# ABSOLUTE PROPER AND SPACE MOTIONS OF GLOBULAR CLUSTERS

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## ABSTRACT

Absolute proper motions of ten globular clusters with respect to the Hipparcos system are presented. Our new data led to orbits in the Milky Way with smaller apogalactic distances. They are therefore in better agreement with the actual distribution of the globular clusters in the Milky Way. The kinematics of our clusters with respect to the metallicity is discussed.

Key words: reference stars; kinematics of globular clusters.

## 1. INTRODUCTION

Globular clusters are important tracers of the chemical evolution and dynamics of the Milky Way. Of special interest are the kinematics of globular clusters, which, however, require accurate absolute proper motions of these objects. We have started a program for the determination of space motions of globular clusters (e.g. Geffert 1987, Brosche et al. 1991) using plates of our refractor in combination with extragalactic calibrated proper motions of stars determined on plates of the Lick astrograph. Several other groups were also active in the determination of absolute proper motions of globular clusters. From a systematic search in the literature Geffert et al. (1993a) and Dauphole et al. (1996) have collected absolute proper motions of 26 mainly northern globular clusters. This sample was recently extended by Dinescu et al. (1997) with five southern clusters. However, the data collected by Dauphole et al. (1996) represent a very inhomogenous sample mainly due to problems of reference stars, which, in the ideal case, should establish an inertial system.

The problem of unsuited reference stars has been a general drawback of photographic astrometry in the past. Since the development of automatic measuring machines, the potential of photographic astrometry has increased. According to the most accurate studies also the internal motions of globular and open clusters are measurable. However, one may doubt the results of these studies, because the proper motion obtained cannot be easily converted to physical velocities. An example showing how the choice of the reference stars can alter the results is given in a study of the Pleiades (Geffert et al. 1995). The recent results of the Hipparcos and Tycho mission will improve the situation for all astrometric reductions, ranging from solar system objects up to distant galactic objects, in a significant way.

Here we will give a first application of the use of Hipparcos stars for the determination of absolute proper and space motions of ten globular clusters. A statistical analysis of the space motions and orbits of 15 globular clusters based on Hipparcos reference stars is given by Brosche et al. (1997).

## 2. OBSERVATIONS AND REDUCTIONS

All first epoch plates were taken between 1900 – 1922 by F.W. Küstner (1856 – 1936) with the (D=0.3 m, f=5.1 m) refractor of Bonn (now located at Hoher List observatory). Due to recent mechanical problems of our refractor we had to include for the second epoch plates from other telescopes and wide field CCD observations obtained with the 1 m telescope of Hoher List observatory and the 1.23 m telescope of Calar Alto. In order to test the astrometric quality of the different CCD frames, a proper motion study for the globular cluster M10 (NGC 6254) is under way (Chen et al. 1997) using plates from Bonn and Shanghai and CCD observations from different telescopes.

The measurements were performed either on the ASCORECORD measuring engine of Hoher List observatory or the PDS 2020 GM$^{\rm plus}$ in Münster. A central plate overlap algorithm was used for the reduction of our data. The results of our reduction were accurate (mainly $\sigma_\mu$ = 1 mas/yr) absolute proper motions of stars in the fields of ten globular clusters. Bivariate Gaussian fitting was used to separate cluster and field stars. For all clusters, we found a sufficient separation and calculated the mean absolute proper motions of clusters members.

Although the number of Hipparcos reference stars in our fields is poor (only 4 to 9 stars), there are certain advantages when using Hipparcos reference stars in the astrometric reduction:

*Table 1. U, V, W velocities of our ten globular clusters in a system of galactic standard of rest. Using a simple logarithmic potential we calculated also peri- and apogalactic distances, eccentricities and z-components of the angular momentum. We used $R_{gc-\odot}$ = 8.5 kpc for the distance of the Sun from the galactic centre and $\Theta_\odot$ = 220 km/s for the rotation of the Milky Way at the place of the Sun.*

| Object | U [km/s] | V [km/s] | W [km/s] | $R_a$ [kpc] | $R_p$ [kpc] | e | $I_z$ [kpc km/s] |
|---|---|---|---|---|---|---|---|
| NGC 4147 | +73 | −113 | +124 | 25 | 10 | 0.42 | +1392 |
| NGC 5024 | +38 | +260 | −76 | 33 | 16 | 0.35 | −1391 |
| NGC 5466 | −227 | +124 | +193 | 46 | 6 | 0.76 | 32 |
| NGC 5904 | +295 | +46 | −173 | 22 | 3 | 0.79 | −257 |
| NGC 6218 | +65 | +52 | −96 | 5 | 1 | 0.65 | −279 |
| NGC 6254 | +83 | +134 | +97 | 5 | 4 | 0.18 | −734 |
| NGC 6779 | −110 | +143 | +5 | 13 | 1 | 0.89 | +369 |
| NGC 6934 | −77 | −300 | −108 | 34 | 7 | 0.66 | +813 |
| NGC 7078 | +293 | −90 | −95 | 28 | 9 | 0.52 | −2070 |
| NGC 7089 | −100 | −32 | −375 | 49 | 8 | 0.73 | 863 |

Note that U points from the Sun to the galactic centre!

- the mean deviation of our measurements from the Hipparcos catalogue of one recent plate is in good agreement with the measurement errors determined from the intercomparison of plates of the same epoch;
- the reduction is extremely stable. Omitting stars does not change the final proper motions in a significant way. For NGC 4147 (9 Hipparcos reference stars) we calculated a solution based on five and a second one based on the remaining four stars. Mean proper motion differences of the solutions were less than 1 mas/yr;
- the proper motion dispersion of cluster members is equal for both coordinates and nearly identical to the proper motion errors;
- the proper motion system of Hipparcos represents in a better way an inertial system than classical star catalogues. With known distances Hipparcos calibrated proper motions can be directly converted to velocities.

## 3. ABSOLUTE PROPER MOTION OF M15

As an example we discuss here the results for the globular cluster M15 (NGC 7078). From 12 refractor plates ranging from 1916 – 1989 we determined Hipparcos calibrated absolute proper motions of 182 stars with a median accuracy of 1 mas/yr. The measurements have been used in an earlier proper motion study of M15 (Geffert et al. 1993b). Figure 1 shows the vector point plot diagram of our proper motions. From a bivariate Gaussian fitting to the vector point plot diagram 111 cluster stars with a rms of the proper motions of 1.1 mas/yr were selected. We obtained for these stars a mean absolute proper motion of $\mu_\alpha \cos\delta = -2.4$ mas/yr and $\mu_\delta = -8.3$ mas/yr. These values are in good agreement with our earlier determination of $\mu_\alpha \cos\delta = -1.0$ mas/yr and $\mu_\delta = -10.2$ mas/yr for M15 (Geffert et al. 1993b), but in contradiction with the results of Scholz et al. (1996), who obtained $\mu_\alpha \cos\delta = -0.1$ mas/yr and $\mu_\delta = +0.2$ mas/yr. Scholz et al. (1996) have argued, that the small number of galaxies used in our first investigation for the calibration of the proper motion has led to the large discrepancies between our proper motions and their data. However the confirmation of our earlier results by the use of Hipparcos reference stars rules out such an explanation.

In principle, we cannot rule out the existence of undetected systematic errors of the proper motions determined with our refractor. The number of Hipparcos stars in our fields is by far too small to detect such effects. We have therefore also plotted the proper motions of our cluster stars versus magnitude. There was no systematic trend of our data, but we have to note that the cluster members span only a range of two magnitudes. Moreover, we compared our proper motions with the relative proper motions from Cudworth (1976). For 89 stars in common we obtained a rms of the proper motions of 1.2 mas/yr. Due to the better internal accuracy of the data of Cudworth (1976) this value reflects mainly the uncertainty of our proper motions. This value is in very good agreement with the scatter of the proper motions of the cluster members mentioned above.

## 4. SPACE MOTIONS OF 10 GLOBULAR CLUSTERS

The space velocity components $U, V, W$ in a system of galactic standard of rest were calculated from the absolute proper motions. They are given in Table 1. A complete discussion of the orbits of our globular clusters is given elsewhere (see Brosche et al. 1997). Here we have used a simple logarithmic potential for the calculation of orbital characteristics like eccentricity, apogalactic distance and z-component of angular momentum in order to draw only some rough conclusions. The data show a general trend in the sense that the apogalactic distances are smaller than in our earlier studies. Having in mind that the globular clusters spread only to $R_{gc} = 30 - 40$ kpc (Zinn 1985), our present result is in better agreement with the actual distribution of the globular clusters than that of Geffert et al. (1993a, 1993b). Nevertheless

M2 and NGC 5466 remain with large apogalactic distances.

## 5. COMPARISON WITH EARLIER RESULTS

We have compared our absolute proper motions based on Hipparcos reference stars with the results of previous studies. We include in this comparison all clusters used in Brosche et al. (1997). In their study on absolute proper motions of globular clusters Cudworth & Hanson (1993) have presented data for 14 clusters, 6 of them in common with our sample. Table 2 gives the differences for each cluster and the mean differences along with their rms.

*Table 2. Differences ($\Delta\mu_\alpha$, $\Delta\mu_\delta$) of absolute proper motions determined with respect to Hipparcos stars to the corresponding ones from Cudworth & Hanson (1993). The differences are given in the sense ours minus others.*

| Object | $\Delta\mu_\alpha$ [mas/yr] | $\Delta\mu_\delta$ [mas/yr] |
|---|---|---|
| NGC 104 | +3.6 | −3.4 |
| NGC 5272 | +2.1 | −4.6 |
| NGC 5904 | −1.9 | +4.1 |
| NGC 6341 | +3.7 | −0.9 |
| NGC 7078 | −2.1 | −4.1 |
| NGC 7089 | +0.8 | −1.5 |
| Mean | +1.0 | −1.7 |
| St. Dev. | ± 2.6 | ± 3.2 |

Scholz and coworkers (Scholz et al. 1996, and references herein) have used extragalactic objects on deep Schmidt plates to calibrate their proper motions. There are five clusters in common with our sample. These differences in the proper motions are presented in Table 3.

*Table 3. Differences ($\Delta\mu_\alpha$, $\Delta\mu_\delta$) of absolute proper motions determined with respect to Hipparcos stars to the corresponding ones from Scholz et al.(1996). The differences are given in the sense ours minus others.*

| Object | $\Delta\mu_\alpha$ [mas/yr] | $\Delta\mu_\delta$ [mas/yr] |
|---|---|---|
| NGC 5272 | +4.0 | +0.1 |
| NGC 5904 | −3.4 | −2.3 |
| NGC 6218 | −3.9 | −0.5 |
| NGC 6341 | +3.5 | −2.6 |
| NGC 7078 | −2.3 | −8.5 |
| Mean | −0.4 | −2.8 |
| St. Dev. | ± 3.8 | ± 3.4 |

In Table 4 we give the comparison of our Hipparcos calibrated proper motions with previous values determined with respect to extragalactic calibrated proper motions of stars measured on plates taken with the Lick astrograph.

*Table 4. Differences ($\Delta\mu_\alpha$, $\Delta\mu_\delta$) of absolute proper motions determined with respect to Hipparcos stars to the corresponding ones determined with respect to stars with extragalactic calibrated proper motions from old and new plates of the Lick astrograph.*

| Object | $\Delta\mu_\alpha$ [mas/yr] | $\Delta\mu_\delta$ [mas/yr] |
|---|---|---|
| NGC 4147 | +1.7 | −4.4 |
| NGC 5466 | +1.5 | +0.4 |
| NGC 6218 | −2.4 | 0.0 |
| NGC 7089 | −1.2 | −2.8 |
| Mean | −0.1 | −1.7 |
| St. Dev. | ± 2.0 | ± 2.2 |

## 6. KINEMATICS VERSUS METALLICITY

From a study of radial velocities of globular clusters Rodgers & Paltoglou (1984) found seven globular clusters in the metallicity range of[Fe/H] = $-1.3$ to $-1.7$ with strong retrograde motions in the Galaxy, which also exhibit similar horizontal-branch-morphology. On the base of these findings they conclude that the halo of the galaxy may have formed through mergers. However including proper motions, Dinescu et al. (1997) recently found two of these clusters (NGC 1851 and NGC 6584) on orbits with prograde motion. Moreover, our data for NGC 6934, also suggested as a cluster on a high retrograde orbit, show only a slight retrograde motion ($\Theta = -70$ km s$^{-1}$).

In comparison with our earlier study (Dauphole et al. 1996) the diagrams of the kinematical quantities like total energy, eccentricity, apogalactic distance, and z-component of the angular momentum versus metallicity have not changed very much due to the use of Hipparcos calibrated proper motions. The main reason is, that the clusters with Hipparcos calibrated proper motions are distributed mainly at the metal poor end of the globular cluster distribution. Therefore the earlier data remained as before for the more metal rich clusters.

As in our previous study (Dauphole et al. 1996) an indication of an abundance gradient in the halo clusters is seen, which would be an argument for a pressure supported collapse of the Milky Way. This effect is seen in the Hipparcos calibrated proper motions alone as well as in the data of all globular clusters with known absolute proper motions (including the absolute proper motions of Dauphole et al. (1996) and Dinescu et al. (1997)). However, the number of about 30 globular clusters, for which absolute proper motions exist, is so small, that selection effects may influence our results in a significant way.

## 7. SUMMARY

The first use of Hipparcos reference stars for the determination of absolute proper motions of globular clusters may be summarised in the following way:

- we have determined the absolute proper motions of ten globular clusters with an accuracy of 1mas/yr. The data are in good agreement with our earlier results calibrated by galaxies on plates from the Lick astrograph;
- we find a significant fraction of globular clusters on retrograde orbits. The mean z-component of the angular momentum is $-130\pm340$ kpc km s$^{-1}$ corresponding to a rotational velocity of $+15\pm40$ km s$^{-1}$ at the place of the sun;
- the use of Hipparcos reference stars leads to smaller apogalactic distances. These are now more compatible with the actual distribution of globular clusters;
- there is still a need for future astrometric satellite missions (GAIA, DIVA) to improve the number of reference stars.

A more comprehensive presentation of our results will be given in Geffert et al. (1997a, 1997b) and Odenkirchen et al. (1997).

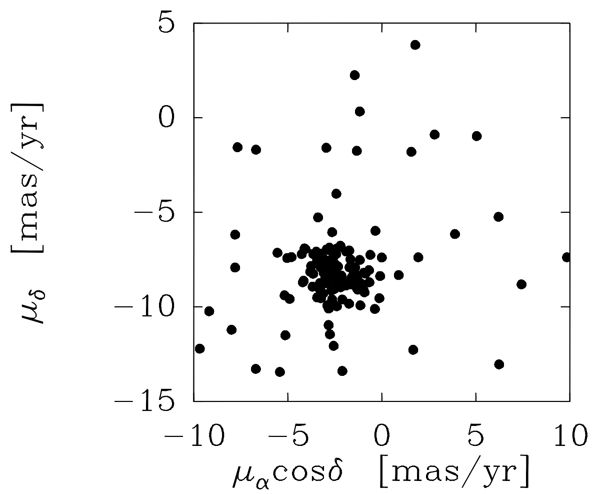


*Figure 1. The vector point plot diagram of our M15 data.*


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