Astron. Astrophys. 333, 531–539 (1998)

ASTRONOMY
AND
ASTROPHYSICS

New space motion of Galactic globular cluster Palomar 5

R.-D. Scholz[1], **M. Irwin**[2], **M. Odenkirchen**[3], **and H. Meusinger**[4]

[1] Astrophysikalisches Institut Potsdam, Sternwarte Babelsberg, An der Sternwarte 16, D-14482 Potsdam, Germany
[2] Royal Greenwich Observatory, Madingley Road, Cambridge CB3 OEZ, UK
[3] Observatoire de Bordeaux, CNRS/INSU, BP 89, F-33270 Floirac, France
[4] Thüringer Landessternwarte Tautenburg, D-07778 Tautenburg, Germany

Received 30 October 1997 / Accepted 9 February 1998

Abstract. A new space motion of the Galactic globular cluster Pal 5 has been obtained on the basis of the proper motion determination from 11 Schmidt plates with a time baseline of 39 years. A field of 1 square degree with nearly 400 galaxies defining the absolute reference frame has been used in the differential astrometry from plate-to-plate solutions. Residual systematic errors after the solutions with 2×6 plate constant polynomials have been investigated and removed. Typical proper motion errors of 2 to 3 mas/yr were obtained for individual stars with magnitudes $12 < B < 20$. Although our result for the mean absolute proper motion of Pal 5 $(\mu_\alpha, \mu_\delta) = (-1.0 \pm 0.3, -2.7 \pm 0.4)$ mas/yr looks similar to the result of Schweitzer, Cudworth & Majewski (1993) based on different observations and reduction technique, the direction of the space motion we derive is completely different from theirs. Although the position of Pal 5 is near the orbital plane suggested for the Sagittarius dwarf galaxy by Ibata et al. (1997), both proper motion results suggest a total space velocity of Pal 5 significantly different from that to be expected from a tidally stripped fragment of the Sgr dwarf galaxy. In addition, our direction of motion of Pal 5 is almost in the opposite sense to that of the Sgr galaxy. Our Galactic orbit determination of Pal 5 and the star counts on the deep Schmidt plates indicate a smaller tidal radius of this globular cluster compared to previously published data of Webbink (1985) and Trager, King & Djorgovski (1995).

Key words: globular clusters: individual: Pal 5 – methods: statistical – astrometry – stars: kinematics – Galaxy: kinematics and dynamics

1. Introduction

The kinematics of the Galactic globular clusters and of local galaxies are of great interest with regard to a number of issues related to the formation history of the Galaxy, its dark matter content, and the dynamical evolution of stellar systems (for a more detailed discussion see e.g. Majewski & Cudworth 1993). We have shown that the use of full-scanned Schmidt plates allows the direct and accurate measurement of the cluster proper motions against the absolute reference frame represented by large numbers of galaxies. From APM scans of Tautenburg Schmidt plates with 25 years baseline we have obtained mean absolute proper motions of the Galactic globular clusters M 3 and M 92 with an accuracy of 0.5 mas/year and used the results for the determination of Galactic orbits (Scholz, Odenkirchen & Irwin 1993, 1994). Extending our work to the dSphs in Draco and Ursa Minor with very large distances ($\sim$ 70 kpc) we combined APM measurements of POSS 1 glass copies, second epoch Palomar and third epoch Tautenburg Schmidt plates (Scholz & Irwin 1994). In a continuation of our programme to investigate the proper motion of Galactic halo globular clusters, we have used the APM facility to directly determine the tangential motion of the globular clusters M 5, M 12 and M 15 from Palomar, Tautenburg and UKST plates (Scholz et al. 1996).

For the very interesting case of M 5 we obtained a smaller absolute proper motion still leading to a high space velocity but not to the extremely large value known till now (cf. Cudworth & Hanson 1993). Whereas the presently observed Galactocentric distances of M 3, M 92, M 12 and M 15 are typical for their calculated orbits, we conclude from our results that M 5 is apparently an outer halo cluster only briefly visiting the nearer regions.

With a heliocentric distance of 21.8 kpc (Harris 1996) the globular cluster Pal 5 is one of the more distant clusters within our programme. There is a special interest in Pal 5 since it has such a low space motion according to the results of Schweitzer, Cudworth & Majewski (1993) who obtained an absolute proper motion of the cluster with respect to a reference frame of only $\sim$ 20 background galaxies. As the corresponding space velocity vector is exactly perpendicular to its radius vector to the Galactic center, Schweitzer, Cudworth & Majewski conclude a rather eccentric orbit with the present locus of Pal 5 likely at apogalacticon.

Both the sparse appearance of the cluster Pal 5 and its stellar mass function (Smith et al. 1986) are likely explained by advanced destruction due to Galactic tidal forces. Owing to its orbital parameters, it seems possible that Pal 5 is on one of its last orbits before total dissolution. Therefore, Pal 5 is considered as an ideal example for detailed dynamical studies of such

---

Send offprint requests to: R.-D. Scholz

a destruction process (Smith & Miller 1995). Accurate space velocity data are necessary ingredients for such investigations.

Moreover, the understanding of the dynamical history, and therewith the accurate knowledge of the orbital parameters are also relevant to the chemical evolution of globular clusters: Enrichment of cluster stars by accretion of the ejecta from the intermediate-mass stars (Bell et al. 1981) depends on the strength of cluster winds and, therefore, on the evolution of the depth of the gravitational potential. The extremely low mass of the cluster Pal 5 makes it an important test for the hypothesis of such self-enrichment. If Pal 5 was not much more massive in the past than at present accretion is not a likely origin for CN-enhanced stars in this cluster (Smith 1985, 1996).

Following Zinn's (1993) classification of globular clusters Pal 5 belongs, with [Fe/H] ≈ -1.4 and a an anomalously red horizontal branch (Smith 1985), to the "younger halo" class. According to the halo formation scenario by Searle & Zinn (1978) these objects have been suggested to be formed in separate fragments which did not participate in the initial halo collapse (e.g. Lin & Richer 1992; Majewski 1993, and references therein) but were captured more recently by the Galaxy. The recent discovery of the disrupting Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1994) has strongly reinforced this point of view. Globular cluster streams perhaps indicating such satellite accretion have been suggested by Lynden-Bell & Lynden-Bell (1995).

At the Donald Lynden-Bell 60th birthday conference Pal 5 has been suggested as a candidate stripped globular cluster from the Sagittarius dwarf galaxy (Lin 1996). But although the position of Pal 5 is near the orbital plane suggested for the Sagittarius dwarf by Ibata et al. (1997) the stripping scenario seems highly unlikely for Pal 5 with respect to its low space motion.

So, we decided that it would be useful to verify the Schweitzer, Cudworth & Majewski (1993) result by other observations and reduction methods. In our opinion measuring large numbers ($\sim$ 1000) of reference galaxies, cluster stars and field stars in one measuring process yields a better estimate and correction of systematic errors and should, therefore provide the most reliable results.

2. Observations and measurements

In order to get a better accuracy in the proper motion determination of Pal 5 we used more deep plates from the UKST archive in addition to the plates earlier measured with the APM facility in Cambridge (two POSS 1, one UKST and two Tautenburg plates). Altogether, 10 plates were measured with the APM facility (see Table 1). The POSS 1 plates and the UKST plate j5193 had already been used in the determination of the absolute proper motion of the globular cluster M 5 (Scholz et al. 1996) which is located near to the northern edge of the UKST plates listed in Table 1. All measured objects were classified into stars, nonstellar objects, noise images and merged objects using the standard APM software.

On all plates listed in Table 1 the globular cluster Pal 5 is more than 1 degree from the plate edges so that in principle a large, e.g. $2.5° \times 2.5°$ field could be used in the reduction. Nevertheless, we selected a smaller, 1 square degree region centered on Pal 5 ($\alpha(2000) = 15^h16^m4.9^s, \delta(2000) = -0°6'13''$), in order to reduce the systematic effects in combining the plates of different Schmidt telescopes. However, the removal of systematic errors is the most extensive part of the proper motion reduction, described in Sect. 3.1.

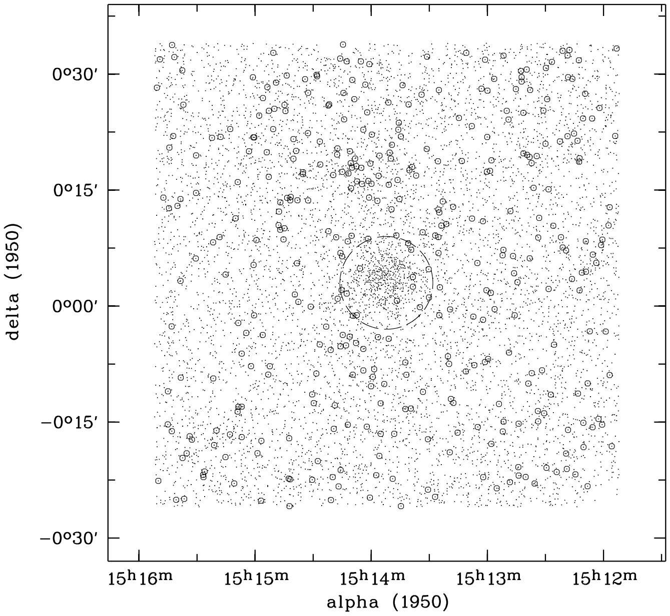

Fig. 1. The 1 square degree field around the globular cluster Pal 5 used in the proper motion determination. About 8000 objects measured on at least 3 out of 11 Schmidt plates are shown. The dashed circle shows the cluster region with a radius of 6 arcmin. The open circles denote the positions of the galaxies used to define an inertial reference frame.

Table 1. Plate material

Telescope/ Plate No.	pass-band	epoch [year]	Δt_{exp} [min]	scale [arcsec/mm]
POSS 1/o1402	U+B	1955.30	12	67.2
POSS 1/e1402	R	1955.30	45	67.2
UKST/j1721	B	1975.58	60	67.2
UKST/j5193	B	1979.54	75	67.2
UKST/r5201	R	1979.55	80	67.2
UKST/r9115	R	1984.19	80	67.2
UKST/or13078	R	1989.29	100	67.2
UKST/or14989	R	1992.41	60	67.2
Tautbg/8600	B	1994.27	30	51.4
Tautbg/8626	B	1994.35	27	51.4
POSS 2/sf05770*	R	1994.37	65	67.2

* FITS frame taken from the Digitised Sky Survey

In addition to the plates measured with the APM facility in Cambridge, the data of the second epoch Palomar survey plate were received from the Digitised Sky Survey. For the image detection and determination of image parameters in this 1 square degree FITS frame we used the software developed for the Münster Redshift Project (Horstmann et al. 1989).

The internally calibrated instrumental APM magnitudes (Bunclark & Irwin 1983) measured on the blue reference plate j5193 were transformed to approximated B magnitudes with photoelectric standards in the globular cluster M 5 from Arp (1962). From 21 standards identified only 15 with stellar classification on the plate j5193 were included in the external magnitude calibration using a linear polynomial fit.

From several runs of the plate matching with different reference plates and the number counts of matched objects plate j5193 was found to be the deepest plate with a limiting $B \approx 22$ and was therefore used as the reference plate for the proper motion study.

The Tautenburg plates have a better scale for astrometric work (and for the classification of merged objects) but their limiting $B \approx 20$ is about 1-2 magnitudes below the limiting magnitude of the other Schmidt plates used in this study.

3. Determination of absolute proper motions

With respect to the available plate material, i.e. with a relatively wide spread of observation epochs, we followed the same principles of the proper motion determination as in our extended work in the field of the globular cluster M 3 (Scholz, Meusinger & Irwin 1997). The idea is to build up a time series of coordinates for each single object measured on n plates. Within the plate matching process objects measured on the comparison plates are identified with objects measured on a deep reference plate. The plate matching is done iteratively starting with bright objects and large search radii (up to several mm), finally iterating down to faint objects within a target search radius of about 30μm, corresponding to 2 arcsec in the scale of the UKST reference plate.

All matched objects are used in a plate-to-plate solution for transforming the measured coordinates on the comparison plate into the coordinate system of the reference plate. After removing residual mean positional differences between the transformed coordinates and the coordinates on the reference plate as a function of the field position (for more details see Sect. 3.1), a zero point correction is applied by subtracting the mean coordinate difference of all available galaxies measured on the comparison plate and on the reference plate (see Sect. 3.2). The absolute proper motion of each object is then determined from the linear regression of the coordinates $(x, y)_j$ over the epochs Ep_j, with $j = 1...n_{pl}$, where the number of plates n_{pl} for a given object is mainly dependent on its magnitude. The advantage of this method are the large numbers of objects used in the differential plate-to-plate solutions. It is independent of an external reference catalogue (and the errors of such a catalogue).

3.1. Systematic error removal

The error correction is a substantial part of the reduction in the differential astrometry with full-scanned Schmidt plates. For a detailed description of the error reduction technique developed for the correction of APM scans of Schmidt plates see Evans (1988) and Evans & Irwin (1995). We followed the same principles in our systematic error removal, i.e. we applied a two-dimensional and one-dimensional correction of errors as a function of field position. The basic assumption of this technique is a constant motion over the whole field of all objects used in the error reduction. The central globular cluster region ($r < 3$ arcmin), all faint objects ($B > 19.5$) as well as the bright objects ($B < 12$) were excluded from the sample of objects used for the determination of the corrections.

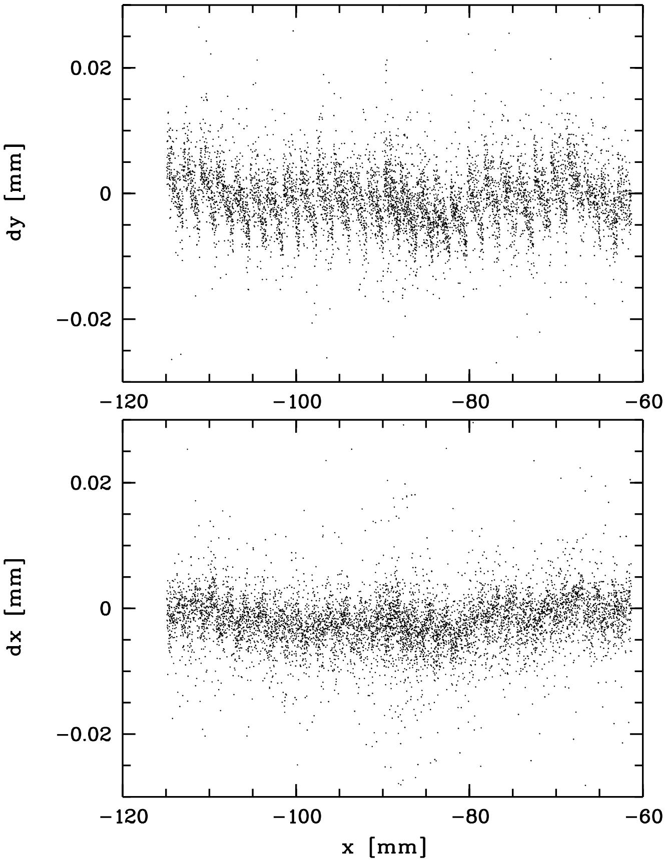

Fig. 2. Residual errors after the plate-to-plate solution with quadratic 2×6 plate constant polynomial and before any correction. As an example the differences dx and dy between the coordinates on the reference plate j5193 and the comparison plate or13078 as a function of the x-coordinate are shown. There are no y-dependent periodic errors due to the APM.

In this process we remove periodic errors of the measuring machine as well as residual distortions after a global plate-to-plate solution. These distortions are expected to be larger in the case of Schmidt plates from different telescopes taken with different plate centres. The measuring coordinate frame of each comparison plate was therefore transformed to that of the reference plate by using a quadratic 2×6 instead of the linear 2×3 plate constant polynomial relationship, usually applied in plate-to-plate solutions of Schmidt plates of the same telescope taken with similar conditions.

Although the residual systematic errors after the quadratic polynomial transformation are considerably reduced in comparison to the linear polynomial transformation we first used

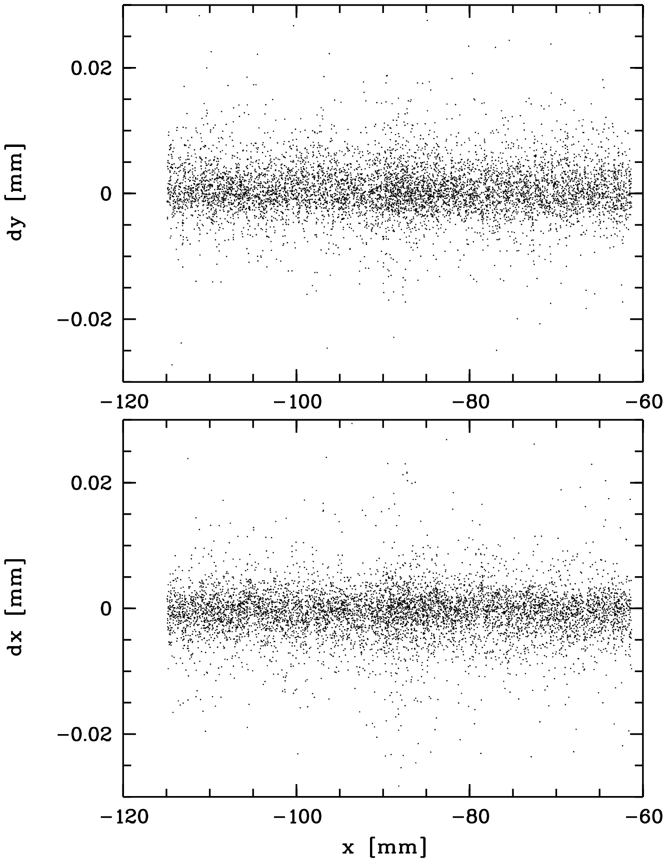

Fig. 3. Residual errors after the two- and one-dimensional error removal (cf. previous figure).

a two-dimensional error correction. The two-dimensional correction is done by binning the whole field into subareas and simply subtracting the mean shift $\Delta x = x_{ref} - x_{comp}$ and $\Delta y = y_{ref} - y_{comp}$ separately for each subarea and for each pair of comparison/reference plates. In our case we binned the 1 square degree field into 8 × 8 subareas.

After the two-dimensional error correction removing large scale systematic effects we applied a one-dimensional error correction removing the periodic errors of the APM in dependence on the x-coordinate. A detailed description of these errors can be found in Evans (1988) and Evans & Irwin (1995). There are no periodic errors of the APM as a function of the y-coordinate.

As an example, Fig. 2 shows the uncorrected coordinate differences as a function of the x-coordinate for the plate or13078 with respect to the reference plate j5193. The result of the two- and one-dimensional error correction is seen in Fig. 3.

Note that all corrections are carried out with respect to the reference plate, i.e. differentially. This technique works well in the differential determination of proper motions from plate-to-plate comparisons but does not improve the determination of equatorial coordinates by the use of an external reference catalogue with an object density far below the measured object density on the Schmidt plates.

Throughout the paper we use x- and y-proper motion components, which are equal to μ_α and μ_δ in this zero declination field.

3.2. Selection of reference galaxies

The reference galaxies defining the absolute reference frame in our 1 square degree field were carefully selected using the 4 deepest R plates with first priority. The APM image classification becomes uncertain near the plate limits. Therefore, we selected all objects classified as galaxies on at least three out of four deep R plates. All objects classified as merged on at least one of the 10 APM measured plates were excluded from the sample of galaxies. The FITS frame of the POSS 2 plate was used for a visual check of the automated image classification using the MRSP software (Horstmann et al. 1989). 384 reference galaxies were selected. Their distribution over the field is shown in Fig. 1.

The central region ($r < 3$ arcmin) of the globular cluster was excluded in the selection of reference galaxies due to crowding effects. For comparison with our selection of reference galaxies, we have also looked for galaxies in the NASA/IPAC extragalactic database (NED). North from the globular cluster, at $\alpha(1950) = 15^h 13^m 48^s, \delta(1950) = +0°17'$ there is a known cluster of galaxies, Abell 2050, also seen in our selection (Fig. 1).

The absolute zero point shift was determined for each comparison plate with respect to the reference plate using all available galaxies (from 384) measured on the comparison plate. The formal zero point error varied in dependence on the number of galaxies (only 50 galaxies on the Tautenburg plates but from 230 to 375 galaxies on the other comparison plates) and on their measuring accuracy on the comparison plate and on the reference plate. The zero point error was about 70 mas for the Tautenburg plates and < 30 mas for all other comparison plates.

3.3. Internal accuracy of proper motions

The x- and y-components of the absolute proper motion of each individual object were obtained from the linear regression of all available x- and y-coordinates of this object over the time. The coordinates were used independently of the image classification of the object. No weights were given to the different plates the object was measured on.

Measurements on at least three plates were required for the determination of the proper motion of an object. The final catalogue of proper motions contains nearly 8000 objects in a 1 square degree field centered on the globular cluster Pal 5. Their internal errors as obtained from the linear regression of min. 3 to max. 11 data points are shown in Fig. 4 (mean errors as a function of magnitude) and Fig. 5.

On the average the errors of objects with stellar classification on the reference plate are about 1 mas/yr smaller than the overall proper motion errors.

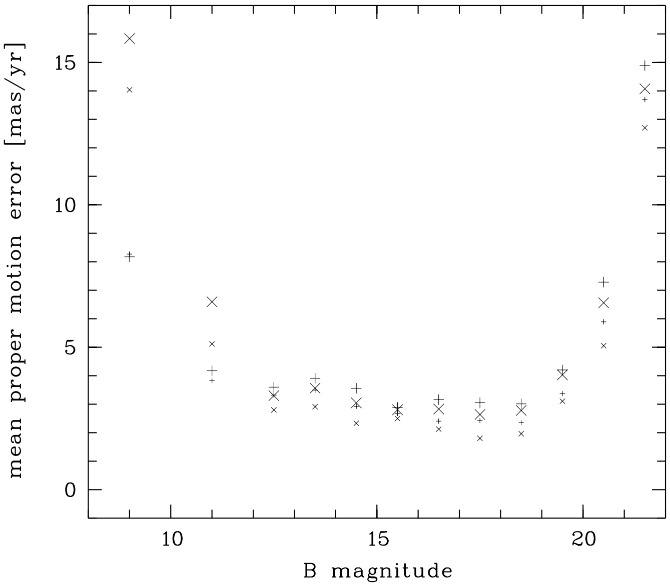

Fig. 4. Mean proper motion errors as a function of magnitude. The individual proper motion errors of the bright objects ($B < 12$) were binned in two intervals of 2 mag width, whereas the binning for fainter objects was done using a width of 1 mag. The × and +, respectively show the internal proper motion errors in μ_x and μ_y for all objects measured on at least three plates. Smaller symbols represent mean proper motion errors of objects with stellar classification on the reference plate.

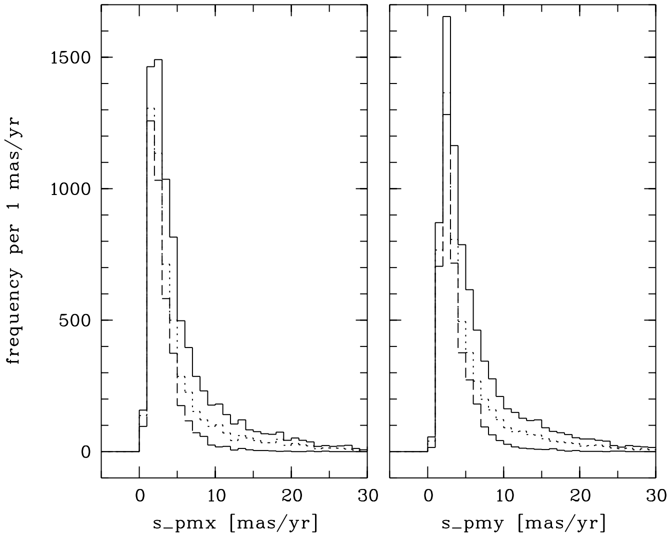

Fig. 5. Histogram of internal proper motion errors in μ_x and μ_y for all objects measured on at least three plates (solid line), objects with stellar classification on the reference plate and with measurements on at least three plates (dotted line) and star-like objects measured on more than 6 plates (dashed line).

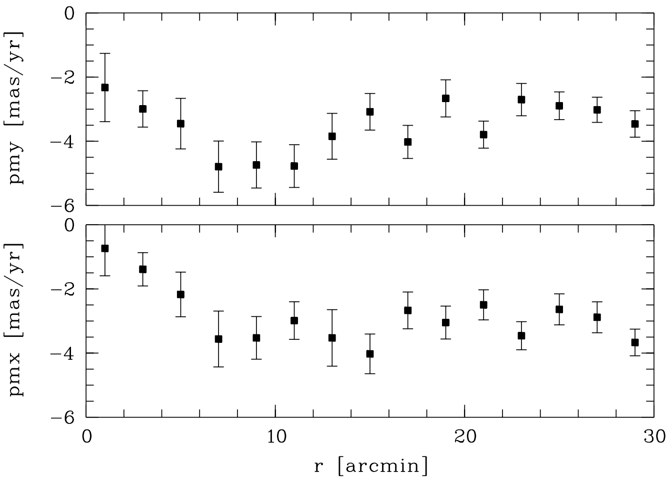

Fig. 6. Mean proper motion of all star-like objects in the magnitude interval $16.5 < B < 21.0$ measured on at least 5 plates with internal proper motion errors < 12 mas/yr as a function of the distance from the cluster centre. The data were binned in radial annuli of 2 arcmin width around the cluster. Error bars show the error of the mean proper motion in an annulus.

4. Mean absolute proper motion of the cluster

Due to the large heliocentric distance of Pal 5 and the moderate accuracy in the proper motions of individual stars (in comparison to the high accurate relative proper motion studies of many Galactic globular clusters by Cudworth and coworkers, e.g. Schweitzer, Cudworth & Majewski 1993) we have not tried to obtain membership probabilities. For the determination of the mean absolute cluster proper motion μ_c we averaged the proper motions of all stars within a given cluster radius r_c and corrected the result μ_{c+f} for the contamination with field stars in the selected cluster region:

$$\mu_c = (1 + n_f/n_c)\mu_{c+f} - (n_f/n_c)\mu_f \tag{1}$$

The number of contaminating field stars in the cluster region n_f was estimated from the comparison of the number density in the cluster region with that of the field stars outside the cluster region. The mean absolute proper motion of the field stars μ_f can be determined very accurately due to their large numbers in a sufficiently large sky region between r_{f1} and r_{f2} outside the globular cluster ($r_c < r_{f1} < r_{f2}$).

Systematic errors are always a significant concern in proper motion reductions. Therefore, several selection criteria for the objects used in the determination of the mean absolute cluster proper motion were tested and the results from different samples of objects compared:

- number of observations per star
- internal proper motion accuracy
- image classification
- radius of the cluster region r_c
- field region between r_{f1} and r_{f2}
- magnitude interval (in order to investigate possible systematic errors as function of magnitude)

Fig.6 shows as an example the mean absolute proper motion as a function of cluster radius for all objects in the magnitude interval $16.5 < B < 21.0$, classified as stars on the reference plate, measured on at least 5 plates, with proper motion errors less than 12 mas/yr.

According to the observed radial density profile of the globular cluster (Fig. 7a and b) the cluster region with $r_c < 6$ arcmin contains almost all cluster stars. On the other side, the number of cluster stars in a sufficiently large field region, e.g. between $r_{f1} = 10$ arcmin and $r_{f2} = 24$ arcmin can be neglected in the determination of the mean absolute proper motion of the field stars μ_f. However, a contamination of the field star sample with galaxies has to be considered.

The tidal radii of Pal 5 given in the literature are relatively large: 18.2 arcmin according to Webbink (1985) and 15.9 arcmin according to Trager, King & Djorgovski (1995). However, the slightly increased number density from 10 arcmin to 18 arcmin in comparison to the region outside $r > 18$ is obviously not an indication of the tidal radius of Pal 5 but caused by the galaxy cluster Abell 2050. This can be seen in the comparison of the radial density profile for objects with stellar classification with those for objects with non-stellar classification and for merged objects (Fig. 7a and ba). The image classification near the plate limits is problematic so that a relatively large fraction of galaxies can be expected among the faint objects measured on the deep Schmidt plates with stellar classification.

Due to strong image crowding in dense globular clusters, such as M 3 or M 5, there is a central minimum in the density profiles of these clusters measured on deep Schmidt plates, i.e. the core region can not be resolved into single objects. Unless the Pal 5 cluster centre can be resolved on the Schmidt plates, the image crowding causes some problems. As seen in Fig. 7a, there is a concentration of objects with non-stellar and merged classification, which is in the sum even larger than the central density of stellar objects. On the other hand, as a result of image crowding there is no concentration of the faintest objects toward the cluster centre (Fig. 7b).

In order to reduce systematic effects in the determination of the mean absolute proper motion of the cluster due to image crowding and different contamination of the cluster and field stars with galaxies, the objects with non-stellar classification and all faint objects ($B > 21$) were not used. In dependence on further parameters describing the reliability of the proper motion determination of single stars the number of cluster stars n_c in the magnitude interval $16 < B < 21$ and with $r_c < 6$ arcmin varied from 250 to 100. The ratio n_f/n_c varied between 1/2.5 and 1/1.

The mean result of the absolute cluster proper motion from about 20 alternative computations changing the selection criteria - internal proper motion errors of single stars, number of plates they were measured on, smaller magnitude intervals - was: $(\mu_\alpha, \mu_\delta) = (-1.0 \pm 0.3, -2.7 \pm 0.4)$ mas/yr. All single runs yielded a result within the given errors which were also comparable to the formal errors of each computation. No systematic magnitude dependent effects were found.

Our results and the results of Schweitzer, Cudworth & Majewski (1993) $(\mu_\alpha, \mu_\delta) = (-2.44 \pm 0.17, -0.87 \pm 0.22)$ mas/yr look superficially similar in heliocentric terms. However, the results differ at the 4-sigma level in both μ_x and μ_y, using the quadratically combined errors to estimate sigma. If we compare the results in Galactocentric terms, i.e. ours: $(0.50, -1.05)$ mas/yr versus theirs: $(-0.94, 0.78)$ mas/yr we see that the direction of the space motion we derive is completely different from theirs.

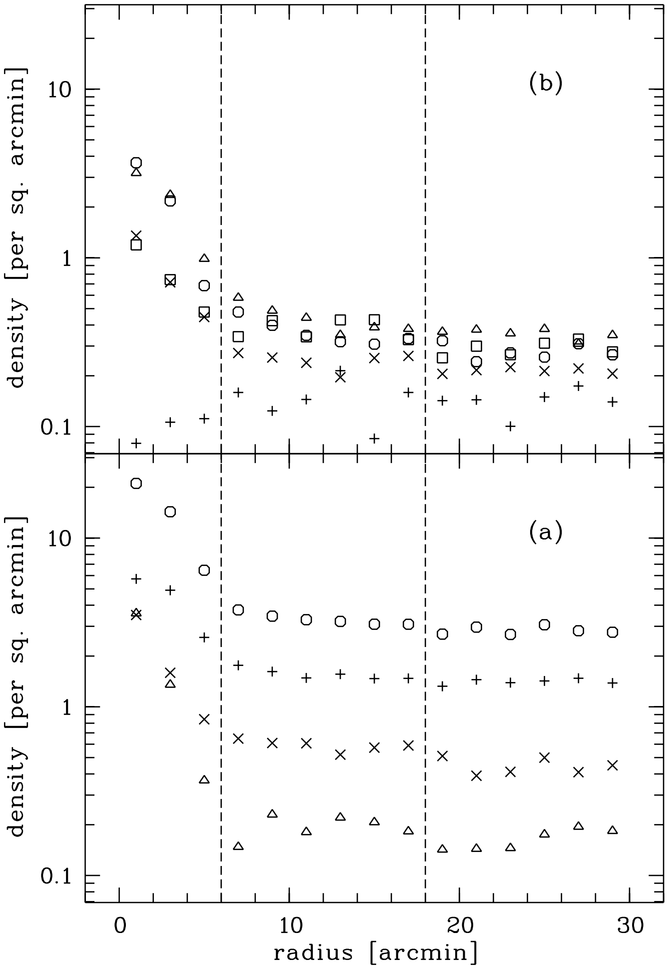

Fig. 7a and b. Radial density profile obtained from counts in annuli around Pal 5 with a width of 2 arcmin. **a** in dependence on image classification: all objects measured on the reference plate (open circles), objects with stellar classification with additional measurements on at least two other plates (+), non-stellar classification (×), merged objects (triangles). **b** all faint objects measured on the reference plate and at least two other plates: $B > 21.5$ (+), $21.0 < B \leq 21.5$ (triangles), $20.5 < B \leq 21.0$ (open boxes), $20.0 < B \leq 22.5$ (open circles), $19.5 < B \leq 20.0$ (×). The dashed lines show the cluster region ($r < 6$ arcmin) used in the determination of the mean cluster motion and the tidal radius of 18 arcmin according to Webbink (1985).

5. Space motion and Galactic orbit of Pal 5

Knowing the cluster's absolute proper motion and also its distance ($d = 21.8 \pm 2.2$ kpc, Harris 1996) and radial velocity ($v_r = -56 \pm 4$ km/s, Smith 1985) with respect to the Sun, we finally proceed to its motion in three-dimensional Galactic space. On the assumption of $R_\odot = 8.5$ kpc for the distance Sun - Galactic center and $v_{LSR} = 220$ km/s for the rotation of the local standard of rest (IAU 1986) and with the 'basic solar motion' of Delhaye (Mihalas & Binney 1981) as a reasonable estimate of the Sun's peculiar motion in the LSR , the cartesian

Table 2. Galactocentric position and space velocity

	X	Y	Z	U	V	W
		[kpc]			[km/s]	
(1)	+6.7	+0.2	+15.6	+50	−47	−108
	±1.6	±0.0	±1.6	±27	±51	±26
(2)	+6.7	+0.2	+15.6	−121	−4	+57
	±1.6	±0.0	±1.6	±17	±37	±17

(1) this work. (2) with the p.m. from Schweitzer et al. (1993)

components of the Galactocentric position and velocity of Pal 5 come out as shown in Table 2. As viewed from a point near the Sun the present location of the cluster lies on the opposite side of the Galaxy. It has a height of 16 kpc above the Galactic plane and a projected distance of 7 kpc from the Galactic center. While the direction of the velocity vector depends on the choice between the two different proper motion results given above (see the two cases in Table 2), the absolute value of the velocity is in both cases close to 130 km/s (see Table 3b). This confirms that Pal 5 is indeed among the clusters with the lowest space velocity in the globular cluster system of the Galaxy.

Schweitzer, Cudworth & Majewski (1993) have pointed out that using their proper motion for Pal 5, the velocity vector is perpendicular to the position vector and hence the cluster is very close to apogalacticon. Our proper motion results do not confirm this particular orientation of the velocity vector. Nevertheless, the conclusion that Pal 5 is near apogalacticon remains true also with regard to the proper motions obtained in this paper. This can be anticipated from the fact that the total space velocity is much below the circular velocity of the Galaxy, and it is confirmed in a more precise manner by the results of a numerical calculation of the cluster's Galactic orbit.

In analogy to our previous studies on other globular clusters we integrated the orbit of Pal 5 for the past 10 Gyrs, using the model by Allen & Santillan (1991) as a representation of the Galactic gravitational potential. The resulting orbital parameters are summarised in Table 3 and a plot of the orbital path is shown in Fig. 8. While with the proper motion from Schweitzer, Cudworth & Majewski (1993) the distance of the cluster from the Galactic center is limited by the current distance of 17 kpc, with our proper motion the orbit yields a maximum distance of 18.9 kpc and the most recent apogalacticon lies 0.05 Gyr (i.e. 1/8 of a mean orbital period) back from present. Perigalactic distances are found to be not smaller than 5.3 kpc. The eccentricity of the orbit (as measured by $e = (R_{max} - R_{min})/(R_{max} + R_{min})$) returns a value of 0.56. Naturally, the distribution of values of Galactocentric distance R is such that most of the time the cluster is seen at relatively large distances ($R > 14$ kpc). Since the orbit is highly inclined, the distance from the Galactic plane can rise up to 18.5 kpc, but on the time average along the orbit this distance has only about half of the maximum size. The inclination of the (instantaneous) orbital plane with respect to the Galactic plane remains almost constant at about 79°. Following the proper motions of this paper, the cluster is in prograde rotation around the Galactic z-axis with an average rotation velocity of about 56 km/s, which is similar to the overall mean rotation velocity of the globular cluster system. On the other hand, with the proper motions found by Schweitzer, Cudworth & Majewski (1993) the cluster yields a z-angular momentum almost zero and hence a nearly polar orbit (i.e. 90° inclination) with an average rotational velocity component Θ of only 1 km/s. Despite these differences one finds agreement in the fact, that in both cases the cluster has a mean period of revolution of 0.4 Gyr (corresponding to 25 revolutions around the Galactic z-axis within 10 Gyrs).

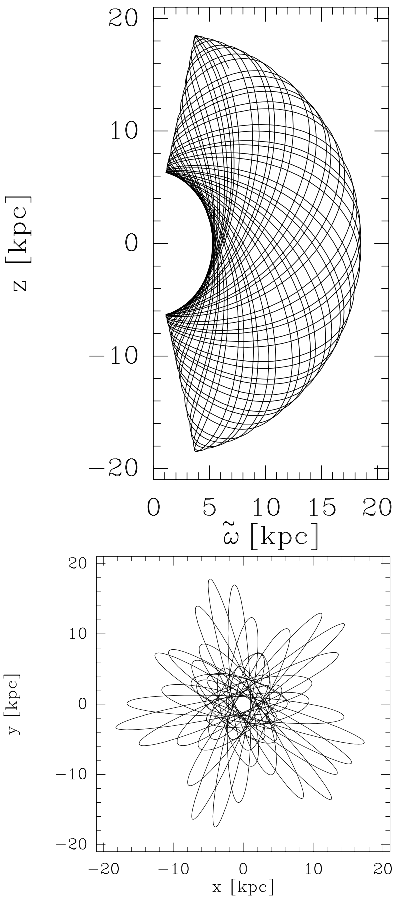

Fig. 8. Orbit of Pal 5 in the time interval [−10 ; 0] Gyr. Upper plot: Meridional Projection onto cylindrical coordinates $\tilde{\omega}$, z. Lower plot: Projection on the Galactic plane.

In order to find out how much the orbital characteristics change within the estimated range of error in our proper motions, we modified the cluster's initial velocity accordingly and calculated a number of alternative orbits. The result of this test was, that the distance parameters do not undergo extreme changes, i.e. R_{max} and $|Z|_{max}$ fell within 18 and 20 kpc and R_{min} was between 3 and 8 kpc. The direction of rotation was in all cases prograde with average rotational velocities between 30 and 70 km/s. Although the z-angular momentum of Pal 5 is on a low level, (in the range 130 to 450 kpc·km/s) there was no indication for the appearance of chaotic motion, because all

Table 3. Orbital parameters for time interval $[-10\,;0]$ Gyr

a) Geometry of the orbit

	R_{min}	R_{max}	$\overline{R}$	$R_{t=0}$	e	$\vert Z\vert_{max}$	$\overline{\vert Z\vert}$
		[kpc]				[kpc]	
(1)	5.3	18.9	13.7	17.0	0.56	18.5	9.2
(2)	8.6	17.0	13.4	17.0	0.33	17.0	9.0

b) Absolute velocity and kinetic energy

	v_{min}	v_{max}	$\overline{v}$	$v_{t=0}$	$\overline{v^2/2}$
		[km/s]			[km^2/s^2]
(1)	88	366	188	128	20471
(2)	131	299	198	134	20535

c) Rotation around z-axis

	Θ_{min}	Θ_{max}	$\overline{\Theta}$	$\Theta_{t=0}$	$\overline{T}$	n_{rev}
		[km/s]			[Gyr]	
(1)	18	300	56	49	0.40	24.9
(2)	0	130	1	0	0.40	25.0

d) Angular momentum and orbital plane

	J_z	$\overline{J}$	$\Delta J/\overline{J}$	$\overline{i}$	Δi
		[kpc · km/s]		[degree]	
(1)	-325	1893	$\pm 15\%$	79	± 2
(2)	-3	2408	$+25\%; -12\%$	90	± 0

(1) this work. (2) with the p.m. from Schweitzer et al. (1993)

test orbits showed the characteristics of regular (quasiperiodic) motion, similar to the orbit of Fig. 8.

6. Discussion of the results

The total space velocity and hence specific angular momentum of Pal 5 are significantly different from that to be expected from a tidally stripped fragment of the Sgr dwarf galaxy (eg. Lynden-Bell & Lynden-Bell 1995). Our (mean) angular momentum of Pal 5 is only about half of that of the Sgr dwarf, if we take the Sgr dwarf proper motion obtained by Ibata et al. (1997). Furthermore, our direction of motion of Pal 5, south toward the Galactic Plane, is almost in the opposite sense to that of the Sgr galaxy which at the equivalent point in its orbit would be heading north away from the Galactic Plane (Ibata et al. 1997). Admittedly, if we used the proper motion obtained by Schweitzer, Cudworth & Majewski (1993) then this latter problem would be much reduced. Nonetheless both proper motion results suggest an apogalacticon for Pal 5 of only 17–19 kpc which is virtually impossible to reconcile with a detached satellite of the Sgr dwarf which has a perigalacticon of this order, but whose apogalacticon is likely be greater than 50 kpc or more.

It is possible that Pal 5 could be a detached cluster of an alternative, now defunct, satellite galaxy since that would help to explain how such a low density cluster could have survived for the best part of a Hubble time in such a low attitude orbit. Dynamical friction would have a negligible effect on the orbit of an isolated Pal 5, but could well have significantly decayed the orbit of a previously much more massive host system, leading to capture and eventual tidal disruption.

Considering our results of the Galactic orbit of Pal 5 we may also conclude that the tidal forces along this orbit would lead to a smaller tidal radius compared to the 18.2 arcmin of Webbink (1985) and 15.9 arcmin of Trager, King & Djorgovski (1995). With $r_t = 15.9$ arcmin and $d = 21.8$ kpc the linear radius is 101 pc. Assuming a mass of Pal 5 of logM = 3.92 (Mandushev et al. 1991) and using common formulae for the classic tidal radius (e.g. formula (4) in Odenkirchen et al. 1997) we get a tidal radius between 12 pc at perigalacticon and 43 pc at apogalacticon. The conservative value of 43 pc corresponds to 7 arcmin which is in good agreement with our Fig. 7a and b and our discussion of possible errors in the measurements of the tidal radius of Pal 5 caused by the galaxy cluster Abell 2050.

Acknowledgements. We thank the Tautenburg, Palomar and UKST Observatories for supplying the plates. The APM is a national astronomy facility financed by the Particle Physics and Astronomy Research Council. The data of the second epoch Palomar plate were received via the STScI Digitised Sky Survey. This research has made use of the NASA/IPAC extragalactic database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration. We would also like to thank H.-J. Tucholke for his help with the Münster (MRSP) software installation. MO gratefully acknowledges financial support from the European Community through a postdoctoral research fellowship (ERBFMBICT961511). We wish to thank the referee, Dr. Cudworth for his suggestions and comments.

References

Allen C., Santillan A., 1991, Rev. Mex. Astron. Astrofis., 22, 255
Arp H., 1962, ApJ, 135, 311
Bell R. A., Harris G. L. H., Hesser J. E., Cannon R. D., 1981, ApJ 249, 637
Bunclark P.S., Irwin M.J., 1983, in Rolfe E.J., ed, Proc of Internat. Colloq. on Statistical Methods in Astronomy, ESA SP-201, p.195
Cudworth K.M., Hanson R.B., 1993, AJ, 105, 168
Cudworth K.M., 1998, private communication
Evans D.W., 1988, PhD Thesis, Cambridge
Evans D.W., Irwin, M., 1995, MNRAS, 277, 820
Harris W.E., 1996, AJ 112, 1487
Horstmann H., Schücker P., Seitter W., Aniol R., Budell R., Cunow B., Meijer J., Teuber D., Tucholke H.-J., 1989, Bull. Inf. CDS, 37, 43
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nature 370, 194
Ibata R.A., Wyse R.F.G., Gilmore G., Irwin M.J., Suntzeff N.B., 1997, AJ 113, 634
Lin D.N.C., 1996, The mass of the Galactic halo, Magellanic stream, Galactic satellites, and the warp of the Galactic disk. In: O. Lahav, E. Terlevich, R.J. Terlevich (eds.), Gravitational dynamics, Cambridge University Press, Cambridge, p. 15
Lin D. N., Richer H. B., 1992, ApJ 388, L57
Lynden-Bell D., Lynden-Bell R. M., 1995, MNRAS 275, 429
Majewski S. R., 1993, ARA&A 31, 575
Majewski S. R., Cudworth K. M. 1993, PASP 105, 987
Mandushev G., Stanova A., Spasova N., 1991, A&A 252, 94

Mihalas D., Binney J., 1981, Galactic Astronomy, Freeman, San Francisco, p. 398

Odenkirchen M., Brosche P., Geffert M., Tucholke H.-J., 1997, NewA, in press

Scholz R.-D., Irwin M., 1994, Absolute proper motions of the dwarf spheroidal galaxies in Draco and Ursa Minor. In: MacGillivray H.T. et al. (eds.) Proc. IAU Sympos. 161, Astronomy from wide-field imaging, Kluwer Acad. Publ., Dordrecht, p. 535

Scholz R.-D., Meusinger H., Irwin M., 1997, A&A, submitted

Scholz R.-D., Odenkirchen M., Irwin M., 1993, MNRAS, 264, 579

Scholz R.-D., Odenkirchen M., Irwin M., 1994, MNRAS, 266, 925

Scholz R.-D., Odenkirchen M., Hirte S., Irwin M.J., Börngen F., Ziener R., 1996, MNRAS, 278, 251

Schweitzer A.E., Cudworth K., Majewski S., 1993, ASP Conf. Ser., 48, 113

Searle L., Zinn R., 1978, ApJ 225, 357

Smith B.F., Miller R.H., 1995, BAAS 187, 8206

Smith G.H., 1985, ApJ 298, 249

Smith G.H., 1996, PASP 108, 176

Smith G. H., McClure R. D., Stetson P. B., Hesser J. E., Bell R. A., 1986, AJ 91, 842

Trager S.C., King I.R., Djorgovski S., 1995, AJ, 109, 218

Webbink R.F., 1985, Structure parameters of Galactic globular clusters, In: Goodman J., Hut P. (eds.), Dynamics of Star Clusters, Proc. IAU Symp. 113, Kluwer Acad. Publ., Dordrecht, p.541

Zinn R., 1993, In: G. H. Smith, J. P. Brodie (eds.), The Globular Cluster-Galaxy Connection, ASP Conf. Ser. 48, San Francisco, p.38

Note added in proof: Cudworth (1998) reported that the preliminary result of Schweitzer, Cudworth & Majewski (1993) has been improved so that their final result of the cluster's absolute proper motion is $(\mu_\alpha, \mu_\delta) = (-2.55 \pm 0.17, -1.93 \pm 0.17)$ mas/yr. Their revised motion is closer to our result in μ_δ, but the disagreement in μ_α remains.