HUBBLE SPACE TELESCOPE ASTROMETRY OF M4 AND THE GALACTIC CONSTANT $V_0/R_0$¹

LUIGI R. BEDIN AND GIAMPAOLO PIOTTO

Dipartimento di Astronomia, Università di Padova, Vicolo dell’Osservatorio 2, I-35122 Padova, Italy;
bedin@pd.astro.it, piotto@pd.astro.it

IVAN R. KING

Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580;
king@astro.washington.edu

AND

JAY ANDERSON²

Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720-3411;
jay@astron.berkeley.edu

Received 2003 January 23; accepted 2003 April 1

ABSTRACT

From multiepoch WFPC2/HST observations we present astrometric measurements of stars in the Galactic globular cluster M4 (NGC 6121) and in the foreground and background. The presence of an extragalactic point source allows us to determine the absolute proper motion of the cluster and, through use of the field stars in this region only 18° from the Galactic center, to measure the difference between the Oort constants, $A - B$. We find $(\mu_x, \cos \delta, \mu_y)_{2000.0} = (-13.21 \pm 0.35, -19.28 \pm 0.35) \text{ mas yr}^{-1}$, and $A - B = V_0/R_0 = 27.6 \pm 1.7 \text{ km s}^{-1} \text{kpc}^{-1}$.

Key words: astrometry — Galaxy: fundamental parameters — globular clusters: individual (NGC 6121)

1. INTRODUCTION

It is well known that the Wide Field Planetary Camera 2 (WFPC2) on the Hubble Space Telescope (HST) provides unequaled high-resolution photometry, compared with ground-based work or with any other instrument on astronomical satellites. However, only recently has it been shown (King et al. 1998; Anderson & King 2000) that WFPC2 and ACS astrometry—with well-dithered observations separated by a few years—allows astrometric accuracy superior to that obtained from ground-based plates and/or CCDs with a much longer time baseline (up to a factor of ~20).

In this work we present an astrometric study of the geometrically closest Galactic globular cluster M4 (NGC 6121; see Table 1 for its fundamental parameters), for which a large number of WFPC2 observations exist. These data allow studying the motion of the background and foreground objects too.

The paper is structured as follows: In § 2 we describe the complex multiepoch data; in § 3 we describe the astrometric procedure and show how the field and the cluster stars have been separated. In § 4 we address the absolute proper motion of M4. We devote § 5 to the information we can get on the Galaxy from the present study, and § 6 summarizes our results. The color-magnitude diagrams, luminosity functions, and mass functions will be treated in a separate paper (Bedin et al. 2003).

2. OBSERVATIONS

Three fields in M4 were observed by Richer and collaborators (GO-5461) in 1995 March–April with the WFPC2 camera of the Hubble Space Telescope.

The color-magnitude diagrams (CMDs) extracted from this database have been presented by Ibata et al. (1999), while the extended white dwarf sequence is discussed by Richer et al. (1995, 1997). The same group reobserved the outermost of the GO-5461 fields in 2001 January–April—with a very deep survey (123 orbits, GO-8679)—looking for the white dwarf turnaround in the color-magnitude diagram, as caused by H$_2$ opacity (Hansen et al. 2002) and repeating with a larger database (Richer et al. 2002) the work presented by Bedin et al. (2001, hereafter B01) on the lower main sequence. Here we complement their work with an astrometric study enabled by the second-epoch observations of their innermost fields in 2000 April (GO-8153, PI: I. R. K.), to determine high-precision proper motions in the outermost field.

In the following, we label the 1995 fields as “Center,” “Near,” “Far,” with obvious meaning. Their locations are shown in Figure 1. For completeness, the figure also shows other observations not used in the present work.

For the center and near fields the first epoch consists of $7 \times 1500 \text{ s} + 1300 \text{ s}$ in F336W, $7 \times 700 \text{ s} + 600 \text{ s}$ in F555W, and $15 \times 1000 \text{ s}$ in F555W; the second epoch has $8 \times 700 \text{ s} + 4 \times 20 \text{ s}$ in F814W. (Short exposures were taken in order to get proper motions of the brighter stars, using the first epoch in F336W.) All sets of images are well dithered, following the recipe by Anderson & King (2000). First- and second-epoch data of field Far have already been fully described in B01. The third epoch for this field (GO-8679) consists of $98 \times 1300 \text{ s}$ in F606W and $148 \times 1300 \text{ s}$ in F814W. (We use the ACS wide-field images, which consist of $5 \times 360 \text{ s}$ in F775W, only to produce the median super-sampled image in Fig. 5.)
3. PROPER MOTIONS

We carried out the astrometry, for each filter and each epoch, with algorithms based on the effective point-spread function (ePSF) fitting procedure described by Anderson & King (2000). The essence of the method is to determine a finely sampled PSF of high accuracy, from images at several dither offsets. Fitting of this PSF to individual well-exposed science images gives a positional accuracy of \( \pm 0.02 \) pixel, with relative proper motion less than 5 mas yr\(^{-1}\), with relative proper motion less than 5 mas yr\(^{-1}\). The separation between cluster and field stars is clear. We arbitrarily consider to be cluster members all the stars with relative proper motion less than 5 mas yr\(^{-1}\). With this membership criterion, cluster members have been plotted in Figure 2 as small points, and the field stars as heavier points.

For convenience we will hereafter refer to F336W, F555W, and F814W as \( U, V \) and \( I \), respectively, although it should be clearly understood that all photometry presented here is in the uncalibrated instrumental passbands.

The separation between cluster and field stars is clear. We arbitrarily consider to be cluster members all the stars with relative proper motion less than 5 mas yr\(^{-1}\). With this membership criterion, cluster members have been plotted in Figure 2 as small points, and the field stars as heavier points.

It is worth noting that the difference of motion of the cluster and the field stars reflects the low tangential motion of M4 around the Galactic center (which we shall show below is much lower than the circular velocity, so that M4 is close to its apogalacticon).

### 4. ABSOLUTE PROPER MOTION

For fields Near and Center, unlike field Far (studied in B01), we have F336W images, which allow us to build two-color diagrams (TCDs).

In Figure 3 we show the proper-motion separation for field Near. The top panels show the 5 yr displacements in the \( V \) images, and in the bottom panels are the corresponding TCDs in \( U-V, V-I \) for all the stars for which we have magnitudes in all three bands. The main limitation in the number of stars in Figure 3 comes from the fact that faint main-sequence stars are missed in \( U \).

In these diagrams the white dwarf sequence and main sequence of the cluster are clearly visible, plus the main sequence of the field. Note that there are no field white dwarfs in the small WFPC2 field.

An important result is the detection of an extragalactic point-source candidate, highlighted in the right panels of Figure 3 with an open circle, and labeled “QSO.” This source falls in a position in the TCD beyond the locus defined by black bodies, incompatible with a star but compatible with an active galactic nucleus.

To show this, in Figure 4 we present a simulated two-color diagram for QSOs (three-pointed asterisks) and a mixture of field stars (small dots), kindly provided by A. Grazian (2002, private communication), superposed on the M4 stars of Figure 4 (open squares). The figure shows that our QSO (vertical and horizontal lines) falls in the region where QSOs with \( z < 2.8 \) are most concentrated. The code that created the simulated diagram is a modified version of Hyperz (Bolzonella, Miralles, & Pelló 2000) in HST filters, using template stars from Lejeune & Schaerer (2001) and composite spectra of QSOs from Cristiani & Vio (1990).

Visual inspection of the presumed QSO on an image reveals a faint surrounding blur that is not starlike. Figure 5 shows a part of a median image of 3 F775W ACS/WFC images, supersampled by a factor of 2 in each direction. (The ACS images were chosen because of their better sampling. These images are raw, i.e., without flat-fielding or removal of bias and cosmic rays, but they are adequate for the present purpose.) In this figure the stars labeled “1–3” are brighter than our extragalactic source candidate (labeled “QSO”), but they do not show any blur. Though
its extragalactic nature should be confirmed by spectroscopy, the color and the morphology of this source make the hypothesis that it is a background QSO very likely. Its extragalactic nature is further supported by the fact that the absolute proper motion of M4 that we will obtain in the following is consistent with the Hipparcos-based value in the literature (see below). The fact that this source is very close to pointlike allows us to use our effective PSF to measure its luminosity and position accurately.

We can consider the extragalactic point source as an absolute reference point, from which we can infer absolute motions of objects in our fields. Having derived this reference point, we can now use the stars from all three of our fields, as shown in Figure 2.

We find for the cluster

\[
(\mu_\alpha \cos \delta)_{J2000.0} = -13.21 \pm 0.35 \text{ mas yr}^{-1}, \\
\mu_\delta_{J2000.0} = -19.28 \pm 0.35 \text{ mas yr}^{-1}.
\]

The error in this proper motion comes almost completely from the error in measuring the positions of the QSO. It is somewhat larger than the error in a well-exposed star position.

Since QSOs behind other globular clusters will be useful too, it is of interest to ask what positional accuracy can be expected for them. We believe that the answer is that they should have the same accuracy as stars. The lower accuracy in the present case arises from an error in the first-epoch position that was 0.046 pixels, compared with 0.020 (just like a well-exposed star) in the second epoch. We believe that this error comes from the fact that the QSO is about 1 mag fainter than what we would consider well-exposed and from the fact that a diffraction spike was only 4 pixels away at the first epoch (5 pixels at the second epoch).

(This spike corresponds to the one visible in Fig. 5 to the left of the QSO, but on account of a difference in telescope orientation it was considerably closer to the QSO in the two-epoch WFPC2 images on which our measurements were necessarily made.)

This proper motion was obtained only from the data sets F814W 1995 and F814W 2000 deep. The other data set pair available for this object (F336W 1995 and F814W 2000...
shallow) was taken with different filters, and this fact might introduce systematic biases. Moreover, the latter sets of images have significantly lower signal-to-noise ratio.

The error has been calculated as the sum in quadrature of the errors in each epoch and also an estimate of the error in the transformation, based on the number of stars used in the local transformation and on the rms of the displacement of these (Anderson & King 2003b).

Our proper motion is in agreement with that of Dinescu, van Altena, & Girard (1999), $(\mu_\alpha \cos \delta, \mu_\delta)_{2000.0} = (-12.50 \pm 0.35, -19.93 \pm 0.49)$, in which they use Hipparcos-measured stars to link relative motions to an absolute system; our difference is 1.4 in the right ascension direction and 1.1 in the declination direction. As we have said, this agreement with the solidly based Hipparcos system strengthens our identification of our reference object as extragalactic.

In Galactic coordinates our proper motion becomes:

$$(\mu_\alpha \cos \delta)_{2000.0} = -23.30 \pm 0.35 \text{ mas yr}^{-1},$$

$$\mu_\delta_{2000.0} = -1.81 \pm 0.35 \text{ mas yr}^{-1}.$$

In Figure 6 we show the vector-point diagram of the proper motions in Galactic coordinates, after placing the origin at the extragalactic source.

The mean displacement of the cluster stars with respect to the extragalactic source is the combined effect of the motions of the Sun and the cluster around the Galaxy. We use the computational matrix in Johnson & Soderblom (1987) to derive the cluster space velocity with respect to the Sun $(U, V, W)_{\text{helio}}$. [Note that $(U, V, W)$ is a right-handed coordinate system, so components are positive in the direction of the Galactic center, Galactic rotation, and the north Galactic pole, respectively.]

Assuming the following: (1) mean coordinates $(\alpha, \delta)_{2000.0} = (245^\circ 898', -26^\circ 525')$ for the M4 fields; (2) J2000.0 Galactic coordinate system defined as before; (3) a distance of M4 from the Sun of 1.8 kpc (a mean of various values in the literature) with an uncertainty of 10%; (4) a radial velocity of $70.5 \pm 0.3$ km s$^{-1}$ (from the Harris 1996 on-line catalog, 1999 June update); (5) a right ascension proper motion $\mu_\alpha \cos \delta = -13.21 \pm 0.35$ mas yr$^{-1}$, and a declination proper motion of $-19.28 \pm 0.35$ mas yr$^{-1}$ for M4, we get: $(U, V, W)_{\text{helio}} = (43 \pm 3, -207 \pm 20, -7 \pm 4)$ km s$^{-1}$.

Then, assuming a Galactocentric distance for the Sun of 8.0 kpc and adopting a solar motion of $(U, V, W) = (10.0, 5.2, 7.2)$ km s$^{-1}$ (Binney & Merrifield 1998, p. 628), we get for M4:

$$(U, V, W) = (53 \pm 3, -202 \pm 20, 0 \pm 4) \text{ km s}^{-1},$$

which is the cluster space velocity relative to the local standard of rest (LSR).

If we assume a LSR circular motion of $V_0 = 220$ km s$^{-1}$ at our distance of 8.0 kpc, the cylindrical velocity components of M4 in a Galactic rest frame are

$$(U, V, W)_{\text{absolute}} = (54 \pm 3, 16 \pm 20, 0 \pm 4) \text{ km s}^{-1},$$

which corresponds to a Galactic rest-frame speed of $56 \pm 20$ km s$^{-1}$.

We note how a small variation in the assumed parameters—in particular in the distance—well within the uncertainties, can turn the orbit from prograde into retrograde. (If we were to assume a distance of 2.2 kpc for M4—as in the on-line catalog of Harris—we would get $V \sim -28 \pm 24$ km s$^{-1}$.)

Our measure of the absolute proper motion of M4 is not affected by its annual parallax (which is $\sim 0.5$ mas), given that the observations used in the present work were all taken at the same time of year.

5. MEASUREMENT OF THE GALACTIC CONSTANT $V_0/R_0$

M4 is a globular cluster projected near the edge of the Galactic bulge ($\ell \sim -9^\circ, b \sim 16^\circ$), at a distance of about 2 kpc from the Sun. We expect a modest number of foreground disk stars in our fields (from here on we use “foreground” to mean in front of the bulge rather than in front of the cluster), but in the background we look through the outer edge of the bulge, and the inner part of the halo, at a height of $\sim 2$ kpc above the plane. Although at such heights the density of the bulge and halo are both rather low, the volume we are probing is sizable, so that we see a large number of these stars. Their absolute proper motion is just the reflection of the Sun’s angular velocity with respect to that point; from that we can derive the value of the angular velocity of the LSR with respect to the Galactic center, which is the fundamental Galactic-rotation constant $A - B = V_0/R_0$ (see Kerr & Lynden-Bell 1986; Olling & Merrifield 1998). In this respect we do not need to involve ourselves with the complicated question of whether the distant field stars (after elimination of foreground stars) belong to the bulge, the halo, or some transition population; the
geometry along our line of sight is the same in any case, with the average velocity of these stars having no component toward or away from the Galactic center.

To derive the value of $V_0/R_0$ we need three steps: (1) find the mean distance of the stars whose motion we are observing, (2) correct the observed proper motion for the velocity of the Sun with respect to the LSR, and (3) relate the corrected proper motion to the angular velocity of the LSR with respect to the Galactic center.

For the distance of the stars that we are observing, we adopt the following working hypotheses:

1. The field stars are mainly bulge/halo members. (We will show below, on the basis of the observed distribution of the proper motions and colors, that the foreground stars have a negligible influence.)

2. The stars whose motion we are studying are part of a spherical spatial distribution around the Galactic center. We use this hypothesis just for simplicity in the estimation of the distance of its centroid; a modest flattening (like that of the bulge) makes very little difference in this.

3. Our observations go deep enough that we do not lose stars on the far side of our sample, so that on the average they are indeed at the tangent point. (In asserting this we neglect the small effect of the $r^2$ flare-out of our cone of observation, which puts the average distance a little beyond the tangent point. In the nonrotating halo this has no effect, and in the modestly rotating bulge the stars in front of the tangent point and those behind it, closely equal in number, have oppositely directed transverse motions, which cancel each other in the mean.)

From these it follows that we can express the distance of the centroid, in our line of sight, of the bulge/halo stars (which, for brevity, we will refer to simply as the bulge) as a geometrical constant times the distance of the Sun from the Galactic center. This distance is

$$R = R_0 \cos \ell \cos b .$$

(1)

If we take $R_0 = 8.0 \text{ kpc}$, then $R = 7.6 \text{ kpc}$.

Next, the difference between the proper motion of the bulge stars and that of the extragalactic point source is the
absolute proper motion of that point in the bulge. To measure that motion, however, we must remove the foreground stars from our sample of field stars. To do this we draw a putative halo main sequence by shifting that of M4 down by 3.1 mag, to allow for the difference in distance. Then we draw a line 0.5 mag redder in color, to allow for the presence of stars of higher metallicity and for a small amount of observational error. We exclude the 411 stars to the right of this line.

Figure 6 shows the proper motions of M4 and of the surviving 1086 field stars, in Galactic coordinates. The origin has been set at the extragalactic point source, labeled “QSO.” The error bars show the uncertainties in the motions with respect to the mean motion of the cluster stars. We have drawn a heavy circle at a radius of 4 times the semi-interquartile distance of the field stars from their median position. We considered stars inside it to be reliable members of the population whose motion we are studying, so we calculated the mean motion from them. This is the mean absolute proper motion of the bulge, and is shown as an arrow in Figure 6. Its error—calculated as \( \sigma = \sqrt{\text{number of stars} / 2} \) is indicated on the head of the arrow with a tiny error bar. (The larger error bar at the foot of the arrow shows the measurement error in the position of the QSO.) The results are \( \mu_\ell \cos b = -6.25 \pm 0.09 \) mas yr\(^{-1} \), \( \mu_b = +0.47 \pm 0.08 \) mas yr\(^{-1} \). Inclusion of the error in the QSO position increases the sigmas to \( \pm 0.36 \) mas yr\(^{-1} \), however.

We also carried out the same procedure with the entire set of field stars. The resulting mean motion differed by a little less than 5% from what we got from the purified sample, showing that the foreground stars did indeed need to be removed but that our results are not sensitive to exactly how we did the rejection.

The apparent motion of the field stars is the reflection of the Sun’s motion with respect to that point. What we need instead, however, is the velocity of the LSR with respect to our region of observation; this requires a correction for the solar motion with respect to the LSR.

Both for this step and for the final step of converting the proper motion in this field into the apparent motion that we would observe at the Galactic center, we need to rotate the components of a vector \((U, V, W)\), in the local Galactic system, into an orientation that accords with the direction of M4 from us, so that \( U_0 \) is in the radial-velocity direction, \( V_\ell \) in the \( \ell \) direction, and \( W_b \) in the \( b \) direction. That rotation is easily accomplished in two steps. First, rotate around the north celestial pole so that the new \( U_1 \) axis points toward longitude \( \ell \) rather than the Galactic center:

\[
U_1 = U \cos \ell + V \sin \ell , \quad V_1 = -U \sin \ell + V \cos \ell , \quad W_1 = W .
\]

Then rotate around the \( V_1 \) axis by an angle \( b \), in the direction from \( U_1 \) toward \( W_1 \):

\[
U_\| = U_1 \cos b + W_1 \sin b , \quad V_\| = V_1 , \quad W_\| = -U_1 \sin b + W_1 \cos b .
\]

The effect of the Sun’s motion with respect to the LSR, for which we assume \((U, V, W) = (10.0, 5.2, 7.2) \) km s\(^{-1} \) (Binney & Merrifield 1998, p. 628), then becomes \( V_\| = 6.06 \) km s\(^{-1} \), \( W_\| = 4.4 \) km s\(^{-1} \). The corresponding corrections to our observed proper motion of the bulge are these linear velocities divided by 4.74\( R \) (where 4.74 is the equivalent in kilometers per second of one astronomical unit per tropical year, and expressing \( R \) in kiloparsecs will give a result in milliarcseconds per year). Thus \( \Delta U_{\|} \cos b = 0.186 \) mas yr\(^{-1} \), \( \Delta U_{\|} \sin b = 0.123 \) mas yr\(^{-1} \). Since it is the reflection of this that shows up at the bulge, we must subtract these quantities from the observed proper motion of the bulge.

The resulting angular proper motion of our bulge field with respect to the LSR is thus \( \mu_{\|} \cos b = -6.06 \pm 0.36 \) mas yr\(^{-1} \), \( \mu_{\|} \sin b = +0.35 \pm 0.36 \) mas yr\(^{-1} \). (Note that because the correction for solar motion is a small one, [1] our choice of a value for \( R_0 \) was not critical and [2] we need not increase our quoted errors on account of any uncertainty in the solar motion.)

For the final step of moving from the apparent proper motion of bulge stars at the position of M4 to the angular velocity of the LSR around the Galactic center, we note that if we assume circular motion for the LSR, then its velocity \( V_0 \) is perpendicular to a line from the Sun to the Galactic center, so that \((U, V, W) = (0, V_0, 0)\). Equations (2a)–(2c) then give

\[
V_\| = V_0 \cos \ell , \quad W_\| = -V_0 \sin \ell \sin b .
\]
On the other hand, the relation between transverse velocities and proper motions gives, with substitution from equation (1),

\[ V_{cl} = -4.74 R \mu_\ell \cos b, \]
\[ W_{cl} = -4.74 R \mu_b, \]

Combining these two pairs of equations then gives

\[ \frac{1}{\cos b} \frac{V_0}{R_0} = -4.74 (\mu_\ell \cos b), \]
\[ \tan \ell \tan b \frac{V_0}{R_0} = 4.74 \mu_b. \]

These are two equations for \( V_0/R_0 \), which give independent estimates of its value:

\[ \frac{V_0}{R_0} = -4.74 \cos b(\mu_\ell \cos b), \]
\[ \frac{V_0}{R_0} = 4.74 \frac{\mu_b}{\tan \ell \tan b}. \]

If we were to take a weighted mean (or what is equivalent, find \( V_0/R_0 \) by least squares from the two equations), the second equation would make only a very small contribution. Since the referee has pointed out to us, besides, that \( \mu_b \) would need to be corrected for a systematic contribution from bulge rotation seen at an oblique angle—a very uncertain quantity—we choose to solve for \( V_0/R_0 \) from the \( \mu_\ell \cos b \) equation alone. The result is \( V_0/R_0 = 27.6 \pm 1.7 \) km s\(^{-1}\) kpc\(^{-1}\).

This is an independent measurement of this quantity, of which there are various other values in the literature. It is related in complicated ways to the other constants of Galactic rotation, and a full discussion of that problem would be far beyond the scope of this paper. Suffice it to say that our value is close to the \( 26.4 \pm 1.9 \) km s\(^{-1}\) kpc\(^{-1}\) that is quoted in the comprehensive review by Kerr & Lynden-Bell (1986).

Although we have argued that our results do not depend on whether our field stars are members of the Galactic bulge or halo population, we conclude this section by presenting some evidence that relates to this question, in the form of the sizes of the velocity dispersions. We took each of these to be half of the interval, centered on the mean, that includes...
68.3% of the sample. The results are

$$\sigma_{\mu_b \cos b} = 2.99 \pm 0.09 \text{ mas yr}^{-1},$$
$$\sigma_{\mu_b} = 2.63 \pm 0.08 \text{ mas yr}^{-1},$$

corresponding to 108 and 95 km s\(^{-1}\), respectively, under the assumption of \( R = 7.6 \text{ kpc} \) (corresponding to \( R_0 = 8.0 \text{ kpc} \), according to eq. [1]). For what it is worth, these values correspond to those found by Spaenhauer, Jones, & Whitford (1992), and by Kuijken & Rich (2002), for bulge fields closer to the Galactic center. The higher dispersion along Galactic parallels than along Galactic meridians is suggestive of Galactic rotation, which should be seen in the bulge but not in the halo.

6. CONCLUSIONS

In this work we have presented an astrometric study of the closest Galactic globular cluster M4, based on multi-epoch HST observations. We have been able to separate almost perfectly the member stars from the field objects, and to identify an extragalactic point-source candidate (QSO). The QSO allowed us to measure the absolute proper motion of M4, for which we find \((\mu_\alpha \cos \delta, \mu_\delta)_{2000,0} = (-13.21 \pm 0.35, -19.28 \pm 0.35) \text{ mas yr}^{-1}\). Moreover, we have been able to measure the apparent proper motion of the bulge and from it to derive an estimate of the value of \( A - B = V_0 / R_0 = 27.6 \pm 1.7 \text{ km s}^{-1} \text{ kpc}^{-1} \).

In a future paper we will use these proper motions to study the cluster members in more detail, studying the color-magnitude diagram, two-color diagram, luminosity function, mass function, and mass segregation. We are also working on the full database, including the new ACS/WFC images, to derive internal proper motions. It should soon be possible to derive a precise geometrical distance (with an accuracy of a few percent) based on the comparison of the proper-motion dispersion with that of the radial velocities for a large sample of stars, using newly available multi-fiber high-resolution spectroscopic facilities such as FLAMES+GIRAFFE at VLT, a project we have already submitted to ESO.

We are grateful to Andrea Grazian for providing us simulated two-color diagrams of QSOs in HST filters, and to Harvey Richer for pointing out that we needed to consider possible contamination by foreground stars. This project has been partially supported by the Ministero dell’Istruzione e della Ricerca Scientifica and by the Agenzia Spaziale Italiana. I. R. K. and J. A. acknowledge support from STScI grant GO-8153.

REFERENCES

Anderson, J., & King, I. R. 2000, PASP, 112, 1360
Anderson, J., & King, I. R. 2003a, PASP, 115, 113
Anderson, J., King, I. R., & Piotto, G. 2001, ApJ, 560, L75 (B01)
Bedin, L. R., et al. 2003, in preparation
Binney, J., & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton Univ. Press)
Bolzonella, M., Miralles, J. M., & Pelló, R. 2000, A&A, 363, 476
Cristiani, S., & Vio, R. 1990, A&A, 227, 385
Dinescu, D. I., van Altena, W. F., & Girard, T. M. 1999, AJ, 117, 277
Hansen, B. M. S., et al. 2002, ApJ, 574, L155
Harris, W. E. 1996, AJ, 112, 1487
Ibata, R. A., Richer, H. B., Fahman, G. G., Bolte, M., Bond, H. E., Hesser, J. E., Pryor, C., & Stetson, P. B. 1999, ApJS, 120, 265
Johnson, D. R. H., & Soderblom, D. R. 1987, AJ, 93, 864
Kerr, F. J., & Lynden-Bell, D. 1986, MNRAS, 221, 1023
King, I. R., Anderson, J., Cool, A. M., & Piotto, G. 1998, ApJ, 492, L37
Kuijken, K., & Rich, R. M. 2002, AJ, 124, 2054
Lejeune, T., & Schaerer, D. 2001, A&A, 366, 538
Olling, R. P., & Merrifield, M. R. 1998, MNRAS, 297, 943
Richer, H. B., et al. 1995, ApJ, 451, L17
Richer, H. B., et al. 2002, ApJ, 574, L151
Spaenhauer, A., Jones, B. F., & Whitford, A. E. 1992, AJ, 103, 297