MOTIONS OF GLOBULAR CLUSTERS

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ABSTRACT. Absolute proper motions of seven globular clusters have been determined with respect to extragalactic references and with accuracies of $\sim$ 1 mas/yr. Derived quantities and qualitative implications are described.

1. Introduction

A conservative manner for elucidating the objectives of sub-milliarcsecond optical astrometry consists in the consideration of already existing results with an accuracy not too far from the envisaged one. Since the *radial velocities* of almost all galactic globular clusters are known with a typical accuracy of ± 10 km s^{-1} (and since we shall not discuss motions *within* globular clusters), the bottleneck of our topic is the determination of *absolute proper motions* of the clusters as a whole. The informational value of such a determination will be seen if one compares the possible volumes in velocity space occupied by a cluster with and without the knowledge of a proper motion: while the third dimension is given by the radial velocity, in the tangential components a circle with a radius of the order of 300 km s^{-1} is a priori possible (letting aside transient intergalactic visitors). Even a crude determination of a proper motion which pins down the cluster just within 100 km s^{-1} bins (but in two dimensions!) leaves a posteriori only $\sim 1/30$ of the a priori volume as possible locus of the cluster in velocity space.

In what follows we provide examples of the results obtained by the Bonn group, partly in cooperation with other colleagues, for the globular clusters NGC 4147, NGC 5466, M 12 (Brosche et al. 1991), M 15 (Geffert et al. 1993), M 3 (Scholz et al. 1993, Tucholke et al. 1994), M 92 (Scholz et al. 1994), and M 5 (Scholz et al. 1995).

2. Photographic Astrometry, Direct Results and Invariants

Earlier attempts to find the proper motions of globular clusters have been corrupted by the errors in the motions of reference stars which entered directly into the results. In order to make use of the potentially higher accuracy of photographic data it is absolutely necessary to eliminate the influence of classical catalogue errors from the final results.

First, one would think that instead of using the few *individual* brighter stars lying around

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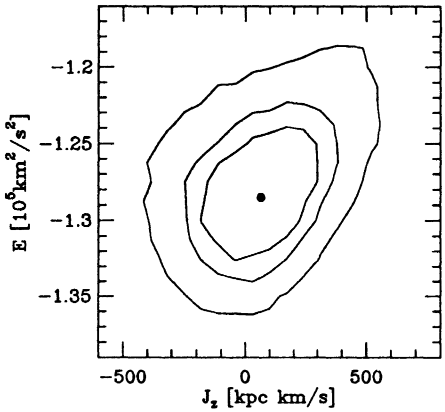

Fig. 1: **Uncertainty in the determination of the constants of motion E and J_z of the globular cluster M 92. The dot corresponds to the values at the mean orbit. The contours are 50, 66 and 90% confidence limits.**

a cluster, one should use merely the *essence* of the catalogues, i.e., a complete model of galactic motions. Such a model would describe the collective motions of many faint stars around a cluster, thus arriving at a statistically sound relative motion between cluster and stars. And because the motions of the stars are known from the model, so we had the motion of the cluster too, if the model were correct. However, as Brosche & Schwan (e.g. 1986) have demonstrated, the standard model is not sufficient to describe all systematic motions, neither for the FK 4-, nor N30-, nor FK 5-system.

Therefore we preferred to determine absolute proper motions with extragalactic reference, either directly relative to quasars or galaxies or indirectly through stellar proper motions measured with respect to galaxies provided by our colleagues A.R. Klemola (Lick Observatory) and R.–D. Scholz (Potsdam).

The most direct result consists in the two components of the absolute proper motion of a globular cluster, say in galactic coordinates. Adding its radial velocity and using the space velocity of the Sun with respect to the galactic center, we can derive the absolute space motion of the cluster. While such an 'instantaneous' information is interesting in itself, one would like also to obtain parameters of a less transient meaning, especially invariants of the motion. For an axisymmetric structure (which the Galaxy should possess approximately) there exist J_z, the specific angular momentum around the axis of symmetry, and E, the specific orbital energy (taken as vanishing at infinity). While the first can be obtained without further input directly from the space motion and the spatial position, the latter involves the knowledge of the galactic potential distribution. So far we have applied the one of Allen & Martos (1986). The two invariants depend on the input data in a complex manner. Although their errors are dominated by the errors of the proper motion components (and sometimes by distance errors) of the globular cluster, the magnitude of the errors often does not allow a linear treatment. Instead, the confidence area in the proper motions has to

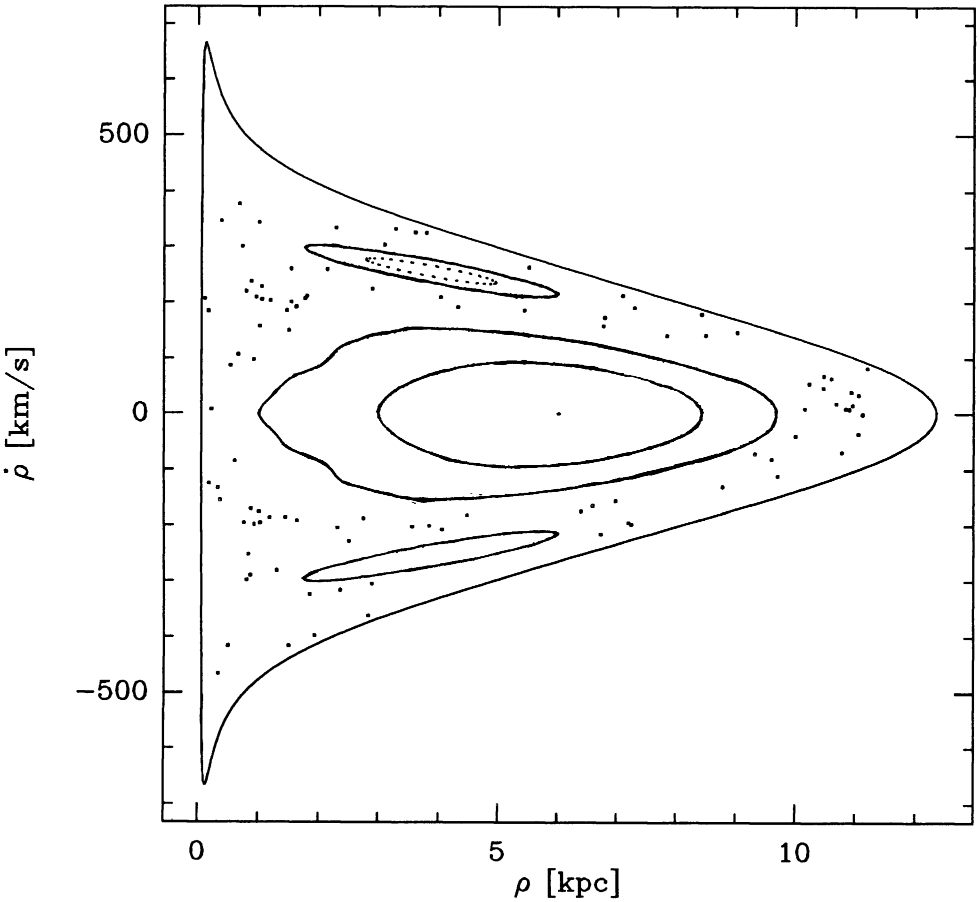

Fig. 2: Poincaré section for the mean values E and J_z of M 92. ρ denotes the radial distance to the galactic centre in a cylindrical coordinate system, while $\dot{\rho}$ is its time derivative. For the Poincaré section their values at the passages through the galactic plane are used.
Outer envelope: zero-velocity surface
Central ovals: family of box orbits
Upper oval: family of tube orbits containing the mean orbit of M 92 (dotted)
Isolated dots: stochastic orbit with initial conditions not far from those of M 92
Lower oval: another island of tube orbits.

be transferred into the surface of the two invariants. Fig. 1 shows a typical situation. Note the deviations from ellipses and the existence of correlations. We consider such figures to represent the overall concentrate of our results.

3. Further Interpretation and Conclusions

If the path of every globular cluster would totally fill the space allowed by its two invariants, the latter would be sufficient for the description. However, this is not generally true and the integration of the orbits in the potential quoted above reveals a rich variety of possibilities and of questions to be answered. Starting from short time scales, one can find the times, loci and velocities of the last transits through the galactic plane. If these values become more precise in the future, it may be useful to look for traces in the interstellar medium. Furthermore, at least the projections of the orbits allow the definition of some parameters prevailing for some time or oscillating in a characteristic manner (e.g. by precession): extremal distances and thereby tidal radii, or some kind of eccentricities and angles describing the position of an instantaneous orbital 'plane'. One can pose — and answer! — the question whether the present values of the parameters lie in a probable interval of their distribution for the whole history of the orbit.

It is possible to classify the orbits according to their behaviour in the Poincaré section (Fig. 2): stochastic or chaotic orbits leave a scattered distribution of crossing points while regular orbits produce pointwise closed contour lines of "islands of regularity". Inside the central island we find the usual type of (meridional) box orbit, which is symmetric with respect to the galactic plane (see Fig. 3 for an example). In outer islands we also obtain asymmetric orbits, usually confined in a rather narrow "tube" in the meridional section (Fig. 4). This type is not a rare exception, e.g. M 92 spends more than 80% of the time north of the galactic plane (Odenkirchen et al. 1994). Due to the proper motion errors, a probability can only be ascribed to each cluster for belonging to one or the other type of orbits. In some favourable cases like M 12, however, there is a high probability for a regular orbit. Taken together with the long periods of revolution, this enables us to integrate backwards a cluster orbit for the whole stationary life of the Galaxy.

With increasing numbers, one will be able to tackle the quest for correlations between orbital and astrophysical characteristics, e.g. maximal distance from the galactic plane and metallicity (Geffert et al. 1995).

An important problem not treated here is the sensitivity of the results to the underlying galactic model. Amongst the various competing ones, those based on the family designed by Miyamoto & Nagai (1975) seem especially attractive because of the explicit knowledge of both the potential and the mass distribution.

A most recent attempt to improve the outer part of the galactic potential from globular cluster space velocities has been performed by Dauphole & Colin (1995); clearly, the future use of velocities will strengthen the basis for such conclusions.

Due to the sparsity of our data basis, the main aim of this contribution consisted in the illustration of the potentialities of sub-mas-astrometry in the field of globular clusters.

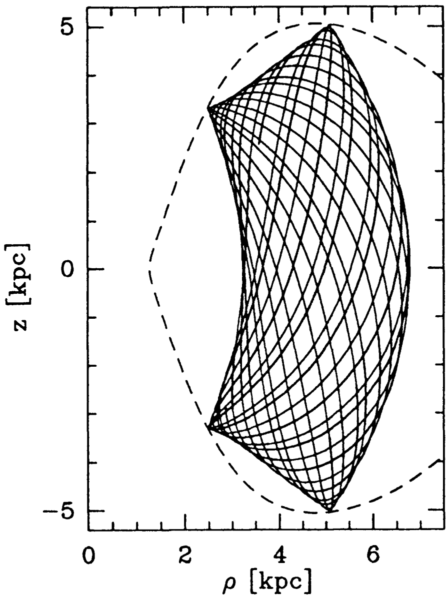

Fig. 3: Example for a box orbit: motion of the globular cluster M 12 in the meridional plane for the time interval [-2, 0] Gyr. ρ is the distance to the galactic centre, projected onto the galactic plane, and z the distance to the galactic plane. The dashed line shows the zero-velocity curve.

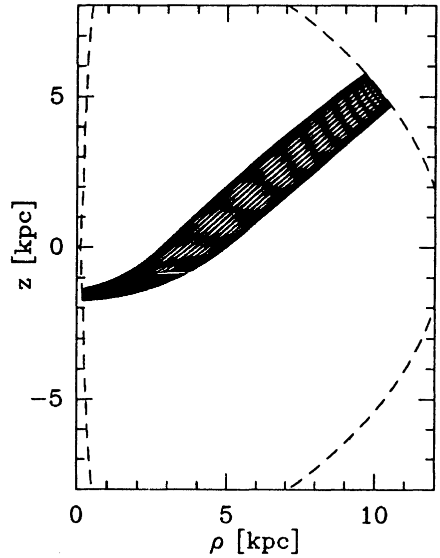

Fig. 4: Example for an asymmetric orbit: motion of the globular cluster M 92 in the meridional plane for the time interval [-20, 0] Gyr.

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