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Hipparcos based astrometric analysis of M 3 and M 92 fields: optical identification of X-ray and radio sources, space motions of globular clusters M 3 and M 92 and a galactic orbit of the sdB star PG 1716+426

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Abstract. We present positions and proper motions with respect to the Hipparcos system of stars in the fields of the globular clusters M 3 and M 92. The data were used for the optical identification of X-ray and radio sources, a new determination of the absolute proper and space motions of the globular clusters M 3 and M 92. Moreover, we derived an accurate proper and space motion of the sdB star PG 1716+426, located in the M 92 field.

Key words: stars: individual: PG 1716+426 – globular clusters: individual: M 3 – globular clusters: individual: M 92

1. Introduction

The importance of Hipparcos as a new tool for the determination of distances of stars with implications for the complete distance scale in the universe has been stressed in recent publications. Among the applications using distances or proper motions from the satellite mission, Hipparcos has also provided a net of very accurate reference stars for photographic astrometry. Possible applications of this new reference system range from solar system measurements up to the determination of the kinematics of globular clusters.

In this paper we will give an example of the use of Hipparcos stars for the determination of positions and proper motions of stars in the fields of the globular clusters M 3 and M 92. Since astrometric reduction is normally done for the stars of the complete field, positions and proper motions for different objects and topics are obtained. We will demonstrate three applications: the optical identification of radio and X-ray sources; the determination of space motions of two globular clusters and the determination of the galactic orbit of an sdB star.

2. Determination of positions and proper motions of the stars

First results of absolute proper motions in the fields of globular clusters using Hipparcos reference stars were published by Geffert et al. (1997) and Odenkirchen et al. (1997). However, the absolute proper motions of M 3 and M 92 used in Odenkirchen et al. (1997) were determined by calculating only mean corrections of the differences of the proper motions of the Hipparcos reference stars to the PPM stars and shifting the proper motions from Tucholke et al. (1994, 1996). In this study we have undertaken a complete new reduction of the data used by Tucholke et al. (1994, 1996). The plate material and the scanning of the plates was already discussed in Tucholke et al. (1994, 1996). Here five Hipparcos reference stars (ESA 1997) were used in the first step of the iterative reduction of the M 3 field and seven Hipparcos stars for the M 92 field. A comparison of the proper motions of the final catalogues with the Hipparcos data showed a rms of the deviations of less than 1 mas/yr. Due to large deviations (5 mas/yr) in the proper motion we have omitted Hipparcos star No. 66770 in the reduction of the M 3 field. After three iteration steps we obtained a catalogue of 758 stars in the field of M 3 and a catalogue of 1606 stars in the field of M 92 with Hipparcos based positions and proper motions.

3. Application 1: optical identification of radio and X-ray sources

3.1. *On the optical identification of the central radio source in M 3*

Since Hipparcos provides absolute positions more suited than any other reference system for photographic astrometry, we have reexamined the optical identification of the central radio source in M 3 found by Kulkarni et al. (1990). In a first step 90 reference stars of our catalogue were used to determine spherical coordinates from the data of Ferraro et al. (1997). Since their positions were truncated at the 100 mas level, the accuracy is limited to the same value. We found a rms of the deviations of their positions from our catalogue of the same value. In a second step the HST-data of Guhathakurta et al. (1994) (GYBS) were linked to the Hipparcos system by 170 tertiary reference stars from the catalogue mentioned above. The final error of the positions is of the order of 100 mas. From this uncertainty and from the uncertainty of the radio position of 150 mas, we

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Table 1. Candidates selected from Guhathakurta et al. (1994) (GYBS) for the optical counterpart of the central radio source of M 3 from Kulkarni et al. (1990). The differences are given in the sense radio position minus our position.

Star	α_{2000} [hhmmss.sss]	δ_{2000} [ddmmss.ss]	$\Delta_{\alpha cos\delta}$ [mas]	Δ_{δ} [mas]
GYBS 1124	134211.399	+282237.83	+480	+840
GYBS 1165	134211.432	+282238.33	+40	+340
GYBS 1178	134211.445	+282238.10	–130	+570
GYBS 1196	134211.452	+282239.36	–230	–690
GYBS 1203	134211.457	+282239.14	–290	–470

would expect a positional coincidence of 180 mas for a possible identification.

Table 1 gives all stars from GYBS, which are located within R $< 1''$ from the position of the radio source. The positions in Table 1 may also be used for the determination of the spherical coordinates of any other object in the catalogue of Guhathakurta et al. (1994). In an earlier investigation Laget et al. (1998) used HST/WFPC2 observations and secondary reference stars from the APM survey based on the PPM catalogue to identify the radio source. Based on our astrometry we may rule out candidate GYBS 1247 proposed by Laget et al. (1998) as optical counterpart of the radio source and even GYBS 1196 seems to be very unlikely due to its separation of 700 mas from the radio source. Only star GYBS 1165 has a separation of less than 3σ from the radio source. However, since this star is an ordinary cluster star, it seems in our opinion very likely, that the radio source does not have an optical counterpart up to the limiting magnitude of the study of Guhathakurta et al. (1994). Our result would place the position of the radio source a few 100 mas in western direction in Fig. 1 of Laget et al. (1998). We note from a comparison of our data with Fig. 1 of Laget et al. (1998), that there exists another star with nearly the same separation from the position of the radio source as GYBS 1165 but not measured by Guhathakurta et al. (1994).

3.2. Optical identification of X-ray sources in the field of M 3

X-ray sources and their optical identifications may give valuable information about the nature of double stars in globular clusters. However, the optical identification of ROSAT X-ray sources suffers from a possible shift up to $10''$ in the X-ray positions. Therefore it is also important to identify X-ray sources in the field of globular clusters. If several sources were identified, a systematic shift and the accuracy of the X-ray positions can be determined.

Hertz et al. (1993) have detected six X-ray sources in the field of the globular cluster M 3. Two of them (B,C) were identified as background quasars, which previously also were known as radio souces (see references in Hertz et al. 1993). From a search in Simbad we found an additional identification of source E with a quasar from the list of Hook et al. (1996). For all three quasars an accurate radio position is given in the FIRST survey (White et al. 1997).

Since all quasars are too faint to be members of our catalogue from Sect. 2, we have determined optical positions of these objects by the use of the APM scans of the POSS and secondary reference stars from our study. Positions of the APM survey were transformed to rectangular coordinates and reduced with about 20 stars from our catalogue from Sect. 2. From the rms of the deviations of the APM data from our catalogue, we obtained a precision of 200 mas for each quasar position. Table 2 gives our optical positions for the three quasars and the differences to the radio and X-ray position.

While the optical and radio positions in Table 2 agree on the level of better than $1''$, the X-ray positions are only accurate to 3–$5''$. For the identification of the central X-ray source A we have therefore within an error circle of $5''$ more than 30 candidates from our catalogue from Sect. 3.1. No corresponding radio source from the FIRST survey (White et al. 1997) and no corresponding UV object in M 3 from the data of Whitney et al. (1995) was found. Note that objects 21 and 23 from Whitney et al. (1995) correspond to the stars 1849 and 13049 from Ferrero et al. (1997).

Although in general we cannot rule out that the X-ray source A has no optical counterpart or a counterpart not distinguishable from a normal star, we note that there exists a blue (F10688) and a variable object (F10537 = Sawyer V224) among our candidates with distances from the X-ray source of $1\farcs9$ (F10537) and $4\farcs2$ (F10688). A final choice can be made, when a more accurate X-ray position of source A is available, or coincident variability in the optical and X-ray is measured.

3.3. Identification of X-ray sources in the field of M 92

Johnston et al. (1994) have detected in ROSAT PSPC observations 13 X-ray sources in the field of M 92. Six of them were also observed with ROSAT HRI by Fox et al. (1996). The identifications given in their Table 1 do not correspond to galactic foreground stars, as quoted by the authors, but are cross identifications to the objects from Johnston et al. (1994). Moreover, source B and C from Fox et al. (1996) correspond to the sources no. 6 and 8 from Johnston et al. (1994).

Fox et al. (1996) found an additional source (E) not visible in Johnston et al. (1994) and proposed V798 Her as its optical counterpart. V798 Her corresponds to star No 14 from Hachenberg (1939), who classified it as a W Uma system. Using the identification of Tucholke et al (1994) we have determined the difference of the X-ray and optical position, which is of the order of $14''$. No other object of our catalogue and of the FIRST survey (White et al. 1997) could be found within $R < 8''$ of any X-ray source. On the other hand, shifting the X-ray positions by the differences of our optical position of V798 Her to the X-ray position E we obtained three additional identifications (one radio source and two stars): X-ray source 4 from Johnston et al. (1994) corresponds to the radio source FIRST J171821.4+431523, while X-ray sources 1 and 10 could be identified with Tycho stars 3085 1254 (1) and 3081 510 (10).

Table 2. Optical Positions of three X-ray sources from Hertz et al. (1993), which could be identified with quasars. Differences to the radio positions from the FIRST survey (White et al. 1997) and differences to the X-ray positions (Hertz et al. 1993) are given in the sense ours minus others are given.

Quasar	α_{2000} [hhmmss.sss]	δ_{2000} [ddmmss.ss]	$\Delta X_{\alpha cos\delta}$ [$''$]	ΔX_{δ} [$''$]	$\Delta R_{\alpha cos\delta}$ [$''$]	ΔR_{δ} [$''$]
QSO 1339+2843	134210.890	+282847.08	–4.8	+1.5	–0.41	–0.67
QSO 1340+287	134254.414	+282806.52	–1.0	+3.1	–0.66	+0.60
QSO 1338+2831	134115.306	+281604.38	+4.7	–2.4	+0.20	–0.81

Table 3. Transformed positions of the X-ray sources of Johnston et al. (1994) (JVH) and source E from Fox et al. (1996) (FLMPV).

X-ray source	α_{2000} [hhmmss.sss]	δ_{2000} [ddmmss.ss]
JVH 1	171715.459	+432446.15
JVH 2	171729.932	+431933.96
JVH 3	171610.448	+431558.70
JVH 4	171821.352	+431516.22
JVH 5	171713.550	+431304.53
JVH 6	171701.565	+431042.79
JVH 7	171810.161	+430853.97
JVH 8	171707.454	+430813.67
JVH 9	171644.784	+430446.40
JVH 10	171632.800	+430228.67
JVH 11	171802.260	+425626.04
JVH 12	171648.668	+425453.22
JVH 13	171728.709	+425448.63
FLMPV E	171638.101	+431214.17

According to their colour index of the order of $B-V$=0.65 the latter objects seem to be foreground G stars. For X-ray source 4 from Johnston et al. (1994), we found a faint object on the POSS, which is located within $0\farcs7$ of the position of the radio source and which is more blue than other objects in that region. Using these identifications we were able to transform the X-ray positions of the sources of Johnston et al. (1994) and source E from Fox et al. (1996) to the radio/optical system. The rms of the deviations between the X-ray and optical/radio positions of our identified objects was $2''$. The transformed X-ray positions are given in Table 3. The transformation of the X-ray positions puts the core source of M 92 (JVH8) very near ($4''$) to the centre of M 92. An optical identification of this source, however, will be only possible by the use of HST data.

4. Application 2: space motion of globular clusters M 3 and M 92

Based on our new proper motions from Sect. 2 we determined new absolute proper motions of the globular clusters M 3 and M 92. The vector point plot diagram of each cluster region was fitted by a two-dimensional gaussian function according to Sanders (1971). Since the individual membership was discussed earlier (Tucholke et al. 1994, 1996) and since the parameters of the gaussian fitting (except the centers of the cluster and field motion) were similar to the previous studies, we will restrict ourself here to the absolute proper motion of M 3 and M 92. Table 4 gives our new absolute proper motions together with differences to the previous determinations of Cudworth & Hanson (1993) and Scholz et al. (1993, 1994).

Table 4. Hipparcos calibrated absolute proper motions of M 3 and M 92 and differences to the earlier determinations of Cudworth & Hanson 1993 (CH), and Scholz et al. 1993, 1994 (S93, S94) in the sense ours minus others.

Object	$\mu_{\alpha}cos\delta$ [mas/yr]	μ_{δ} [mas/yr]	$\Delta_{\mu_{\alpha}}cos\delta$ [mas/yr]	$\Delta_{\mu_{\delta}}$ [mas/yr]	
M 3	–1.2	–3.2	0	–5.6	CH
	±0.8	±0.8	±2.6	±3.1	
			1.9	–0.9	S93
			±0.8	±0.9	
M 92	–4.4	–1.4	0.2	–0.8	CH
	±0.9	±0.9	±1.4	±2.0	
			0.0	–2.5	S94
			±1.1	±1.0	

Our absolute proper motions are in very good agreement with the data of Scholz et al. (1993, 1994) and, with exception of the declination component of M 3, also in good agreement to the data of Cudworth & Hanson (1993). Note, that the errors of the absolute proper motion of M 3 from Cudworth & Hanson (1993) are untypical large for their study. The coincidence between the different determinations of absolute proper motions of M 92 based on three different techniques is remarkable!

Using distances and radial velocities from the compilation of Harris (1996) we have determined the space velocity components of M 3 and M 92 in a system of galactic standard at rest and –based on a logarithmic potential of the Milky Way– peri- and apogalactic distances (R_p, R_a), eccentricity (e) and z-component of the angular momentum (I_z). These data are given in Table 5. Both clusters are near their apogalactic distance on a prograde orbit. A more detailed discussion of the kinematics of globular clusters including M 3 and M 92 based on Hipparcos reference stars will be given later.

Table 5. Velocity components in a system of galactic standard at rest and kinematical data of the orbits of globular clusters M 3 and M 92 using a simple logarithmic galactic mass model. (Note that U points from Sun to galactic centre!). In addition, velocity components and kinematical data for the sdB star PG 1716+426 are given (see Sect. 5). A positive z component of the angular momentum indicates a prograde rotation in the galaxy.

Object	U [km s^{-1}]	V [km s^{-1}]	W [km s^{-1}]	R$_a$ [kpc]	R$_p$ [kpc]	e	I$_z$ [kpc km s^{-1}]
M 3	+41 ±30	+63 ±25	–123 ±10	14.2 ±0.8	2.5 ±1.4	0.71 ±0.15	+500 ±200
M 92	+7 ±30	+30 ±20	+72 ±25	10.1 ±0.3	1.3 ±0.6	0.76 ±0.07	+228 ±140
PG 1742+426	+128 ±40	+211 ±30	–44 ±30	12.5 ±3.0	6.2 ±0.8	0.33 ±0.9	+1832 ±200

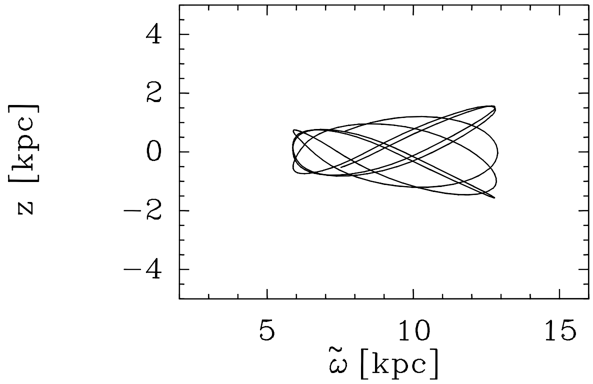

Fig. 1. The meridional section of the orbit of PG 1716+426 calculated backwards over 1 Gyr.

5. Application 3: proper and space motion of PG 1716+426

PG 1716+426 is a blue subdwarf located by chance in the direction to the globular cluster M 92. Its absolute proper motion with respect to Hipparcos reference stars was also determined within this study. Theissen et al. (1993) have classified its spectrum as a sdB type and determined its distance to d = 1200 ±300 pc from the sun. Together with the heliocentric radial velocity of –10.6 ±30 km s^{-1}(Theissen 1991) and our proper motion of $\mu_\alpha cos\delta$= +7.1 ±1 mas/yr and μ_δ= –21.8 ±1 mas/yr we were able to determine the space motion and the orbit of PG1716+426 in the galaxy according to the method developed by Allen & Santillan (1991). The kinematical data of PG 1716+426 are presented also in Table 5. The errors of these quantities are mainly caused by the uncertainty of the distance and the radial velocity of the star. Fig. 1 shows the meridional section of the orbit of PG 1716+426 calculated backwards over 1 Gyr. The orbit of PG 1716+426 does not extend far from the galactic disk ($z < 2$ kpc) and is similar to the orbits found in a study of the kinematics of sdB stars (de Boer et al. 1997). In future, the high accuracy of the proper motions of 1 mas/yr, which corresponds at a distance of PG 1716+426 to 6 km s^{-1}, will –in combination with precise radial velocities– allow a more precise determination of the kinematics of subdwarfs or other astrophysically interesting stars as was possible before Hipparcos reference stars became available.

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