnitude. Sources brighter than F814W = 24.0—a total of 634 objects—have mean values (μx, μy) = (−0.23, −0.08) millipixels yr⁻¹ with a dispersion (σμx, σμy) = (2.54, 2.60) millipixels yr⁻¹. The lower panel shows all of the resolved objects (sources with a sharpness factor Λ > 1.3). All of the unresolved sources produce a CMD consistent with Leo II membership. The resolved sources fall along two distinct loci: they are either coincident with the low-mass stellar locus of Leo II and hence are likely visual binaries or they have very red colors, which then strongly suggest that they are extended extragalactic sources (galaxies/quasars). Objects enclosed in the dashed-line box are formally identified as extragalactic sources. One faint source within the extragalactic cut (black dot within the dashed area) was rejected because of a large astrometric uncertainty.

Since no comparable sources are detected in the unresolved population, we conclude that these are, in fact, extended objects, with PSFs that are locally wider that the fiducial ePSF. This, combined with the fact that they are found significantly off the main stellar locus, suggests that they are background galaxies.

A close examination of the sources confirms this impression (Figure 3).

We use the CMD to separate probable Leo II members from extragalactic background sources. The idea is that most extragalactic objects should fall off the stellar locus. Distant

Figure 2. Color–magnitude diagram of the Leo II field. All stars identified and measured with our astrometric code are shown. The upper panel shows the stars which remain unresolved after the ePSF fit. The lower panel shows all of the resolved objects (sources with a sharpness factor Λ > 1.3). All of the unresolved sources produce a CMD consistent with Leo II membership. The resolved sources fall along two distinct loci: they are either coincident with the low-mass stellar locus of Leo II and hence are likely visual binaries or they have very red colors, which then strongly suggest that they are extended extragalactic sources (galaxies/quasars). Objects enclosed in the dashed-line box are formally identified as extragalactic sources. One faint source within the extragalactic cut (black dot within the dashed area) was rejected because of a large astrometric uncertainty.

(A color version of this figure is available in the online journal.)
charge transfer efficiency (CTE) effects are negligible in this context, otherwise one would expect a larger scatter in the proper motion along the columns (Y). Sources fainter than F814W = 24.0—2593 sources—have mean proper motion values \((\bar{\mu}_X, \bar{\mu}_Y) = (+0.20, +0.01)\) millipixels yr\(^{-1}\) with a dispersion \((\sigma_{\mu_X}, \sigma_{\mu_Y}) = (6.30, 6.10)\) millipixels yr\(^{-1}\). The astrometric errors are thus a factor of 2.5 larger than for the brighter sources; the scatter is also observed to increase as the magnitudes get fainter.

To further examine possible CTE effects, we plot \(\mu_X\) as a function of \(X\) and \(\mu_Y\) as a function of \(Y\) (Figure 5, right panels). CTE effects yield systematic offsets between the centroid of bright and faint sources at large \(Y\). Degradation of CTE over time would increase this offset in the later epochs, resulting in an apparent proper motion \(\mu_Y\) of the faint sources relative to bright ones. In Figure 5, we plot \(\mu_X, \mu_Y\) as individual points for the bright sources (F814W < 24.0) and plot the mean proper motions \(\mu_X, \mu_Y\) for the faint sources, in seven bins along the \(X\) and \(Y\) positions (broken lines). For the faint sources, the dispersion \(\sigma_{\mu_X}, \sigma_{\mu_Y}\) is noted for each bin with error bars. We observe that the bright sources do not show any systemic offset in their proper motion as a function of \(X\) or \(Y\), except for perhaps a weak increase in \(\mu_Y\) for \(Y > 600\). The faint sources have their mean proper motions \(\mu_X, \mu_Y\) within 3\(\sigma\) of 0.0 for all \(X\) and \(Y\); there is, however, a weak trend of \(\mu_X\) increasing with \(X\) and \(\mu_Y\) increasing with \(Y\), which could possibly be due to CTE effects. However, the extragalactic objects are also bright sources, and we expect them to behave more like the bright stars, which show negligible CTE effects, if any.

The 17 extragalactic (resolved) sources have mean motion values \((\bar{\mu}_X, \bar{\mu}_Y) = (-0.18, -1.37)\) millipixels yr\(^{-1}\) with a dispersion \((\sigma_{\mu_X}, \sigma_{\mu_Y}) = (6.71, 8.04)\) millipixels yr\(^{-1}\). Their
extragalactic sources: this is because the WF2, WF3, and WF4 extragalactic sources by a factor of about three. Part of this any case, the scatter in the motions is clearly larger for the (resolved) sources. Additionally, the scatter appears to be larger scatter is thus significantly larger than that of the stellar (resolved) sources. Additionally, the scatter appears to be larger in Y, though this may be due to small number statistics. In any case, the scatter in the motions is clearly larger for the extragalactic sources by a factor of about three. Part of this scatter could be due to a net relative proper motion of the extragalactic sources: this is because the WF2, WF3, and WF4 frames have their XY grids rotated by 90°; a net offset in (μ_X,μ_Y) would result in a scatter in (μ_X,μ_Y) since the sources come from different frames. Indeed, the opposite should be true for systematic offsets in (μ_X,μ_Y), which would conspire to yield a large scatter in (μ_X,μ_Y); see below. Aside from the possibility of a net proper motion, the larger scatter in the extragalactic sources could simply be due to their resolved nature. The ePSF would not be the best model for those sources, which would result in larger astrometric errors. Individual ePSF profiles, tailor made for each source, would yield more accurate results as suggested by Mahmud & Anderson (2008); however, such models require large numbers of sampling (>100) of each object individually, whereas the ePSF of point sources is built from the sample of all of the point sources on the image, requiring fewer exposure frames. Our current data set does not contain nearly enough frames of Leo II to build such individual ePSF profiles.

Reported in the equatorial frame, the stellar sources in Leo II with F814W < 24 mag have mean proper motion (μ_X,μ_Y) = (-2.7, -7.8) μas yr⁻¹ with a dispersion (σ_μ_X,σ_μ_Y) = (271.9, 297.2) μas yr⁻¹. The dispersion yields an estimate of the accuracy in the proper motion of individual sources, while the near-zero value of the mean proper motion confirms the stability of our astrometric reference frame. The distribution of proper motions for these unresolved sources is shown in Figure 6 (dots).

The proper motion distribution of our 17 selected extragalactic sources is also plotted in Figure 6, where we also plot the estimated internal uncertainties in the proper motion estimates for each individual source (error bars). The unweighted mean value is (μ_X,μ_Y) = (+31.9, +25.9) μas yr⁻¹ and the points have a dispersion (σ_μ_X,σ_μ_Y) = (790.5, 683.9) μas yr⁻¹. Since 1 pixel on the WF cameras is ≈100 mas, a 700 μas yr⁻¹ motion is equivalent to 7 millipixels yr⁻¹. Hence, the scatter in (μ_X,μ_Y) is comparable to the scatter in (μ_X,μ_Y). However, the scatter in the data points is significantly larger than the estimated statistical uncertainties of the individual points, which are ±450 μas yr⁻¹ on average. This indicates that the proper motion of the extragalactic sources suffers from systematic errors, which are probably due to the sources being resolved and the local ePSF a marginal fit to their profile. The dispersion in the data points suggests that the uncertainties on individual measurements are underestimated by a factor of ≈1.7. We account for these systematic errors by increasing the uncertainties of the individual proper motions by the same factor. We then estimate the systematic proper motion of the extragalactic sources by calculating

| ID      | α (J2000) | δ (J2000) | μ_X (mas yr⁻¹) | μ_Y (mas yr⁻¹) | F555W (mag) | F814W (mag) | F555W–F814W (mag) | A | Camera |
|---------|-----------|-----------|----------------|----------------|-------------|-------------|-------------------|---|--------|
| EGR-01  | 168.357273 ± 0.0000024 | +22.1751675 ± 0.0000007 | 0.36 ± 0.82 | -0.29 ± 0.37 | 25.33 | 22.23 | 3.10 | 0.64 | 3 |
| EGR-02  | 168.3578068 ± 0.0000018 | +22.1667783 ± 0.0000010 | -0.03 ± 0.70 | 0.48 ± 0.51 | 26.78 | 23.92 | 2.85 | 0.73 | 3 |
| EGR-03  | 168.3625705 ± 0.0000007 | +22.1525700 ± 0.0000004 | 0.52 ± 0.24 | -0.06 ± 0.24 | 25.47 | 23.15 | 2.32 | 0.53 | 2 |
| EGR-04  | 168.3629439 ± 0.0000015 | +22.1628222 ± 0.0000011 | -0.90 ± 0.66 | -0.32 ± 0.60 | 25.41 | 23.58 | 1.84 | 1.03 | 2 |
| EGR-05  | 168.3635967 ± 0.0000008 | +22.1521349 ± 0.0000004 | 0.53 ± 0.26 | -0.65 ± 0.24 | 25.91 | 23.49 | 2.42 | 0.51 | 2 |
| EGR-06  | 168.3650347 ± 0.0000011 | +22.1560831 ± 0.0000009 | 0.78 ± 0.49 | 1.08 ± 0.49 | 25.24 | 22.96 | 2.28 | 0.73 | 2 |
| EGR-07  | 168.3658434 ± 0.0000004 | +22.1526715 ± 0.0000007 | 1.09 ± 0.32 | 0.37 ± 0.39 | 24.27 | 21.65 | 2.62 | 0.59 | 2 |
| EGR-08  | 168.3667410 ± 0.0000007 | +22.1786564 ± 0.0000006 | -0.25 ± 0.39 | 0.73 ± 0.28 | 24.76 | 22.33 | 2.43 | 0.46 | 3 |
| EGR-09  | 168.3665803 ± 0.0000012 | +22.1513390 ± 0.0000010 | -1.13 ± 0.50 | 0.14 ± 0.52 | 25.87 | 23.18 | 2.69 | 1.10 | 2 |
| EGR-10  | 168.3684006 ± 0.0000003 | +22.1693588 ± 0.0000008 | -0.46 ± 0.26 | -0.10 ± 0.51 | 25.02 | 22.58 | 2.44 | 0.75 | 3 |
| EGR-11  | 168.3718307 ± 0.0000008 | +22.1709446 ± 0.0000005 | -0.49 ± 0.36 | -0.62 ± 0.30 | 23.82 | 21.59 | 2.24 | 0.42 | 3 |
| EGR-12  | 168.3815968 ± 0.0000001 | +22.1718691 ± 0.0000009 | -0.38 ± 0.12 | -0.87 ± 0.47 | 25.07 | 22.70 | 2.37 | 0.48 | 4 |
| EGR-13  | 168.3853748 ± 0.0000007 | +22.1681213 ± 0.0000006 | 0.71 ± 0.34 | 0.68 ± 0.34 | 24.61 | 22.61 | 2.01 | 0.46 | 4 |
| EGR-14  | 168.3858761 ± 0.0000006 | +22.1704062 ± 0.0000014 | -1.23 ± 0.47 | -1.53 ± 0.75 | 24.62 | 22.57 | 2.04 | 1.05 | 4 |
| EGR-15  | 168.3900591 ± 0.0000008 | +22.1725934 ± 0.0000010 | 1.47 ± 0.46 | 0.70 ± 0.55 | 25.06 | 23.09 | 1.97 | 0.91 | 4 |
| EGR-16  | 168.3910732 ± 0.0000003 | +22.1715817 ± 0.0000004 | -1.08 ± 0.16 | 0.77 ± 0.29 | 23.90 | 21.48 | 2.42 | 0.56 | 4 |
| EGR-17  | 168.3927718 ± 0.0000006 | +22.1669444 ± 0.0000006 | -0.18 ± 0.24 | -0.42 ± 0.42 | 24.86 | 22.53 | 2.32 | 0.47 | 4 |

Note. * Relative proper motions in the defined Leo II stellar grid.
Figure 5. Proper motions $\mu_X$ and $\mu_Y$ of the Leo II field sources along the $X$ and $Y$ coordinates of the camera, for all three WF cameras. Unresolved stellar sources are plotted as black dots, while the extragalactic reference objects are plotted as red triangles (with error bars). Panels on the left show proper motions as a function of the source magnitude in the F814W band. The stability of the reference frame allows for proper motion measurements with a mean accuracy of $\pm 4$ millipixels yr$^{-1}$ for unresolved sources brighter than F814W $= 24$, but resolved extragalactic sources show a noticeably larger scatter. Panels on the right show $\mu_X$ and $\mu_Y$ as a function of column number $X$ and row number $Y$, respectively. Individual points are shown for bright sources (F814W $< 24.0$, both stellar and extragalactic) while the mean values are shown for the fainter sources (broken line) with $1\sigma$ uncertainties noted by error bars. A weak trend at large $Y$ values indicates possible effects from charge transfer efficiency.

(A color version of this figure is available in the online journal.)

6. SPACE VELOCITY AND THE ORBIT OF LEO II

To evaluate the space motion of Leo II and, in particular, to constrain the parameters of its orbit, it is useful to report the position and motion of Leo II in a reference frame centered on, and at rest with respect to, the Galactic center. The most straightforward method is to start with the angular position ($l,b$) and proper motion ($\mu_l,\mu_b$) in the galactic coordinate system and include both the measured distance from the Sun ($r = 233 \pm 15$ kpc) and heliocentric radial velocity ($v_r = +79$ km s$^{-1}$) of Leo II. The position ($r,l,b$) and motion ($v_r,\mu_l,\mu_b$) in this spherical, right-handed coordinate system have a Sun-centered, Cartesian equivalent ($X,Y,Z$) and ($U,V,W$) defined as

$$X = r \cos l \cos b$$

$$Y = r \sin l \cos b$$

$$Z = r \sin b$$

$$U = -4.74 \, r \, (\mu_l \sin l + \mu_b \cos l \sin b) + v_r \cos l \cos b$$

(3)

(4)

(5)

(6)
\[ V = 4.74 \, r \left( \mu_l \cos l - \mu_b \sin l \sin b \right) + v_r \sin l \cos b \]  
\[ W = 4.74 \, r \mu_b \cos b + v_r \sin b, \]

with \( X, Y, \) and \( Z \) expressed in kpc, and \( U, V, W \) expressed in \( \text{km s}^{-1} \).

Here, we recalculate the angular position and distance of Leo II in a galactic coordinate system defined by a Cartesian set \((X_G, Y_G, Z_G)\) and \((U_G, V_G, W_G)\) such that the system has its origin at the Galactic center and, by definition, is also at rest with respect to the Galactic center. Positions and motions can be transformed to this system from the Sun-centered positions and motions following

\[ X_G = X - 7.94 \]  
\[ Y_G = Y \]  
\[ Z_G = Z \]  
\[ U_G = U + 10.00 \]  
\[ V_G = V + 5.25 + 225.0 \]  
\[ W_G = W + 7.17, \]

where we have adopted the galactocentric distance of 7.94 kpc for the Sun from Groenewegen et al. \(2008\), a relative motion of the Sun to the local standard of rest \((U_0, V_0, W_0)\) \(= (+10.00, +5.25, +7.17) \text{ km s}^{-1}\) \(\text{(Dehnen & Binney 1998a)}\), and a Galactic rotation velocity of 225 km s\(^{-1}\) at the solar vicinity. In this system, we calculate for Leo II a position \((X_G, Y_G, Z_G)\) \(\approx (-76.8, -58.2, 214.8) \text{ kpc}\). We convert the motion into this Galactic reference frame, using Monte Carlo simulation to evaluate the range of uncertainties, and find \((U_G, V_G, W_G)\) \(= (100.8 \pm 126.6, 216.0 \pm 156.9, 118.1 \pm 49.3) \text{ km s}^{-1}\), for a total Galactocentric space velocity of \(v_{\text{GRF}} = 266.1 \pm 128.7 \text{ km s}^{-1}\).

This Galactocentric Cartesian system also has an associated spherical coordinate system \((r_G, l_G, b_G)\) and \((v_{\text{GRF}}, \mu_{l_G}, \mu_{b_G})\), which are related to the Cartesian system \((X_G, Y_G, Z_G)\) and \((U_G, V_G, W_G)\) with the same relationships as in Equations (3)–(8). In this system, we calculate that Leo II is located at \((r_G, l_G, b_G)\) \(\approx (235.5 \text{ kpc}, 217.1 \text{°C}, +65.8 \text{°C})\). Its Galactic radial velocity and proper motion is \((v_{\text{GRF}}, \mu_{l_G}, \mu_{b_G}) = (21.5 \pm 4.3 \text{ km s}^{-1}, -99.8 \pm 147.8 \mu\text{as yr}^{-1}, 215.6 \pm 112.8 \mu\text{as yr}^{-1})\). This proper motion yields a total transverse velocity \(v_t = 265.2 \pm 129.4 \text{ km s}^{-1}\), a large value compared to the estimated radial motion \(v_r = 21.5 \pm 4.3 \text{ km s}^{-1}\). This yields a mostly tangential space velocity, from which we infer that Leo II either has a low-eccentricity orbit or is currently close to perigalacticon or apogalacticon distance.

With these kinematic components at hand we integrated its orbit for a variety of Galactic potentials, where the integration was carried out 14 Gyr backward and forward in time. All potentials used for our test cases have disk and bulge components (e.g., Paczynski 1990; Allen & Santillan 1991; Dehnen & Binney 1998b), which, however, do not contribute significantly to the potential given the large distance (in particular its large height above the disk) of the dSph. More importantly, this large distance renders remote satellites like Leo II important tracers of the Galactic halo and its total mass distribution (Wilkinson & Evans 1999). This is already obvious from plotting the escape velocity of such models at the position of Leo II (Figure 7).

In this figure, we show the best-fit scale-free potential from Watkins et al. \(2010\) with its total mass of \((2.7 \pm 0.5) \times 10^{12} \text{ M}_\odot\) that has been established using tracer satellites out to larger distances of \(\sim 300 \text{ kpc}\), but we note that the same arguments hold for the various (dark) MW halo models found in the literature to date (e.g., Battaglia et al. \(2005\); Dehnen & McLaughlin \(2005\); Dehnen et al. \(2006\)). Even if our proper motion measurements were significantly in error and assuming that only the radial velocity component contributed reliably, Leo II’s space velocity of \(v_{\text{GRF, rad}} = 266 \pm 128 \text{ km s}^{-1}\) is still high and similar to the value we obtain from using the full kinematic information. Thus, it is the large distance and radial velocity which govern its derived dynamics. The comparison in Figure 7 implies that Leo II is a true, bound satellite to the MW: the local escape velocity exceeds the space velocity of Leo II by \(1.0 \sigma\). We note, however, that the concept of “escape velocity” for the present arguments should be taken with caution, since its definition commonly neglects all mass outside of the considered radius. Moreover, recent evidence suggests that the rotation velocity of the MW may be larger than that used in the present work and all current Galactic potential models, at \(\Theta_0 \sim 250 \text{ km s}^{-1}\) (Reid et al. \(2009\)). We will address these issues in a future work dealing with the implications of Leo II’s boundedness for current MW mass models (A. Koch et al. \(2011\), in preparation).

In Figure 8, we show the orbital solution based on the aforementioned integrations and our fiducial proper motion measurements. While currently formally “bound” to the MW potential, it is evident that Leo II has come a long way over its recent past. Currently at pericenter, its “orbital” period implied from the calculations is \(50 \text{ Gyr}\) and, rather than an apocenter, it reaches its largest distance from the MW at the limits of our integrations, at \(\sim 1.8 \text{ Mpc}\). Considering these timescales and large distances from the actual Galactic potential, any timing...
Figure 7. Escape velocity as a function of Galactocentric distance for the best-fit halo model from Watkins et al. (2010), which adopts a total mass out to 300 kpc of $2.7 \times 10^{12} M_{\odot}$. Both under exclusion (triangle) or inclusion (cross) of our proper motion measurement it appears likely that Leo II is bound to the MW at present. Also shown are the 1σ, 2σ, and 3σ contours.

Figure 8. Orbital solution from our best velocity measurements in Galactic coordinates. Red and blue curves refer to backward and forward integration, respectively. Its current location (blue solid circle) and the position of the MW (cross) are also indicated, as well as its position along the orbit at ±(2, 4, 6, 8, 10) Gyr (small points).

In order to better understand Leo II’s orbital characteristics, we recomputed its parameters in a Monte Carlo sense by varying the position, velocity, and proper motion within their uncertainties. As a result, we find periods shorter than 6.5 (9.1, 11.6) Gyr in only 5% (10%, 15%) of the realizations. Likewise, in only 4% (6%, 12%) of the cases can we reproduce pericenters within 100 (150, 200) kpc, thus bringing Leo II into the realm of the majority of the MW’s closer, bound satellites (Grebel et al. 2003; Koch 2009).

Therefore, we conclude that this dSph is rather an isolated Local Group satellite that is falling into the MW regions and passing its (dark) halo for the first time (e.g., Chapman et al. 2007; Majewski et al. 2007). In fact, interactions or common origins of dynamical interlopers like Leo II with other Local Group systems appear plausible (Sales et al. 2007).

7. CONCLUSIONS

Our astrometric analysis provides the first-time detection of a proper motion for the dwarf satellite galaxy Leo II. The transverse motion of Leo II is detected, but only after accounting for the solar reflex motion.

The question of its origin and whether or not Leo II is a bound satellite has important implications for our understanding of the infall and merging of cosmological subhalos and the dynamics and structure of the Local Group. On the other hand, Watkins et al. (2010; their Figure 5) estimate that the cumulative contribution of Leo II to the mass budget of the MW is typically less than 8% (thus $< 0.2 \times 10^{12} M_{\odot}$). Removing it from the family of bound MW satellite tracers would thus only have a minor impact.
We can compare the idea that Leo II spent most of its life in seclusion from the MW to the properties of other isolated Local Group dSphs. Mighell & Rich (1996), Dolphin (2002), and Koch et al. (2007a) find evidence of star formation as recent as 2 Gyr ago, which is comparable to another, remote MW dSph, Leo I (Gallart et al. 1999). Tucana (at 900 kpc) and Cetus (775 kpc from the MW) are associated with neither M31 nor the MW and neither of them shows any evidence of past or present interactions with these massive galaxies (Lewis et al. 2007; Fraternali et al. 2009). Despite the lack of any obvious, dynamic gas removing agents at those large distances, none of these dSphs contain any gas; in particular Tucana appears to have had no active star formation over the past 8–10 Gyr (Saviane et al. 1996). This may imply that galaxies like Leo II had experienced efficient galactic winds, which are also consistent with its flat age–metallicity relation during the first seven or so gigayears after the big bang (Koch et al. 2007a).

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