KINEMATICS OF THE GALACTIC GLOBULAR CLUSTER SYSTEM

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ABSTRACT: Constraints on cluster kinematics proper motions, radial velocities and tidal radii are reviewed. Analysis of the cluster radial velocity distribution suggests a rotation law for the system in which the specific angular momentum is nearby independent of galactocentric distance, and the residual velocity dispersion is isotropic. However, the absence of severely tidally truncated clusters indicates that nearly radial orbits are absent from this distribution. The kinematic properties of the remote halo clusters remain largely indeterminate. Absolute proper motions measured directly with respect to background galaxies and quasars are needed to determine the kinematics of these objects, and also to elucidate the process of tidal stripping.

1. INTRODUCTION

The kinematics of the galactic globular cluster system have long been a subject of great interest for two important reasons: (i) they serve as a dynamical probe of the galactic mass distribution; and (ii) they provide a fossil record of the early dynamical and chemical evolution of the Galaxy. Historically, globular clusters have enjoyed a favored status over single stars for these purposes, because they are easily identifiable entities over the entire Galaxy, and because they are usually bright enough to be studied spectroscopically by photographic means. Recent advances in detector technology promise to make kinematic studies of distant halo giants feasible, mitigating some of these advantages, but globular clusters remain the probes of choice, despite their limited numbers, because their distance scale is much more secure than that of single stars.

Most of our present knowledge of cluster kinematics has been derived from studies of their radial velocities. These have the advantage of being relatively quick and easy to obtain. Very high accuracy is now possible using modern cross-correlation techniques

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(whether digital or analog), which are very well-suited to the late-type giants which dominate cluster light. This advance has made possible detailed studies of stellar kinematics within clusters, as described elsewhere in this Symposium. Nevertheless, radial velocity data alone carry some significant drawbacks for studies of kinematics of the cluster system: First, information regarding the tangential velocities of clusters (with respect to the galactic center) is only accessible for clusters near the solar circle or inside it. These velocity components make no significant contribution to the observed radial velocities of clusters far outside the solar circle. Second, with only one-dimensional velocity data for individual clusters, one can obtain only a statistical description of cluster orbits within the Galaxy. Furthermore, the number of clusters known is so small that only the first and second moments of the velocity distribution are statistically significant: kinematic details are washed out.

In principle, cluster proper motions could provide us with much more information regarding their kinematics. In the first place, they are two-dimensional data. Combined with radial velocities, which are now available for the vast majority of clusters, they constitute a complete kinematic description of the cluster system. Moreover, they provide the only observational constraint on rotation of the cluster system about the $\ell = 0$, $b = 0$ axis. (It should be recalled that the Magellanic Stream is nearly perpendicular to this axis [Wannier and Wrixon 1972]. Any direct kinematic evidence of its dynamical interaction with the galactic globular cluster system will be manifested observationally in proper motions of the affected clusters.) The difficulties in obtaining absolute proper motions of clusters are of course well-known: A long time base is both desirable and necessary in most cases. (This is itself a distinct handicap in modern astronomy.) The potentials for systematic errors are legion, making reductions difficult and time-consuming. The accuracy of most studies of cluster proper motions to date is poor, owing to the large and unavoidable dispersion in proper motions of the (foreground) reference stars. This statistical uncertainty is further compounded by the inadequacy of current models for the kinematics of field stars, which renders the correction from relative to absolute proper motions highly uncertain.

An indirect constraint on cluster orbits comes from their observed limiting radii. These limiting radii are generally attributed to the tidal limit imposed by the galactic gravitational field (von Koerner 1957, King 1962), and thus, in principle, provide information about gradients in that field (and hence local mass densities) of a different kind from that obtained through dynamical modeling. Indeed, it should be possible to constrain possible cluster orbits rather strongly through their use. In practice, limiting radii can be readily estimated from star counts (e.g. King, et al. 1968; Peterson and King 1975), although the cluster contribution to the total star density is rarely distinguishable above background beyond one-half the limiting radius. Unfortunately, the accuracy of this method (or indeed of any other method so far devised) is badly degraded by a high or variable background of field stars and by differential reddening. As a result, large uncertainties remain in the determinations for individual clusters, particularly those at low galactic latitude. Moreover, the precise limiting radius extrapolated from a given set of observations depends upon the internal kinematics of the cluster (see, e.g., Gunn and Griffin 1979), and the tidal field implied by that limit depends upon the total cluster mass-to-light ratio. The most serious interpretational problems in exploiting limiting radii, however, come from (i) severe inadequacies in current theories of tidal stripping, which have yet to deal satisfactorily with the problems of eccentric cluster orbits, internal dynamical evolution of clusters, or the fact that marginally unbound stars may not be lost from clusters for many dynamical timescales; and (ii) the fact that the kinematical implications of tidal radii depend on the galactic mass model — the kinematical and dynamical problems are not separable.

Let us turn now to the question of what has been learned of cluster kinematics by these methods.

2. PROPER MOTIONS

Historically, the first attempts to detect the motions of globular clusters (and other "nebulae" as well) were astrometric ones. During the latter half of the 19th Century, efforts were made at nearly every major observatory to secure accurate positions for these objects visually, positions which might have served as a basis for proper motion studies. Unfortunately, these efforts were devoted almost exclusively to the determination of centroid positions, and not those of individual stars, and so are too ill-defined to be of use for kinematic purposes, except to show that the globular clusters were not nearby objects.

The modern era of globular cluster astrometry began with the work of van Maanen (1925, 1927) at Mt. Wilson, and Balanowsky (1928) at Pulkovo, who used photographic plates to study the proper motions of stars in and around several bright Northern Hemisphere clusters. Since this pioneering work, numerous studies of individual clusters have been published (albeit almost exclusively for Northern Hemisphere clusters). For the most part, these have been relative proper motion studies, and so are affected by serious uncertainties in the reduction to absolute proper motions. Hallermann (1965) attempted to measure the proper motions of 11 clusters directly in the NFK coordinate system, Meurers and Prochazka (1969) tied that of NGC 6838 (MT1) directly to the FK4 system, and Brosche and coworkers have recently measured the proper motions of NGC 4147 (Brosche, et al. 1986) and NGC 5466 (Brosche and Geffert 1983) with respect to field stars with known proper motions in the Lick extragalactic reference system. However, the only attempts to determine cluster proper motions directly with respect to extragalactic objects have been a series of studies at Pulkovo of NGC 6205 (M 13) referred to the nucleus of NGC 6207 (Gamalej 1948; Fatchikin 1952; Kadla 1963). These studies have reached inconsistent results, apparently because of difficulties in defining the nucleus of NGC 6207.

In Figure 1 are illustrated the proper motions of the 15 globular clusters and 2 dwarf spheroidal satellites of the Galaxy for which published data are available. Relative proper motions have been reduced to an absolute (inertial) frame assuming the standard open for solar motion (A = 270°, D = +30°); this reduction may differ considerably from that following from use of the Lick apex (Vasilevskis and Klemola 1971), especially for clusters in the vicinity of these apexes (e.g., Cudworth 1976a,b, 1979a,b; Cudworth and Monet 1979). Proper motions in fundamental coordinate systems were corrected to FK4 (Nowacki 1935; Fricke, et al. 1963), as appropriate, and the equinox correction to FK5 (Fricke 1982) was then applied. The results from different published sources have then combined into weighted means.

The reflex proper motion of the cluster system due to the net rotation of the cluster system with respect to the local standard of rest is clearly discernable in Figure 1. However, the residual proper motions of individual clusters, once this effect is removed, are mostly of doubtful significance.

3. RADIAL VELOCITIES

The relative ease and precision with which cluster radial velocities can be determined over galactic distances has made them the preferred avenue for kinematic studies. Since the pioneering work of Strömberg (1925), numerous statistical analyses of cluster motions based on their radial velocities have been published, including important papers by Edmondson (1935), Mayall (1946), Perek (1954), von Hoerner (1955), Kinman (1959), Matsunami (1964), Woltjer (1975), House and Wiegandt (1977), Hartwick and Sargent (1978), Frenk and White (1980), Pier (1984), Rodgers and Paltoglou (1984), Zinn (1985), Hesser, Shawl, and Meyer (1986), and Norris (1986). Radial velocities have, at this writing, been published for a total of 115 galactic globular clusters, as well as for all 7 dwarf spheroidal satellites of the Galaxy, making this the most extensive (as well as the most reliable) body of kinematic data presently available.

Recent studies based on radial velocities, while emphasizing different details, have arrived at a fairly consistent picture of the global kinematics of the cluster system. In the following discussion, the numerical results quoted are those derived by the author from the analysis of the 85 clusters (plus NGC 6569) and 4 dwarf spheroidals contained in his radial velocity catalogue (Webbink 1981). To the extent that they are comparable, however, these

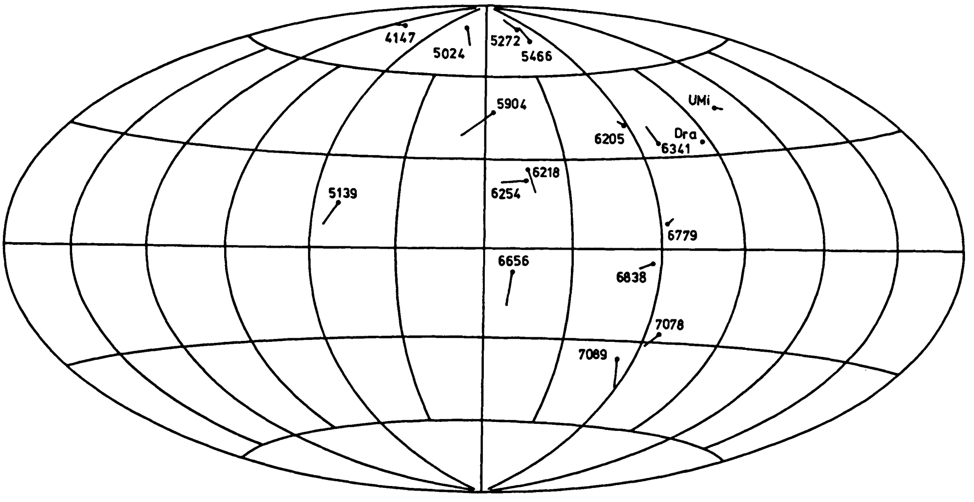

Fig. 1. Absolute proper motions of galactic globular clusters and dwarf spheroidal satellites. The present positions of the clusters are plotted as points in galactic coordinates ($\ell = 0^{\circ}$, $b = 0^{\circ}$ at the center of the figure), with lines indicating the proper motion for 3.6 Myr (i.e., $1^{\circ} = 1$ mas/yr).

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results are entirely consistent with the findings of all of the recent studies cited above.

3.1 Rotation of the cluster system

In order to explore the rotation of the cluster system, we divide the 90 clusters and dwarf spheroidals into six spherical shells, each containing 15 objects. For this purpose, the distances to individual clusters are based on the assumption that $M_V(HB) = +0.60$, and the distance to the galactic center is taken to be $R_\odot = 8.8$ kpc (Harris 1976). The clusters within each shell are assumed to rotate about an axis perpendicular to the galactic plane (the b = +90° axis) with uniform linear velocity, with the circular velocity at the Sun taken to be $\Theta_0 = 220$ km s^{-1} (Gunn, Knapp, and Tremaine 1979). The results of this exercise are listed in Table I.

TABLE I.
ROTATION OF THE CLUSTER SYSTEM

$\bar{R}/R_\odot$	Θ_{cl} (km s^{-1})	σ_{los} (km s^{-1})
0.24±0.01	120±64	100±19
0.44±0.02	68±51	102±17
0.74±0.02	67±37	90±8
1.11±0.04	28±58	145±23
1.87±0.08	31±140	125±10
7.94±1.27	231±303	139±17

As was to be expected, the rotation curve of the cluster system (Θ_{cl}) is not well-defined much beyond the solar circle, but there clearly exists differential rotation within the cluster system as a whole. For the inner four bins, a trend in which the linear rotation velocity increases towards the galactic center is apparent, even though the data for individual bins have large uncertainties. This trend was suspected by Frenk and White (1980), and elaborated considerably by Zinn (1985). Also apparent in the third column of Table I is the abrupt increase in the line-of-sight velocity dispersion beyond the solar circle first noted by Frenk and White. This phenomenon can be explained either by an increase in the total velocity dispersion, or by a slightly elongated velocity ellipsoid in which the major axis points radially toward the galactic center.

On the strength of the above evidence, we may attempt a second solution to the cluster rotation law, treating the entire system as a single entity. We assume a rotation law of the form

$$\Theta_{cl}(R) = \Theta_{cl}(R_\odot)\ (R/R_\odot)^\alpha$$

and permit as well a rate of expansion of the same form:

$$\Pi(R) = \Pi(R_\odot)\ (R/R_\odot)^\alpha .$$

The axis about which the cluster system rotates is left as a free parameter, with components Θ_z about the (b = +90°)-axis and Θ_y about the (ℓ = 90°, b = 0°)-axis. (As noted in the Introduction, rotation Θ_x about the (ℓ = 0°, b = 0°)-axis is indeterminate from radial velocities alone.) In addition, we may treat Θ_0, the local circular velocity, as a free parameter in the solution: it is indeterminate only if α = 1. The best-fit parameters thus obtained are:

$$\alpha = -0.98 \pm 0.51$$

$$\Theta_0 = 203 \pm 27 \text{ km s}^{-1}$$

$$\Theta_z(R_\odot) = 34 \pm 14 \text{ km s}^{-1}$$

$$\Theta_y(R_\odot) = -1.4 \pm 9.2 \text{ km s}^{-1}$$

$$\Pi(R_\odot) = 8.0 \pm 8.8 \text{ km s}^{-1}$$

Clearly, there is no significant rotation of the cluster system about the y-axis, nor is there evidence of any net expansion or contraction of the cluster system, contrary to the conclusions of Clube and Watson (1979). If we therefore set $\Theta_y(R_\odot) = \Pi(R_\odot) = 0$, we obtain:

$$\alpha = -1.08 \pm 0.97$$

$$\Theta_0 = 196 \pm 27 \text{ km s}^{-1}$$

$$\Theta_z(R_\odot) = 25 \pm 13 \text{ km s}^{-1}$$

It appears that the cluster system rotation law is approximately one in which the mean specific angular momentum is independent of galactocentric distance. Note also that the deduced local lag in rotation of the cluster system, $\Theta_z(R_\odot) - \Theta_0$, is practically independent of the assumed rotation law.

3.2 Velocity ellipsoid of the cluster system

We may now remove the systematic effects which the rotation of the cluster system contributes to the observed radial velocities, according to the final set of parameters deduced above, and examine the properties of the cluster velocity dispersion tensor (cf., e.g., Ogorodnikov 1965). We adopt a spherical polar coordinate system in which the Π-axis points from the galactic center to the cluster position, the Θ-axis points in the direction of galactic rotation, parallel to the galactic disk, and the Φ-axis is orthogonal to the other two. (Note that the Θ-Φ notation is reversed from that of Norris [1986], but the same as that of Pier [1984].) The deduced dispersion tensor is listed in Table II.

TABLE II.
THE GLOBULAR CLUSTER VELOCITY DISPERSION TENSOR

σ_{ij}^2 (in 10^4 km s^{-1})			
j\i	Π	Θ	Φ
Π	+1.42±0.27	-0.09±0.33	-0.14±0.37
Θ	-0.09±0.33	+1.37±0.43	+0.08±0.51
Φ	-0.14±0.37	+0.08±0.51	+0.90±0.65

The off-diagonal components of this tensor are all consistent with zero, implying that the principal axes of the velocity ellipsoid (resolved in this way) coincide with those of the adopted coordinate system. The values for the diagonal components agree well with those found by Pier (1984), and Norris (1986) for the cluster system, except for Pier's inexplicably large value for $\sigma_{\theta\theta}^2$. They differ from those found by Woolley (1978; see also Pier 1984) for halo RR Lyrae stars ($\sigma_{\pi\pi}^2$ = 2.11±0.54; $\sigma_{\theta\theta}^2$ = 1.55±0.54; $\sigma_{\phi\phi}^2$ = 0.50±37) only in having a somewhat smaller radial component. Indeed, within the errors, the cluster velocity ellipsoid is isotropic, as deduced by Frenk and White (1980).

4. TIDAL LIMITS

The identification of the limiting radius of globular clusters with the galactic tidal cutoff (von Hoerner 1957; King 1962) opened the possibility that this information could be turned to advantage in exploring cluster kinematics. The physical argument is a simple one: the cluster achieves tidal equilibrium only when it has been stripped down to those members whose orbits remain bound to the cluster in the presence of the strongest tidal field experienced by the cluster, namely, that at perigalacticon. Given an estimate of the total cluster mass (from its integrated luminosity and mass-to-light ratio), the maximum tidal stress, and hence perigalactic distance, can be calculated. This method has been applied to numerous individual clusters, and in recent years to the cluster system as a whole (Peterson 1974; Rastorguev and Surdin 1980; Seitzer and Freeman 1981; Innanen, Harris, and Webbink 1983). As noted in the Introduction, however, this method is plagued not only by large observational uncertainties, but also by unsolved theoretical problems and the dependence of answers on an assumed galactic potential. In recent years, a controversy has arisen over whether clusters ever actually achieve tidal equilibrium, and on what timescale (see, e.g., Seitzer 1985; Angeletti and Giannone 1984; Angeletti, Capuzzo-Dolcetta, and Giannone 1984; and references therein), and over the relationship between the observed spatial cutoff and the tidal energy cutoff (Innanen, Harris, and Webbink 1983).

Notwithstanding the unsolved problems which complicate a naive interpretation of tidal radii, there exist some properties of the distribution of tidal radii which appear to carry significant kinematical implications which are independent of the resolution of these controversies. Innanen, Harris, and Webbink (1983) point out that any truly isotropic velocity dispersion implies the existence of an asymmetric tail to the distribution of cluster tidal mass densities at any given galactocentric distance. The tail extends toward high densities, and represents very compact clusters on nearly radial orbits. The prominence of this tail depends on the nature of the galactic potential, but even for a very "soft" potential (one giving a flat galactic rotation curve) the complete absence of such a tail in the observed distribution of cluster tidal mass densities implies that the population of extant clusters must have a severe deficiency of low angular momentum (i.e., highly eccentric) orbits. Evidently, the portrayal of the cluster distribution in velocity-space as an ellipsoid is very misleading, but the existence of this hole along the Π-velocity axis is not (and cannot be) revealed from a moment analysis of the observed radial velocities. It is possible that this deficiency is related to the larger radial component of the RR Lyrae velocity ellipsoid (see above).

5. PROSPECTUS

We stand at a crossroads in kinematic studies of the galactic globular cluster system. Accurate radial velocities are now known for the great majority of clusters — there is little room for expansion of this data base. Nevertheless, serious questions remain regarding the detailed form of the cluster velocity distribution, particularly outside the solar circle (with its attendant dynamical implications for the mass of the Galaxy), and regarding the physical significance of cluster tidal radii.

The key to further progress is clearly to obtain <u>absolute proper motions</u> of globular clusters directly with respect to background galaxies and quasars. At high galactic latitude, these objects outnumber field stars at magnitudes ($V \gtrsim 20$; Kron 1980) now within reach observationally. The time baselines needed for useful results, even for distant halo clusters, are not unreasonable, provided that background objects can be identified in sufficient numbers, and their

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relative positions established with sufficient accuracy:

$$\Delta t \approx 4.8 \text{ yr } \left(\frac{D}{10 \text{ kpc}}\right)\left(\frac{\epsilon_{xy}}{0\overset{''}{.}10}\right)\left(\frac{\epsilon_v}{10 \text{ km s}^{-1}}\right)^{-1}\left[\left(\frac{n_f}{100}\right)^{-1} + \left(\frac{n_{cl}}{100}\right)^{-1}\right]^{-1/2},$$

where D is the cluster distance, ϵ_{xy} the single-coordinate uncertainty in relative position, ϵ_v the single-coordinate uncertainty in tangential velocity, n_f the number of background reference objects, and n_{cl} the number of cluster stars. The technology is within reach and the need is clear.

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REFERENCES

Angeletti, L., Capuzzo-Dolcetta, R., and Giannone, P. 1984, Astron. Astrophys., **138**, 404.
Angeletti, L., and Giannone, P. 1984, Astron. Astrophys., **138**, 396.
Balanowski, J. 1928, Izv. Gl. Astron. Obs. Pulkovo, **11**, 167.
Brosche, P., and Geffert, M. 1983, Astron. Astrophys., **127**, 415.
Brosche, P., Geffert, M., Klemola, A.R., and Ninkovic, S. 1986, preprint.
Clube, S.V.M., and Watson, F.G. 1979, Monthly Notices Roy. Astron. Soc., **187**, 863.
Cudworth, K.M. 1976a, Astron. J., **81**, 519.
_____. 1976b, Astron. J., **81**, 975.
_____. 1979a, Astron. J., **84**, 1312.
_____. 1979b, Astron. J., **84**, 1866.
Cudworth, K.M., and Monet, D.G. 1979, Astron. J., **84**, 774.
Edmondson, F.K. 1935, Lowell Obs. Bull., **3**, 143.
Fatchikin, N.V. 1952, Izv. Gl. Astron. Obs. Pulkovo, **19**, pt. 1, 150.
Fricke, W. 1982, Astron. Astrophys., **107**, L13.
Fricke, W., Kopff, A., Gliese, W., Gondolatsch, F., Lederle, T., Nowacki, H., Strobel, W., and Stumpff, P. 1963, Veröff. Astron. Rechen-Inst. Heidelberg, No. 10.
Frenk, C.S., and White, N.E. 1980, Monthly Notices Roy. Astron. Soc., **193**, 295.
Gamalej, N.V. 1948, Izv. Gl. Astron. Obs. Pulkovo, **17**, pt. 6, 27.
Gunn, J.E., and Griffin, R.F. 1979, Astron. J., **84**, 752.
Gunn, J.E., Knapp, G.R., and Tremaine, S. 1979, Astron. J., **84**, 1181.
Hallermann, L. 1965, Dissertation, Univ. Bonn.
Harris, W.E. 1976, Astron. J., **81**, 1095.
Hartwick, F.D.A., and Sargent, W.L.W. 1978, Astrophys. J., **221**, 512.
Hesser, J.E., Shawl, S.J., and Meyer, J.E. 1986, Publ. Astron. Soc. Pacific, **98**, 403.

House, F., and Wiegandt, R. 1977, Astrophys. Space Sci., **48**, 191.
Innanen, K.A., Harris, W.E., and Webbink, R.F. 1983, Astron. J., **88**, 338.
Kadla, Z.I. 1963, Astron. Zh., **40**, 691 (English transl: 1964, Soviet Astron.-A.J., **7**, 528).
King, I.R. 1962, Astron. J., **67**, 471.
King, I.R., Hedemann, E., Hodge, S.M., and White, R.E. 1968, Astron. J., **73**, 456.
Kinman, T.D. 1959, Monthly Notices Roy. Astron. Soc., **119**, 157.
Klemola, A.R., and Vasilevskis, S. 1971, Publ. Lick Obs., **22**, pt. 2.
Kron, R.G. 1980, Astrophys. J. Suppl., **43**, 305.
Matsunami, N. 1964, Publ. Astron. Soc. Japan, **48**, 191.
Mayall, N.U. 1946, Astrophys. J., **104**, 290.
Meurers, J., and Prochazka, F. 1969, Ann. Univ.-Sternw. Wien, **28**, 211.
Norris, J. 1986, Astrophys. J. Suppl., **61**, 667.
Nowacki, H. 1935, Astron. Nachr., **255**, 301.
Ogorodnikov, K.F. 1965, Dynamics of Stellar Systems (Oxford: Pergamon), p. 45.
Perek, L. 1954, Contr. Astron. Inst. Brno., **1**, No. 12.
Peterson, C.J. 1974, Astrophys. J. Letters, **190**, L17.
Peterson, C.J., and King, I.R. 1975, Astron. J., **80**, 427.
Pier, J.R. 1984, Astrophys. J., **281**, 260.
Rastorguev, A.S., and Surdin, V.G. 1980, Astron. Tsirk., No. 1102.
Rodgers, A.W., and Paltoglou, G. 1984, Astrophys. J. Letters, **283**, L5.
Seitzer, P. 1985, in IAU Symposium No. 113, Dynamics of Star Clusters, J. Goodman and P. Hut, eds., Reidel, Dordrecht, p. 343.
Seitzer, P., and Freeman, K.C. 1981, in IAU Colloquium No. 69, Astrophysical Parameters for Globular Clusters, A.G.D. Philip and D.S. Hayes, eds., L. Davis Press, Schenectady, p. 185.
Strömberg, G. 1925, Astrophys. J., **61**, 353.
van Maanen, A. 1925, Astrophys. J., **61**, 130.
_____. 1927, Astrophys. J., **66**, 89.
von Hoerner, S. 1955, Zeit. Astrophys., **35**, 255.
_____. 1957, Astrophys. J., **125**, 451.
Wannier, P.G., and Wrixon, G.T. 1972, Astrophys. J. Letters, **173**, L119.
Webbink, R.F. 1981, Astrophys. J. Suppl., **45**, 259.
Woltjer, L. 1975, Astron. Astrophys., **42**, 109.
Woolley, R. 1978, Monthly Notices Roy. Astron. Soc., **184**, 311.
Zinn, R. 1985, Astrophys. J., **293**, 424.

DISCUSSION

KING: The existing tidal radii are only a first try, from star counts. One should now do a second generation study, using color-magnitude arrays to eliminate most of the field stars.

WEBBINK: Anything which distinguishes cluster stars from field stars will no doubt improve estimates of tidal radii.

KING: For proper motion studies, QSO's are essential; one QSO is worth twenty galaxies.

WEBBINK: QSO's are certainly far superior as reference objects, but I think one will still require large numbers of background objects to ensure good proper motion solutions.

COHEN: The new Palomar Sky Survey will include a very short exposure in an effort to extend the system of stars with absolutely known positions to the faintest stars measurable on PSSII. This should enable absolute proper motions to be determined from plates from large reflectors.

NORRIS: Your analysis of globular cluster kinematics makes no distinction between the disk and halo groups of Zinn. Have you repeated the analysis for the halo group alone?

WEBBINK: I have not attempted to do so. The number of free parameters in the solution is so large that I doubt one can obtain meaningful solutions from a much smaller sample, and the tangential components of the velocity ellipsoid become indeterminate unless the sample includes a large number of clusters inside the solar circle, where the Sun appears nearby at right angles from the galactic center, as seen from the cluster. For distant halo clusters, we see only the galacticentric radial component.

CAYREL: My question is about the best observational accuracy attainable in proper motion measurement for globular clusters. Is there a significant statistical gain due to the fact that each globular cluster is made of many point sources and not only one as for a normal single star proper measurement?

WEBBINK: In principal, I suppose what you say must be correct, but I would imagine that variations in seeing would make it very difficult to take advantage of this structure, and most background galaxies will undoubtedly have low signal-to-noise detections.

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