GAIA OBSERVATIONS OF GLOBULAR CLUSTERS AND DWARF SPHEROIDALS: FROM INTERNAL DYNAMICS TO THE MASS OF THE GALAXY

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ABSTRACT

The present concept for the GAIA interferometric astrometry satellite promises after realisation a great step forward for the knowledge of galactic globular clusters and dwarf spheroidals. In addition to the determination of cluster distances with up to 3% accuracy, there would also be dramatic improvements for internal velocities and space velocities of the clusters. The main problems remain in crowding and in the faintness of distant or reddened objects. GAIA observations of distant globulars and dwarf spheroidal galaxies can constrain the mass distribution and total mass of the Galaxy.

Key words: space astrometry; GAIA; globular clusters; dwarf spheroidal galaxies.

1. INTRODUCTION

The GAIA astrometric interferometry satellite in its present concept (Lindegren & Perryman 1994) is planned to measure positions and their changes with time for 50 million objects down to a magnitude of $V = 15$ mag. The accuracy at this magnitude is 10 μas for positions and parallaxes and 10 μas/yr for proper motions. This will be a tremendous step forward for the study of structure and kinematics of our Galaxy, providing e.g., distances accurate to 10% at 10 kpc. In this paper we concentrate on the study of globular clusters and dwarf spheroidal galaxies. We will briefly consider the consequences of accurate distance measurements, and investigate the potential of the GAIA accuracies for the study of internal structure of globular clusters and the space velocities as tracers of the Galactic gravitiational potential. We will show that these faint and crowded objects are difficult even for the present ambitious GAIA concept.

2. SCIENTIFIC OBJECTIVES AND STATE OF THE ART

2.1. Distances

Presently, the distances of population II objects like globular clusters and dwarf spheroidal galaxies are known with an accuracy of 10% at best. The distances are derived from the apparent magnitude $V_{\rm HB}$ of the horizontal branch. $V_{\rm HB}$ is quite easily measured, and the absolute magnitude of the HB is fairly constant, although its exact dependence on metallicity is controversial. Knowledge of the reddening $E(B-V)$ then leads to a distance. Peterson (1993) lists distances derived in this way as well as $E(B-V)$ and $V_{\rm HB}$ for the galactic globular clusters. Generally, higher reddening results in a higher uncertainty of the distance estimate, so that the distances of clusters in the direction of the galactic bulge are sometimes very uncertain. Figure 1 shows the distribution of distances for globular clusters and dwarf spheroidals, the latter taken from Gallagher & Wyse (1994). Some updated distance estimates from more recent papers have been included. The distribution peaks at 8–10 kpc and has a pronounced gap between 40 and 70 kpc.

An astrometric distance determination of a cluster through its brightest stars automatically applies to the fainter cluster members – just to mention astrophysically interesting objects like RR Lyrae stars, Blue Stragglers, X-ray binaries, or millisecond pulsars. One important application is the determination of cluster ages through isochrone fitting to the main sequence/turnoff region. Distance error is one of the major uncertainties of this method along with reddening, metallicity, and details of the evolutionary theory. For nearby clusters the astrometric parallax measurement would be a major improvement compared to the present indirect methods like horizontal branch magnitude or the field Population II subdwarf sequence. The reader is referred to Hemenway (1995) for a more detailed discussion.

2.2. Internal Dynamics

Radial velocities accurate to 0.5–1.0 km/s have now been measured in 36 globular clusters (Pryor & Meylan 1993). They have been used along with luminosity profiles from photometric observations for modelling the internal structure of some clusters (see Meylan & Pryor 1993 for a review). The addition of relative proper motions with comparable accuracy would add internal velocities in the remaining two coordinates, restricting considerably the parameter space for dynamical modelling of clusters. Possible outcomes are hard numbers on rotation, anisotropy, predominant orbital types (Wybo & Dejonghe 1995) and ultimately reliable determinations of the total mass and the mass-to-light ratio of the clusters under study.

An independent distance estimate, called astrometric distance, results from the assumption that the internal rms scatter of radial velocities and proper motions in globular clusters are equal. Clearly, a future astrometric satellite could promote this method, too.

Relative proper motions have been measured from photographic plates for stars in 27 globular clusters (Cudworth 1993 and more recent references). Depending on the plate material, the errors of individual proper motions range from 0.2 to 1.0 mas/yr. At the distances of the clusters, this corresponds to velocity errors of ≥ 3 km/s, but more typically 10 to 20 km/s. Rees & Cudworth (1993) used relative proper motions for the determination of astrometric distances to four globular clusters—some of them being preliminary—with work on six more in progress.

Figure 1. Thin line: histogram of heliocentric distances of globular clusters (Peterson 1993) and dwarf spheroidal galaxies (Gallagher & Wyse 1994). Out of scale are the dwarf spheroidals For, Leo II and Leo I at 145, 215, and 270 kpc, respectively. The thick line shows the distance distribution of the globular clusters with absolute proper motions (Dauphole et al. 1995).

2.3. Orbits and Space Motions

Absolute proper motions, together with radial velocities and distances, lead to space velocities and allow the computation of an orbit once a mass model for the Galaxy is assumed. The orbits are interesting individually and in a statistical manner.

Individual orbits indicate whether a globular cluster or dwarf spheroidal moves on a tube or box-type orbit (Brosche et al. 1995), rotates in a prograde or retrograde sense around the Galactic centre, or reaches very small galactocentric distances (where the survival probability is low). A cluster or dwarf spheroidal may be bound to the Galaxy, the LMC or SMC (Lin & Richer 1992), or to the newly discovered Sagittarius dwarf spheroidal (Ibata et al. 1994).

Once a large sample of orbits is available, correlations of orbital type with other parameters like metallicity (Dauphole et al. 1995) or slope of the mass function (Capaccioli et al. 1993) can be investigated. It is expected that the disk/halo globular cluster subsystems (Zinn 1985) can also be discerned from space motions. Subsystems of halo clusters originating in accreted dwarf galaxies (Searle & Zinn 1978, van den Bergh 1993) can be detected.

The distant group of globular clusters and dwarf spheroidals with $d > 50\,\mathrm{kpc}$ is of great potential interest. With space velocities and orbits of these objects one could constrain the mass of the Galaxy within 100 or even 200 kpc far better than from radial velocities alone (Zaritsky et al. 1989). From this follows the mass fraction of dark matter in the halo of the Galaxy. The orbits of distant Galactic satellites can be used to test the suggestion that dwarf spheroidals and globular clusters apparently aligned along great circles result from accretion and breakup of dwarf galaxies (Majewski 1994a, Majewski 1994b).

Dauphole et al. (1995) list 26 globular clusters for which absolute proper motions have been determined. In Fig. 1 these clusters are highlighted, showing that they do not yet form a representative sample of the Galactic globular cluster population. Moreover, the space motions have been derived by very different means of relating the relative proper motions to an inertial frame. For example, Cudworth & Hanson (1993) derived absolute proper motions for 14 globular clusters by representing the relative proper motions of field stars by a galactic model, while other authors obtained absolute proper motions directly by measuring cluster stars as well as galaxies. Typical errors are 0.5 to 1.5 mas/yr, corresponding to errors in the space velocities of 20 to 70 km/s, disregarding distance errors. Majewski & Cudworth (1993) have started a project to measure absolute proper motions of distant galactic satellites with respect to galaxies from deep photograpic plates. They report preliminary results for Pal 3 and Pal 5. The former result is quite remarkable, since the distance of Pal 3 is 91 kpc.

The Hipparcos astrometry satellite could not measure globular cluster or dwarf spheroidal stars due to faintness and crowding. However, it will provide positions and absolute proper motions for field stars, thus allowing to tie existing relative proper motions indirectly to an inertial frame. With about 2.9 stars per square degree the number of Hipparcos stars is, however, quite low. In addition, the extragalactic calibration of the Hipparcos proper motion system has to be performed indirectly itself, with an accuracy of 0.3 mas/yr at best (Kovalevsky 1996).

Hipparcos has observed several stars of the Magellanic Clouds. Probably the mean proper motions of the LMC and SMC will be known with an accuracy of 0.4 and 0.6 mas/yr, respectively, which is of the order of the effect itself (Jones et al. 1994). For GAIA the Magellanic Clouds will be quite easy objects, offering lots of stars brighter than $V = 15$. Excellent space motions of both Clouds can be expected from GAIA.

3. GAIA OBSERVATIONS

3.1. Crowding

The main problem in imaging observations of globular clusters is crowding. This will also be true for GAIA. In the interferometric mode of the present GAIA concept (Lindegren & Perryman 1994) stars will be observed in 27×13.5 arcsec^2 subfields. Within this subfield there is no spatial resolution, and all stars found in a subfield contribute their light and degrade the modulation (unless they happen to be in phase with respect to the modulating grid). For 2–3 relatively bright stars within the same subfield it will be possible to deal with this difficulty, since each observation is made under a different scan angle and contributes a pair of points in the spatial frequency (uv) plane. Using techniques similar to radio synthesis observations, the full spatial resolution of GAIA (0.05–0.1 arcsec) can be exploited.

This method, however, is not generally applicable for more than three stars in the same subfield. In addition, in the frequent case of stars near the limiting magnitude of the interferometric mode, the modulation itself is quite low and will be disturbed by the sea of underlying, fainter stars not observable individually. Depending on the aspect of the individual observation, the modulation will look different each time. The size of this effect and the limiting magnitude which could be achieved at different distances from a cluster centre would require careful modelling, similar to the case of surface brightness fluctuation observations of E galaxies.

In combination, these effects preclude observations in the very centre of globular clusters (excluding some loose and nearby clusters). It is hard to estimate the number of cluster stars otherwise bright enough which will be lost due to crowding. As a rule of thumb we expect that $\approx 50\%$ of the stars will be lost. The percentage will be lower for nearby, less reddened and loose clusters, but higher for distant, reddened and concentrated ones.

Smaller subfields would reduce this effect. Direct fringe detection would help greatly. In any case, a careful selection of target stars has to be done, either before the mission, if an input catalogue is needed, or after the mission, selecting the stars eventually to be used.

In the direct imaging mode, fainter stars can be observed with reduced accuracy. Using 0.1×4 arcsec^2 pixels, this mode is more favourable in terms of crowding. Still, for distant clusters subtending small areas on the sky a careful selection of stars will be necessary.

Dwarf spheroidals are very loose sytems compared to globular clusters. In addition they are so faint (with the exception of Sgr) that they have to be observed in the direct imaging mode with its small pixels. Thus, observations of dwarf spheroidals will have almost no crowding problems.

3.2. Limiting Magnitude

We now quite arbitrarily require that at least 10 stars have to be observed per cluster in order to obtain reasonable statistics for the mean parameters. Looking at the colour-magnitude diagrams of globular clusters, we suggest that observations down to 1 mag brighter than the HB ($V_{\rm lim} = V_{\rm HB} - 1$) are in the mean sufficient to achieve this requirement. Again, dwarf spheroidals are more favourable objects, since they are rich systems (the dwarf spheroidal with the smallest absolute magnitude is about as bright as the brightest Galactic globular cluster). Thus the giant branch is richly populated, and $V_{\rm lim} = V_{\rm HB} - 2$ is sufficient.

Figure 2 shows the distribution of $V_{\rm HB}$ for globular clusters (Peterson 1993) and dwarf spheroidals (Gallagher & Wyse 1994 and references therein). The $V_{\rm HB}$ distribution of clusters with low reddening peaks at $V = 16$ mag, so that about half of the clusters will provide a sufficient number of stars. For fainter objects, the number of stars observable in the interferometric mode will be smaller, and the direct imaging mode will become more and more important. The few (highly reddened) globular clusters with $V_{\rm HB} > 21$ mag are probably unobservable with GAIA.

Figure 2. Histogram of horizontal branch magnitudes $V_{\rm HB}$ for globular clusters and dwarf spheroidals (thin line) and for those systems with 'low' ($E(B{-}V) < 0.5$) reddening (thick line). The sources of the data are the same as for Fig. 1.

3.3. Distances

Direct distance determinations with an accuracy of 10 μas correspond to a 10% error for individual stars at 10 kpc. If 10 stars per cluster are observed, the same 10% error applies to the mean cluster distance at 30 kpc. Note, however, that parallax estimates within small fields on the sky are correlated for the scanning law of the Hipparcos satellite (Lindegren 1988), so that the full $\sqrt{N}$ factor probably cannot be applied. Due to the similar scanning law this result should also be applicable to GAIA observations.

For clusters at distances larger than about 30 kpc probably the present astrophysical methods will remain superior to direct astrometric measurements. But GAIA can contribute an important calibration step: direct distance determinations of nearby RR Lyrae stars will tie down the slope of the [Fe/H]–M_V(RR) relation, which is presently uncertain by almost a factor of two. This in turn can be used to calibrate the distances of distant globular clusters and dwarf spheroidals.

3.4. Internal Velocities

Since internal radial velocities of globular cluster stars are presently measured with accuracies of 0.5 km/s, we investigate the necessary proper motion accuracies which lead to an error in tangential velocity of 0.5 km/s from proper motions alone (i.e., disregarding distance errors).

In Table 1 we give for some distances d the limiting magnitude $V_{\rm lim}$ to be reached by GAIA, the required proper motion accuracy $\sigma_{\rm req}$ which leads to a tangential velocity error of 0.5 km/s at that distance, the GAIA proper motion error for a single star at $V_{\rm lim}$ and in the last column the real tangential velocity error from $\sigma_{\rm v,real} = 4.74\, d\, \sigma_{\rm GAIA}$. For $V_{\rm lim}$ brighter than 16 the GAIA proper motion errors are estimates for the interferometric mode of the satellite, for fainter magnitudes those of the imaging mode (Tables 3 and 4 of Lindegren & Perryman 1994). One sees from Table 1 that GAIA will indeed be able to measure internal proper motions of the required accuracy up to distances of about 20 kpc.

Table 1. Required proper motion accuracy $\sigma_{\rm req}$ to achieve a tangential motion error of 0.5 km/s at the distance d and the predicted proper motion errors from GAIA at the magnitude $V_{\rm lim}$

d [kpc]	$V_{\rm lim}$	$\sigma_{\rm req}$ [μas/yr]	$\sigma_{\rm GAIA}$ [μas/yr]	$\sigma_{\rm v,real}$ [km/s]
5	13.2	21	3	0.07
10	14.6	11	5	0.24
15	15.5	7	9	0.64
20	16.1	5	12	1.08
25	17.8	4	80	9.48

3.5. Space Velocities

Space velocites of globular clusters may reach some hundreds of km/s. In this paragraph we investigate the consequences of requiring that the contribution to the space velocity error from proper motion alone is 10 km/s (although mean radial velocities are already known with accuracies of 5 km/s or better for many clusters). This applies to the mean cluster motion; if we assume that GAIA observes 10 stars per cluster and that individual proper motions are uncorrelated, this leads to the requirement of a proper motion error for one star of 30 km/s at the distance of the cluster.

Table 2 gives in a way analogous to Table 1 the required proper motion accuracies at various distances and the accuracies achievable by GAIA. Space velocities of the demanded accuracy can be measured up to distances of about 70 kpc. For the majority of clusters the errors in space velocity from proper motion are small. The distant group of globular clusters and dwarf spheroidals, however, still poses a problem. In the next section we look at them in some more detail.

Table 2. Required proper motion accuracy $\sigma_{\rm req}$ to achieve a mean error of the tangential motion of a cluster of 10 km/s at the distance d and the predicted proper motion errors from GAIA at the magnitude $V_{\rm lim}$

d [kpc]	$V_{\rm lim}$	$\sigma_{\rm req}$ [μas/yr]	$\sigma_{\rm GAIA}$ [μas/yr]	$\sigma_{\rm v,real}$ [km/s]
10	14.6	630	5	0.24
20	16.1	320	12	1.08
50	18.1	125	80	19
90	19.5	70	230	98

3.6. Distant Objects

The globular clusters and dwarf spheroidal galaxies at galactocentric distances larger than 70 kpc are very important, since the knowledge of their space velocities would constrain the total mass of the Galaxy to a high degree. However, their individual stars are so faint that almost none of them will be observable by the interferometric mode of GAIA. Instead, the direct imaging mode will have to be used, which is less susceptible to crowding problems, but inherently less accurate.

In Table 3 we list the distant objects individually. Globular clusters and dwarf spheroidals are shown separately due to the different assumptions on the needed limiting magnitude ($V_{\rm lim} = V_{\rm HB} - 1$ and $V_{\rm HB} - 2$, respectively). The table gives the name of the object, its heliocentric distance, $V_{\rm lim}$ derived from the apparent $V_{\rm HB}$, the proper motion accuracy of GAIA for this magnitude (from Tables 3 and 4 of Lindegren & Perryman 1994) and the corresponding error of the space velocity from proper motion alone.

The ultimate column gives the number of stars brighter than $V_{\rm lim}$ for globular clusters, counted from published colour-magnitude diagrams and uncorrected for crowding losses. Only NGC 2419 offers a relatively large number of cluster stars for statistical averaging, while for the rest of the distant globular clusters one has to rely on a very small number of stars.

The situation is more favourable for the dwarf spheroidals. Sagittarius with its small distance is exceptional, but is also a difficult object due to crowding with bulge stars. For the other systems, the number of objects with sufficiently bright magnitudes is always large enough to allow sound statistical averaging. Even the distant Leo systems have ~ 60 and ~ 25 stars brighter than $V = 20$ (Leo II: Demers & Irwin 1993, Leo I: Lee et al. 1993). The achievable uncertainty of the mean space velocity is estimated to be: UMi to Car: 5–10 km/s, For: 15 km/s, Leo II: 45 km/s, Leo I: 110 km/s. Thus, the outermost dwarf spheroidals will at least constrain the parameter space for the available orbits, while the nearer dwarf spheroidals will have good space velocities worth to study on an individual base.

4. SUMMARY

The present GAIA concept (Lindegren & Perryman 1994) will allow to measure good distances out to 30 kpc. It promises a large improvement for the knowledge of internal motions in globular clusters up to 20 kpc. Excellent space velocities up to 50 kpc will result. The more distant objects will still have space motions with significantly small errors. An independent determination of the mass and mass-to-light ratio of the Galaxy would finally be within reach.

The main problems with observations of globular clusters and dwarf spheroidals are crowding and faintness. Crowding necessitates careful (pre- or post-)selection of target stars and could be largely overcome by the hypothetical direct fringe detection in the interferometric mode. The faintness of distant stellar systems will require observations in the less accurate direct imaging mode.

Smaller subfields (and smaller pixels) would reduce the

Table 3: Predicted accuracies per star for distant systems

Name	d [kpc]	$V_{\rm lim}$	σ_μ [μas/yr]	σ_v [km/s]	N ($V < V_{\rm lim}$)
Globular clusters					
Pal 14	72	19.1	170	58	5
Eridanus	80	19.2	190	72	11
NGC 2419	84	19.5	225	90	100
Pal 3	91	19.5	225	97	12
Pal 4	98	19.4	220	102	16
AM–1	126	19.9	300	180	5
Dwarf spheroidals					
Sagittarius	24	16.0	12	1.4	
Ursa Minor	69	18.0	80	26	
Draco	75	18.1	90	32	
Sculptor	78	18.1	90	33	
Sextans	87	18.2	95	39	
Carina	92	18.5	115	50	
Fornax	145	19.4	210	144	
Leo II	215	20.1	320	330	
Leo I	270	20.4	420	540	

crowding problems. The accuracy of results would benefit from pushing the observations to fainter magnitudes and to red passbands (since even unreddened red giant stars to be observed by GAIA have typical colours of $V - I = 1.5 - 2.0$ mag).

ACKNOWLEDGEMENTS

HJT thanks R. Wielen and J.-W. Pel for stimulating discussions. We acknowledge financial support from the Bundesministerium für Bildung, Forschung und Technologie for the Bonn programme on globular cluster proper motions under grant FKZ 50 00 91016.

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