Two Tables of Kinematic Tracers

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ABSTRACT:
Two versions of the table of selected Galactic kinematic tracers are provided. There are essential differences between them, they complement each other and are suited for different purposes. Table 1 adopts one specific absolute magnitude and one distance per tracer and maintains strict mathematical relations between the columns. Table 2 is based on Table 1, but allows a range of absolute magnitudes and distances and is therefore more easily interpreted by non-experts. Put side-by-side the two tables should be useful in technical discussions, e.g. of the GAIA photometric systems. The background and details of the tables are described.

The following Section 1.2 corresponds to Section 1.2 in the GAIA Study Report (GSR) thus the section numbering. The text is nearly identical to that in CUO-70.2, though the sequence of tracers in Table 1 is different. The text in Section 1.2 of the GAIA Study Report is abbreviated, e.g. no formulae are given.

Section 2 describes Table 2 which is identical to Table 1.1 in the GSR.

1.1 Overview

This section from the GAIA Study Report is omitted.

1.2 Structure and Dynamics of the Galaxy

The primary objective of the GAIA mission is the Galaxy, to observe the physical characteristics, kinematics and distribution of stars over a significant fraction of its volume, with the goal of achieving a full understanding of the Galaxy's dynamics and structure, and consequently its formation and history. GAIA will make this goal possible by providing, for the first time, a catalogue which will sample a large and well-defined fraction of the stellar distribution in phase space from which significant conclusions can be drawn for the entire Galaxy. Hipparcos did this for one location in the Galaxy, the Solar neighbourhood; GAIA will accomplish this for a large fraction of the Galaxy.

1.2.1 Galactic Structure

The most conspicuous component of the Milky Way is its flat disk which contains nearly 10^{11} stars of all types and ages orbiting the Galactic Centre. The Sun is located at 8.5 kpc from the Galactic Centre. The disk displays spiral structure, and also contains interstellar material, predominantly atomic and molecular hydrogen, and a significant amount of dust. The inner kpc of the disk also overlaps with the bulge, which is less flattened, and consists mostly of fairly old stars. At its centre lies a supermassive black hole of $\sim 2.9 \times 10^6 M_\odot$. Disk and bulge are surrounded by a halo of about 10^9 old and metal-poor stars, as well as $\sim$140 globular clusters and a small number of satellite dwarf galaxies. The entire system is embedded in a massive halo of dark material of unknown composition and poorly known spatial distribution.

The distributions of stars in the Galaxy over position and velocities are linked through gravitational forces, and through the star formation as a function of position and time. The initial distributions are modified, perhaps substantially, by small and large scale dynamical processes: these include instabilities which transport angular momentum (bars and warps), and mergers. The huge number of stars, impressive accuracy, and faint limiting magnitude of GAIA will quantify our understanding of the structure and motions within the bulge, the spiral arms, the disc and the outer halo, and will revolutionize dynamical studies of our Galaxy.

It is still unclear, for example, whether spiral arms are density wave enhancements in the background stellar distribution, or whether they are predominantly gas-dynamical, being regions of enhanced star formation. If a density enhancement exists, it will affect the stellar motions in a characteristic way, and this could be tested on the relatively nearby Perseus arm, about 2 kpc distant. Stellar motions would be determined for stars near the arm, both foreground and background (distinguished by their parallaxes), with proper motion accuracy requirements of some 100 μas yr^{-1}, corresponding to about 1 km s^{-1} in space velocity.

Understanding our Galaxy requires measurement of distances and space motions for large and unbiased samples of stars of different mass, age, metallicity, and evolutionary stage. GAIA's global survey of the entire sky is the ideal approach to define such samples of kinematic tracers. The following subsections describe GAIA's contributions to the many open issues regarding the structure of the main Galactic components in detail.

1.2.2 Distances and Velocities - Table 1

A schematic overview of the main Galaxy components or sub-populations, covering all Galactic distances, is given in Table 1. This list of relevant kinematic tracers, together with the requirements on astrometric accuracy and limiting magnitude is adapted from several previous studies (see CUO-70.2). A 'tracer' is a collection of objects (often stars) representing the kinematics of a given sub-population. The objects should be uniquely identifiable, and their absolute magnitude must be accurately measureable by means of GAIA astrometry and photometry. One or more tracers are mentioned for each sub-population, together with the typical absolute magnitude and location in the Galaxy (Columns 1–5), relevant photometric qualifiers (Columns 6–8), and relevant astrometric parameters (Columns 9–12), all defined in further detail in the key to the table.

Column 11 (the predicted relative proper motion measurement accuracy for the brighter stars of the population) shows that proper motions for single stars of all listed sub-populations of our Galaxy can be measured by GAIA with a significant, and often a superb, precision using the brightest tracer stars, and that very often the fainter stars, between V_1 and V_2, can also be used. The mean motion of many stars, for instance inside Galaxy satellites or of a whole globular cluster, will be much more accurately determined.

The analysis will often be carried out in terms of distribution functions of velocities using appropriate statistical methods. When velocities, i.e. km/s, are required the accuracy of distances will be crucial as we shall detail henceforth.

The values in Column 12 (the predicted relative error of distances derived only from the trigonometric parallaxes, for the brightest tracer stars) are usually much larger than the relative proper motion errors in Column 11. They will therefore dominate in the errors of tangential velocities since the relative errors combine as in Equation 4.

Typically, individual distances accurate to about 15 per cent and tangential velocities with accuracies of a few km s^{-1} are needed out to 20 kpc. For faint stars, this relative distance accuracy can only be obtained by accurate medium-band photometry, not by astrometry. According to Table 8.2 of the Study Report, the astrometric distance to a star of $V = 15$ mag at a distance of 10 kpc has an accuracy of 10 per cent. The astrometric distances may be used directly for tracer stars and to calibrate the photometric distances. Proper motions with accuracies of tens of μas/yr are required for large numbers of stars and this is possible to $V \simeq 18 - 19$ mag.

We shall here assume for simplicity that the coordinate components of the velocity scatter are equal and uncorrelated, and that the same is true for the measurement errors of proper motion. The velocity scatter is reckoned relative to the overall velocity of the sub-population, normal to the line of sight.

The typical proper motion scatter, ϵ_μ in arcsec yr^{-1}, is obtained as:

$$\epsilon_\mu = \epsilon_T/(C\,d) \tag{1}$$

where the expected tangential velocity scatter, ϵ_T, is given in Column 9, $C = 4.74$ km yr $(\mathrm{AU\ s})^{-1}$ and d is the distance in pc from Column 5.

The measuring precision for a proper motion, σ_μ, is given in Column 10 according to Table 8.2. The typical relative proper motion error is then

$$\sigma'_\mu = \sigma_\mu/\epsilon_\mu \tag{2}$$

given in Column 11.

The relative error on the distance, if obtained only from the trigonometric parallax, is given in Column 12, computed as

$$\sigma'_\pi = \sigma_\pi/\pi = \sigma_\pi d \simeq K\sigma_\mu d \tag{3}$$

The parallax error is here set to $\sigma_\pi \simeq K\sigma_\mu$ with $K = 1.3$ yr, representing the values in Table 8.2.

The observed tangential velocity T_{obs} [km s^{-1}] of a star, corresponding to the true value T, may be derived from the observed μ and d as $T_{\mathrm{obs}} = C\mu d$. The relative standard error of T_{obs} is given by:

$$\sigma_{T_{\mathrm{obs}}}/T_{\mathrm{obs}} \simeq [(\sigma_\mu/\mu)^2 + (\sigma_d/d)^2]^{0.5} \tag{4}$$

if the relative standard errors are $\ll 1.0$, and if the observations of μ and d are uncorrelated. This equation may be used with the Columns 11 and 12 to judge, e.g., for which tracer stars the GAIA trigonometric parallax (at magnitude V_1) is sufficiently accurate to give the tangential velocity. A relative error on tangential velocities about 0.2 or smaller is usually required to achieve the astrophysical goals.

It appears that the main contribution to the uncertainty of the tangential velocity often comes not from the error on proper motion, but from the error on the distance. In the cases where the distance must be obtained from photometry the relative error is at least about 15 per cent. The systematic observation errors will be much smaller than the individual errors so that mean motions and distances should be well determined.

It is also appropriate to emphasize how important it is to refer the proper motions in the Galaxy to a non-rotating reference frame (see Section 1.8.11 of the Study Report). If this were not done and if the GAIA reference system would simply be that of Hipparcos, it would have a residual uncertainty of 250 μas yr^{-1}. This would mean a systematic error of 6 km s^{-1} at 5 kpc and 12 km s^{-1} at 10 kpc. The Galactic rotation speed at these distances is of the order of 250 km s^{-1}. It is possible, with data from tens of thousands stars to determine the galactic rotation curve with an internal precision of 1 km s^{-1} (a few μas yr^{-1}). The addition of an error rotation vector in a random direction of several km s^{-1} would introduce biases not only in the rotation speed which is an indicator of the dynamical properties of the Galaxy, but also in the position of the plane of rotation, equivalent to producing a fictitious warp.

2 The two tables of kinematic tracers

We provide two versions of the table of kinematic tracers, here called Table 1 and Table 2. There are essential differences, they complement each other, they are suited for different purposes.

Table 1 is the basic one described in SAG-CUO-70.2 as Table 2. The present Table 2 was derived from Table 1 by G. Gilmore, which is presented in the SPIE paper version 29 Feb as Table 1 and in the final GSR as Table 1.1.

2.1 Table 1

Table 1 considers in each row a typical tracer star with a specific absolute magnitude M_V (column 1), an optimal distance d (column 5), typical visual extinctions A_V (column 6), and expected velocity dispersions ϵ_T (column 9). From these values the columns 7, 8 and 10 were computed, and finally columns 11 and 12 using the known GAIA astrometric precision as function of magnitude for V_1 (see Section 1 for details, including formulae).

2.2 Table 2

Strict mathematical relations between the column values cannot be given for Table 2. Gilmore gives reasons for producing Table 2:

The value of summary tables is that they indicate the type of science we will achieve, not a few exact specific cases. Thus, typical numbers, and ranges are more suitable than are a few exact numbers, interpretable in context only by an expert after careful reading. A non-expert, reading exact numbers, can easily get a very wrong impression.

Let me give just three examples of how numbers have been generalised to minimise opportunities for readers to make wrong, but nonetheless common, misconceptions of the relevance and significance of GAIA: in the table, numbers are now quoted for the whole range over which globular clusters can be studied, rather than for one specific case, to avoid the incorrect impression that we can study only the nearest one. The distance range for the Galactic bulge HB has also been generalised, to avoid an impression that GAIA will study only a delta-function in magnitude of stars, or that we somehow imagine the bulge has zero depth, or that the HB has zero intrinsic spread: the bulge HB is of course more vertical than horizontal.

2.3 Discussion

The Table 1 should be used by the experts, e.g. in discussing the choice of photometric systems. Table 2 should also be used by experts being fully aware of the differences between Table 1 and 2. Table 2 is better suited for presentation of GAIA to a general audience.

The changes from Table 1 to 2 are not very easily recognised because the headings of the columns and the whole column 1 are identical. The changes are :

One decimal less is given in columns 7, 8, 11.

The quantities V_1, V_2 (in columns 7, 8) have been given a significantly different meaning and obtain different values. They give the "typical" range of apparent visual magnitudes as the

Key says. This range includes the spread of absolute magnitude, while in Table 1 no such spread is included. V_1, V_2 are not always consistent with the extinction in column 6.

The columns 11 and 12 in Table 2 are the same as in Table 1. They do therefore *not* correspond to the GAIA astrometric precision at the magnitude V_1 in Table 2.

A change in Table 2 for the distance in column 5 is very significant. The distance for globular cluster (gK stars) has been changed from 8 kpc to 50 kpc, and $V_1 = 12, V_2 = 21$. The distance is now called "optimal or practical distance", and the relative parallax error in column 12 is 0.10. In Table 1 we have $V_1 = V_2 = 15.5$ as derived from $M_V = +1$ and $d = 8$ kpc. This gives 0.10 as relative parallax error in column 12.

2.4 Conclusion

It seems that both tables can give rise to confusion or misinterpretations unless great care is exercised. Used with caution they are both indispensable. - The user might, e.g., cut out columns 5 to 8 of Table 1 and place them besides of Table 2. The other columns are essentially identical.

The Appendix to CUO-70.2 contains a still valid discussion of the tracers in the tables and of possible further tracers.

3 References

Wozniak P.R., Stanek K.Z. 1996, ApJ 464, 233

Kiraga M., Paczynski B., Stanek K.Z. 1997, ApJ 485, 611

Table 1: Original table from which Table 2 was derived. Summary of selected Galactic kinematic tracers, and the limiting magnitudes and astrometric information necessary to study them.

(1) Tracer	(2) M_V mag	(3) ℓ deg	(4) b deg	(5) d kpc	(6) A_V mag	(7) V_1 mag	(8) V_2 mag	(9) ϵ_T km/s	(10) σ_{μ_1} μas/yr	(11) σ'_{μ_1} –	(12) σ'_{π_1} –
Bulge:											
gM	–1	0	< 20	8	2–10	15.5	23.5	100	10	0.004	0.10
HB	+0.5	0	< 20	8	2–10	17	25	100	20	0.008	0.21
MS turnoff	+4.5	1	–4	8	0–2	19	21	100	60	0.023	0.62
Spiral arms:											
Cepheids	–4	all	< 10	10	3–7	14	18	7	5	0.034	0.06
B–M Supergiants	–5	all	< 10	10	3–7	13	17	7	4	0.027	0.05
Perseus arm (B)	–2	140	< 10	2	2–6	11.5	15.5	< 10	3	>0.003	0.01
Thin disk:											
gK	–1	0	< 15	8	1–5	14.5	18.5	40	6	0.006	0.06
gK	–1	180	< 15	10	1–5	15	19	10	8	0.040	0.10
Disk warp (gM)	–1	all	< 20	10	1–5	15.0	19.0	< 10	8	>0.038	0.10
Disk asymm. (gM)	–1	all	< 20	20	1–5	16.5	20.5	< 10	15	>0.140	0.39
Thick disk:											
Miras, gK	–1	0	< 30	8	2	15.5	15.5	50	10	0.008	0.10
HB	+0.5	0	< 30	8	2	17	17	50	20	0.015	0.21
Miras, gK	–1	180	< 30	20	2	17.5	17.5	30	25	0.080	0.65
HB	+0.5	180	< 30	20	2	19	19	30	60	0.190	1.56
Halo:											
gG	–1	all	< 20	8	2–3	15.5	16.5	100	10	0.004	0.10
HB	+0.5	all	> 20	30	0	18	18	100	35	0.050	1.36
Gravity, $\mathcal{K}_\mathcal{Z}$:											
dK	+7–8	all	all	2	0	19	19	20	60	0.008	0.16
dF8-dG2	+5–6	all	all	2	0	17	17	20	20	0.003	0.05
Glob. clusters (gK)	+1	all	all	8	0	15.5	15.5	100	10	0.004	0.10
kinematics (gK)	+1	all	all	8	0	15.5	15.5	15	10	0.025	0.10
Satellite orbits (gM)	–1	all	all	100	0	19	19	100	60	0.280	7.80

Key: (1) tracer of a specific sub-population: the table is simplified for the sake of a concise overview *[HB: signifies either blue horizontal branch, RR Lyrae, red horizontal branch, or clump giants, as appropriate; data for the bulge MS turnoff in Baade's Window are from Wozniak & Stanek (1996) and Kiraga et al. (1997); for globular clusters, the cluster itself is used as the tracer object, with its proper motion derived from the mean of many cluster star motions; globular cluster and satellite kinematics refer to the internal kinematics of globular clusters and satellites of our own Galaxy];* (2) corresponding absolute visual magnitude of a typical tracer star; (3–4) appropriate Galactic coordinates; (5) optimal distance, or upper distance limit, at which to study such a tracer to achieve fundamental astrophysics; (6) typical visual extinction along the line of sight, but for low latitudes the extinction in a Galactic window is given; (7–8) range of apparent visual magnitudes computed from the range of A_V and the given M_V and d, i.e. $V = M_V + 5\log d - 5 + A_V$, without any spread in the population; (9) approximate expected velocity scatter for tracer stars of the sub-population, normal to the line of sight (i.e. tangential to the celestial sphere); (10) expected GAIA proper motion standard error, σ_{μ_1}, for a single star at magnitude V_1 according to Table 8.2 of the Study Report in which, for example, the error increases by a factor 1.6 per magnitude at $V = 17$; (11) corresponding relative proper motion error at magnitude V_1 (see Equation 2); (12) expected relative error on GAIA astrometric distances at magnitude V_1 (see Equation 3).

Table 2: This table is identical with Table 1.1 in the GAIA Study Report. Summary of selected Galactic kinematic tracers, and the limiting magnitudes and astrometric information necessary to study them. Columns 7–8 demonstrate that the faint magnitude limit of GAIA is essential for probing these different Galaxy populations, while columns 11–12 demonstrate that GAIA will provide data of adequate precision to meet the scientific goals.

(1) Tracer	(2) M_V mag	(3) ℓ deg	(4) b deg	(5) d kpc	(6) A_V mag	(7) V_1 mag	(8) V_2 mag	(9) ϵ_T km/s	(10) σ_{μ_1} μas/yr	(11) σ'_{μ_1} –	(12) σ'_{π_1} –
Bulge:											
gM	–1	0	< 20	8	2–10	15	20	100	10	0.01	0.10
HB	+0.5	0	< 20	8	2–10	17	20	100	20	0.01	0.20
MS turnoff	+4.5	1	–4	8	0–2	19	21	100	60	0.02	0.6
Spiral arms:											
Cepheids	–4	all	< 10	10	3–7	14	18	7	5	0.03	0.06
B–M Supergiants	–5	all	< 10	10	3–7	13	17	7	4	0.03	0.05
Perseus arm (B)	–2	140	< 10	2	2–6	12	16	10	3	0.01	0.01
Thin disk:											
gK	–1	0	< 15	8	1–5	14	18	40	6	0.01	0.06
gK	–1	180	< 15	10	1–5	15	19	10	8	0.04	0.10
Disk warp (gM)	–1	all	< 20	10	1–5	15	19	10	8	0.04	0.10
Disk asymmetry (gM)	–1	all	< 20	20	1–5	16	20	10	15	0.14	0.4
Thick disk:											
Miras, gK	–1	0	< 30	8	2	15	19	50	10	0.01	0.10
HB	+0.5	0	< 30	8	2	15	19	50	20	0.02	0.20
Miras, gK	–1	180	< 30	20	2	15	21	30	25	0.08	0.65
HB	+0.5	180	< 30	20	2	15	19	30	60	0.20	1.5
Halo:											
gG	–1	all	< 20	8	2–3	13	21	100	10	0.01	0.10
HB	+0.5	all	> 20	30	0	13	21	100	35	0.05	1.4
Gravity, $\mathcal{K}_\mathcal{Z}$:											
dK	+7–8	all	all	2	0	12	20	20	60	0.01	0.16
dF8-dG2	+5–6	all	all	2	0	12	20	20	20	0.01	0.05
Globular clusters (gK)	+1	all	all	50	0	12	21	100	10	0.01	0.10
internal kinematics (gK)	+1	all	all	8	0	13	17	15	10	0.02	0.10
Satellite orbits (gM)	–1	all	all	100	0	13	20	100	60	0.3	8

Key: (1) tracer of a specific sub-population. HB: signifies blue and red horizontal branch as appropriate; for globular clusters, the cluster itself is used as tracer, with its proper motion the mean of many cluster star motions; globular cluster kinematics refers to the internal kinematics of globular clusters of our own Galaxy; (2) absolute visual magnitude of a typical tracer star; (3–4) appropriate Galactic coordinates; (5) optimal or practical distance; (6) typical visual extinction along the line of sight; for low latitudes the extinction in a Galactic window is given; (7–8) typical range of apparent visual magnitudes; (9) expected velocity dispersion for tracer stars of the sub-population, in the proper motion direction; (10) expected GAIA proper motion standard error, σ_{μ_1}, for a single star at representative magnitude; (11) relative proper motion error; (12) expected relative error on GAIA astrometric distances at representative magnitudes.