A Table of Kinematic Tracers – Issue 2, 5 Nov.

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ABSTRACT:
Proposed for the red report: new sections 2.2.1, 2.2.2 with Table 2.1
Further explanation to the table is contained in an appendix (Sect. 4).

Your comments are welcome; if received before 12 Nov. they may be taken into account in version 1.5 of the red report. E.g., do you think that the tracer stars in Table 3 should be included in Table 2 ? Comments on Sections 4.2.1 and 4.5, Reservation and Conclusions, are invited.

2.1

2.2 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.

2.2.1 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.

2.2.2 Distances and Velocities

A schematic overview of the main Galaxy components or sub-populations, covering all Galactic distances, is given in Table 2. This list of relevant kinematic tracers, together with the requirements on astrometric accuracy and limiting magnitude is adapted from []gh95 and []gp97. 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 **??**, 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.

Table 2: 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} –
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
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
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
Gravity, $\mathcal{K}_Z$:											
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
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
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
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
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
kinematics (gM)	−1	all	all	100	0	19	19	< 10	60	>2.800	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 **??** 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).

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 (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 **??**. 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 **??**.

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

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

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 **??**). 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.

3 References

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

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

References for the Appendix:

Ryan and Lambert 1995, AJ 109, 2068 [DDO for metal poor giants]

Fresneau A., Acker G., Jasniewicz, Piat M. 1996, AJ 112, 1614

4 Appendix: Further explanation to the table

4.1 Discussion of the table

The table of Galactic kinematic tracers was originally presented by Gilmore and Høg (1995, ESA SP-379, 95). It was contained in version 1.4 of the red report without any changes, except that the original columns 11 and 12, related to the precision of GAIA 'incoherent' mode had been omitted because they were obsolete.

Some problems of the table have been discussed by E. Høg, J. Knude (24 Sep. 1998, SAG-CUO-47). The abstract reads: "Questions to SWG/PWG: Is the present GAIA photometry of stars sufficient to detect significant kinematic tracers and to determine their absolute magnitude and distance as required for study of all parts of the Galaxy ? How frequent are the proposed tracers in the sky ?"

We have only recently made progress in answering these and other questions through discussions among the present authors and with M. Perryman and G. Gilmore.

The table will be important, e.g., in our coming comparison of proposed photometric systems for GAIA, including broad-band and medium-band photometry.

4.2 Changes of description

The description in Section 2.2.2 contains a much more precise definition of the various quantities than given before, including formulae and improved caption to the table. The Column 10 with the precision of GAIA proper motions is reintroduced with the actually expected values. The proper motion scatter, ϵ_μ, is defined in Equation 1, and the typical relative error for a typical single tracer star proper motion, σ'_μ, is defined in Equation 2 and is given in Column 11.

The word 'dispersion' in the original text has been replaced by 'velocity scatter', 'proper motion scatter' etc. Gilmore argued that the word dispersion could imply for some readers that a statistical treatment is meant to determine only the old-fashioned dispersions. Gilmore then proposed to write "rms velocity", but that would be wrong. It is rather the standard deviation of the velocity, i.e. a characteristic width of the distribution function. (The rms velocity for bulge stars would be in excess of 300 km/s.) We do not want to give the typical **velocity**, but the typical **scatter**.

Gilmore writes: "... since the whole emphasis of the scientific case is to quantify distribution functions. This table, which is a short summary of the science case, will probably be the most read part of the case, so it is important to get the subtle impressions conveyed reliably...".

4.2.1 Reservation

This sounds great and we show in Table 2 that the proper motion accuracy is sufficient. But Column 12 shows that the distances are critical. We have not proven that the distances for the faint and far away stars can be determined well enough, or that all tracers can be selected by means of GAIA photometry. Especially the K and M giants are problematic, but also gG. This reservation should be mentioned, e.g. at the beginning of Section 2.2 showing our awareness.

4.3 Changes of tracer stars

The tracer stars have been changed for some sub-populations, or some names have been changed. The capability of GAIA photometry to determine distances and astrophysical parameters for HB and gK stars appears to be crucial. The gM stars are more difficult photometrically than gK by which they have been replaced in a number of cases. But the photometry of gK stars is also a difficult problem which ought to be discussed.

Five new lines of tracer stars have been added, compared with the original table:
Gravity with dF8-dG2 stars;
Perseus spiral arm;
Bulge by HB stars;
Bulge by MS turnoff;
Globular cluster kinematics.

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1) We have changed to the term HB (horizontal branch) for all
   tracers on the HB (which includes clump stars, RR Lyrae stars, and
   red and blue horizontal branch stars). These are all the same thing
   astrophysically, except for different age/metallicity, and all have
   the same absolute magnitude (M_V=+0.5). Hence for the halo we changed
   RR Lyrae --> HB (this would then include about 10 times more tracers,
   since this is the ratio of HB/RR-Lyrae stars in all populations).
   Same comment goes for the thick disk and bulge rows. A footnote
   to the table explains that HB means either "blue horizontal branch,
   RR Lyrae, red horizontal branch or clump stars, as appropriate."

2) On the gM stars. We keep to gM for the problems of

    o disk warp
    o disk asymmetry
    o satellite orbits
    o satellite kinematics

    in these 4 cases gM is the best choice since the distances can be
    established either by other means or is not important.

  for the remaining gM rows in the table, we changed as follows:

    o Halo --- change gM to gG. In the halo, the metal weak stars are
      hotter at the same absolute magnitude as in the disk... in
      other words, in the halo, G-giants are M_V = -1, and there are
      actually very few gM stars.

    o Thin disk --- the brightest K giants are about M_V = -1, as was
      shown by H{\o}g & Flynn (1998, MNRAS 294, 28) on the giants in Hipparcos.
      We have changed gM to gK in the thin disk rows without
      loss of generality. We showed in our paper that their absolute
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magnitudes/metallicities can be established by photometry,
so gK at M_V = -1 is a tractible place to work.
But DDO photometry for metal poor giants has been critized by
Ryan and Lambert (1995). So, our position is that the problem
of determining the metallicity and absolute magnitude of
distant K giants remains a difficult issue. Our hope is that
Stromvil photometry will be adequate for this, but this has
to be demonstrated with observations, not just model
calculations. This is true for any adopted photometric system.

o K_Z --- We have changed the (l,b) in the K_Z column to "all sky"
rather than just at the galactic pole, since a 3-D map of the
mass distribution around the Sun out to about 2 kpc in all
directions should be a simple task with GAIA, i.e. one is not
restricted to the vertical directions above and below the Sun
alone.

4.4 Discussion of other tracer stars

Three lines of tracer stars introduced in issue 1 of CUO-70 have been omitted from the large table since we should restrict discussion to major questions which need GAIA.
Gravity with gK; omitted
Dark halo; omitted
Recent mergers; omitted in the large table, but called 'Young disk' in the following small table.

We introduce A, B and dK–dM spectral type tracer stars for young disk in Table 3.

We propose to introduce these 5 lines in the big table.

Table 3: Examples of proposed faint stars of early spectral type as 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} –
Thick disk:											
dG0	4.5	all	< 30	3	1–5	18	22	40	60	0.021	0.23
Thin disk:											
dG0	4.5	all	< 15	3	1–5	18	22	40	60	0.021	0.23
Young disk:											
A	+1	all	all	5	1–5	15.5	19.5	50	6	0.003	0.05
B	−2	all	all	30	0–8	15.5	23.5	50	6	0.017	0.23
dK–dM	+7	all	all	1	0–2	17	19	5	20	0.019	0.03

Faint F and G stars The dF8–dG2 stars included for the study of 'Gravity' in Table 2 are

at the limit for which radial velocities are obtainable with GAIA.

In the Galactic disk the dF–dG2 stars should be taken to as faint limit as possible (see Table 3) since they will be good tracers of the rotation curve and because their photometry is so well understood, the classification limit is about $V = 18$ mag. They are also important for determining the distribution of W velocities at $z = 0$ pc as function of T_{eff}, log$g$, [Fe/H] and age. GAIA can obtain the W and $(U^2 + V^2)^{\frac{1}{2}}$ velocity component at all longitudes in the Galactic plane from accurate medium-band photometry and astrometry down to $V = 18$. The U and V components may be obtained separately from the same data, but only at certain galactic longitudes (U for $l \sim 90$ and 270 deg, V for $l \sim 0$ and 180). The RVs to $V = 16$ are also important.

FAME satellite In general, the potentials of obtaining the F and G stars to the faint magnitudes possible with GAIA have not been sufficiently discussed in the science case. It is not correct when it has been said that such science can be done with FAME, given its ten times larger astrometric errors, a limiting magnitude about $V = 15$, only Sloan photometry, and no radial velocities. In fact only one of the lines in Tables 2 and 3 can be done with FAME, i.e. the Perseus arm, but still an order of magnitude less accurately than with GAIA.

Young disk The A and B stars are included as tracers of young stars with abnormal kinematics. The A stars have been studied by e.g. Lance 1988 (ApJ 334, 927), Knude 1997 (A&A 327, 90). Such stars and even younger ones, 20 – 50 Myr only, may be related to merging, see Rolleston et al (1999, Rolleston, WRJ, Dufton,PL, McErlean, ND, Venn, KA A&A 348, 728). One could imagine that the Sgr dwarf speroidal, or other systems, could cause similar star formation. The stars do obviously not form a major fraction of the Galaxy's stars but since they are absolutely bright, $M_V \leq -2$ for the B stars and $M_V \leq 1$ for the A stars, and since they possibly trace phenomenae resulting from a dynamic process as merging they seem important. Therefore photometry and astrometry should be obtained to the classification limit. Radial velocities would also be very interesting, but they will be difficult to obtain because the stars may be metal poor as the B stars between SMC and LMC. A search for an HI trail of the Sgr dsph has begun (see Burton, WB, Lockman, FJ 1999 A&A 340, 7), but so far only in a small area.

The B stars between SMC and LMC (see Rolleston et al. 1999) have V=15.5 and are at 45 kpc distance. Proper motions would be very interesting.

The dK–dM stars will possibly allow to determine the dynamic effects from the passing of a density wave (Fresneau et al. 1996).

4.5 Conclusions

The photometric classification of gK stars is a serious problem. The photometric classification of gM stars is even more difficult, but the gM stars are no longer crucial for the table.

dF–dG star have been neglected in the science case.

The B and A stars with abnormal kinematics is an important issue.