Accurate Internal Proper Motions of Globular Clusters

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**Abstract.** We have undertaken a long term program to measure high precision proper motions of nearby Galactic globular cluster (GC) stars using multi-epoch observations with the WFPC2 and the ACS cameras on-board the Hubble Space Telescope. The proper motions are used to study the internal cluster kinematics, and to obtain accurate cluster distances. In this paper, we also show how the proper motions of the field stars projected in the direction of the studied clusters can be used to set constraints on the Galaxy kinematics.

1. **Proper Motions in the Field of M4**

Some of us have recently developed a method (Anderson and King, 2000, 2003), based on multi-epoch HST images, which allows us to derive very accurate proper motions. The key to our success is the removal of systematic errors of many types from our astrometry. Presently, we are able to measure the position of a well exposed star in a single image with a precision of 0.02 pixel, i.e. 2 mas in the WFs, 1 mas in the PC. Multiple observations allow to reduce this uncertainty of a factor $\sqrt{N}$, where $N$ is the number of frames.

1.1. **The Internal Proper Motion of M4 and its Distance**

The internal proper motions of M4 is $\sim0.50$ mas/yr. This means that with our 8 frames in each of two epochs, and with a time baseline of $\sim5$ yrs, we can reach a precision of $\sim0.2$ mas/yr. We can then subtract, in quadrature, the distribution of the errors to the observed distribution, and have a precise measure of the internal dipersion of proper motions. Figure 1 shows some preliminary results. We plan to furtherly improve the proper motions of M4 stars by the reducing the third epoch WF@ACS images which overlap with our fields.

We have recently undertaken a program aimed at obtaining radial velocities for stars located in the same radial interval and in the same magnitude
range of the proper motion data in M4 (and other clusters). A comparison of the proper motion dispersion with the radial velocity dispersion will lead to the direct measurement of the GC distance. The major source of uncertainty being the sampling error (in first approximation $1/\sqrt{2N_{\text{tot}}}$, where $N_{\text{tot}}$ is the total number of measured stars), which gives an error 1.3% for the 3,000 stars we plan to observe in each cluster with the multi-fiber high resolution facility FLAMES@VLT. The statistical limitation will be set by the number of radial velocities, as we have accurate proper motions for a large number of stars.

1.2. Measure of the Galactic Constant $\Theta_0/R_0$

An obvious by-product of our proper motion measurements is a decontamination of the cluster sample from the field stars (King et al. 1998, Bedin et al. 2001). There is a number of studies which can be undertaken with the motions of the fields objects that we get for free. We give a brief description of an example of such applications.

In Bedin et al. (2001), two HST deep observations of the globular cluster M4, separated by a time baseline of $\sim 5$ yrs, allowed us to obtain a pure sample of the cluster main sequence stars. The identification of an extra-Galactic point source enables us to use the proper motions of field stars (which were junk in Bedin et al. 2001) to measure a fundamental parameter of the Galaxy. M4 is a globular cluster projected on the edge of the Galactic bulge ($\ell \approx -9^\circ$, $b \approx 16^\circ$). We expect only a small number of foreground disk stars in our fields, but in the background we look through the edge of the bulge at a height of $\sim 2$ kpc. Although at such heights the density of the bulge is rather low, the volume we are probing is sizable, so that we see a large number of bulge members. Their absolute proper motion (pm) is just the reflection of the Sun’s angular velocity.
with respect to that point; from that pm we can derive the value of the angular velocity of the local standard of rest (LSR) with respect to the Galactic center, which is the fundamental Galactic-rotation constant $A - B = \Theta_0 / R_0$ (cf. Kerr & Lynden-Bell 1986).

To derive this value we need to: (1) find the mean distance of the bulge stars whose motion we are observing, (2) correct the observed pm for the velocity of the Sun with respect to the LSR, and (3) relate the corrected pm to the angular velocity of the LSR with respect to the Galactic center.

For the distance of the bulge stars that we are observing, we assume the following working hypotheses: (1) Disk and halo stars are a negligible component of the field stars in our M4 images, i.e., the field stars are mainly bulge members. (2) The bulge stars on our line of sight are part of a spherical spatial distribution

Figure 2. Vector-point diagram of all the independent measurements of the Galactic proper motions. The arrows indicate the mean motion of the cluster and the bulge with respect to an extragalactic source.
around the Galactic center. (3) Our observations go deep enough that we do not lose stars on the far side of the bulge. From these assumptions, it follows that we can express the distance of the centroid of the bulge stars along our line of sight (we will refer to it as the bulge) as a geometrical constant $\times$ the distance of the Sun from the Galactic center. This distance is $R = R_0 \cos \ell \cos b$. If we take $R_0 = 8.0$ kpc, then $R = 7.6$ kpc.

The absolute motion of the bulge –corrected for the Sun’s peculiar motion– allows us to get a direct estimate of the Oort-constant difference $(A - B)$, which is related to the transverse velocity of the LSR ($\Theta_0$) and its Galactocentric distance ($R_0$), according to equations presented in Bedin et al. (2003a; in Bedin et al. 2003b we will give more details and a more concise formulation leading to identical results), we get: $(A - B) \pm \sigma_{(A-B)} = \Theta_0/R_0 \pm \sigma_{\Theta_0/R_0} = 27.6 \pm 1.7$ km/s kpc. The quoted error is internal and corresponds to an uncertainty of $7\%$.

1.3. Galactic Model

Finally, we mention that the field star data can be used to probe in depth the Galactic structure and stellar content. We are presently collaborating with the research group at the University of Pisa on a project aimed at the definition of a Galactic model. An example on how the field star data from proper motions as those in King et al. (1998) and Bedin et al. (2001) can be used in this kind of investigation is in Castellani et al. (2001).

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