Stellar Dynamics in the Milky Way – issues affecting the GAIA RVS

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Mark Wilkinson, Institute of Astronomy, Cambridge

1 Introduction

A key science driver of the GAIA mission is to determine the current dynamical state and formation history of the Milky Way. Radial velocities provide the 6th phase space coordinate, vital for building a complete picture of the stellar dynamics in the Galaxy. An unbiased sample of radial velocities is an essential complement to the GAIA proper motion data set – the lack of a publicly available, complete radial velocity data set for the Hipparcos catalogue makes the dynamical modelling of the existing data significantly more complicated. In fact, as pointed out by Binney et al. (1997) the non-uniform follow-up of stars in the Hipparcos sample meant that the data set with full velocity information was kinematically biased, greatly reducing its value. Clearly, the spectral resolution and magnitude limit of the RVS determine the fraction of the GAIA data set for which we will have full phase space information. At the RVS-III meeting in Ljubljana I drew the following conclusions for the general requirements of the RVS in order to observe all the main components of the Milky Way, based on existing literature:

1. Required magnitude limit: $\mathrm{M_v} \sim 17.5$
2. Required radial velocity accuracy at this limit: $\Delta v \lesssim 10\mathrm{km\,s^{-1}}$

This contribution focuses on the issue of crowding, and discusses the possible trade-offs which should be made. The main conclusion is that the science goals require further refinement in conjunction with more detailed modelling of the actual performances of the instrument. In particular, optimising the RVS to be able to target some low-latitude fields may not be the optimal use of the instrument.

2 The Bulge/Bar

Understanding the Milky Way Bulge/Bar is a problem which has attracted a great deal of attention in the literature, as it affects our understanding of the formation of bulges and bars, the way in which their stellar populations were built up and the details of the gravitational potential in which they lie. Radial velocities are essential to distinguish between the kinematics of an axisymmetric bulge and a triaxial bar (Vauterin & Dejonghe 1998) – proper motions alone are not sufficient. Further, coverage of many lines of sight through the Bulge is required as the orientation of the Bar means that not all windows provide equally constraining data. Current observations are limited to low extinction windows (e.g. Baade's window) – the patchiness of Galactic extinction will allow GAIA to observe stars in many new regions. Typical line of sight velocity dispersions are $\sim 100\ \mathrm{km\,s^{-1}}$, with variations along l.o.s. of $\sim 30\ \mathrm{km\,s^{-1}}$ depending on model details. Of course, the main limitation comes from crowding as all relevant fields are at low latitudes.

Because the velocity dispersion is fairly large, individual velocity errors of $\lesssim 25\mathrm{km\,s^{-1}}$ are tolerable (if only the only quantity we want to measure is the dispersion). Distance uncertainties will dominate the error budget for Bulge stars, and there is therefore no compelling reason to obtain higher precision radial velocities. To estimate the line of sight velocity dispersion to an accuracy of $\sim 10\mathrm{km\,s^{-1}}$ requires ~ 100 stellar velocities. However, since we also require the dispersion as a function of distance through the bulge a sample of ~ 1000 stars per low extinction window at all distances through Bulge is necessary. Obviously, significantly larger samples are required for more detailed modelling. For example, Vauterin & Dejonghe (1998) required 1400 stars just to distinguish between axisymmetric and non-axisymmetric bulge models assuming uniform coverage of the Bulge. In terms of the RVS, the key parameter to note is that on the near side of the Bulge the RGB tip is at an apparent magnitude of $\mathrm{m_V} \sim 14.5$. To avoid picking up AGB stars whose velocities may be less reliable, we need to observe at least ~ 0.5 mag below the RGB tip. Given that the Bulge has a line of sight depth of ~ 0.5 mag, we must probe significantly fainter than $V \sim 15$ to see both sides.

The primary difficulty with observing the bulge is obviously the crowded nature of the fields. Outside the region $|b| < 15$ and $|l| < 15$ there are < 10 Bulge stars deg^{-2} brighter than $V \sim 16$. The presence of large amounts of foreground extinction reduces this density even further with the result that it is only in low-extinction windows that the Bulge is clearly visible. Unfortunately, these are exactly the regions where crowding most strongly degrades the performance of the RVS. Even the most optimistic estimates of the RVS capabilities (Zwitter, Monte Rosa meeting) show that the number density of stars in regions such as Baade's window is uncomfortably high.

In view of the fact that the majority of fields containing significant numbers of Bulge stars will probably not be accessible to the RVS, it is worth considering removing the Bulge from the list of priorities for the RVS instrument. While this might seem to be a backward step, it is worth noting that a systematic

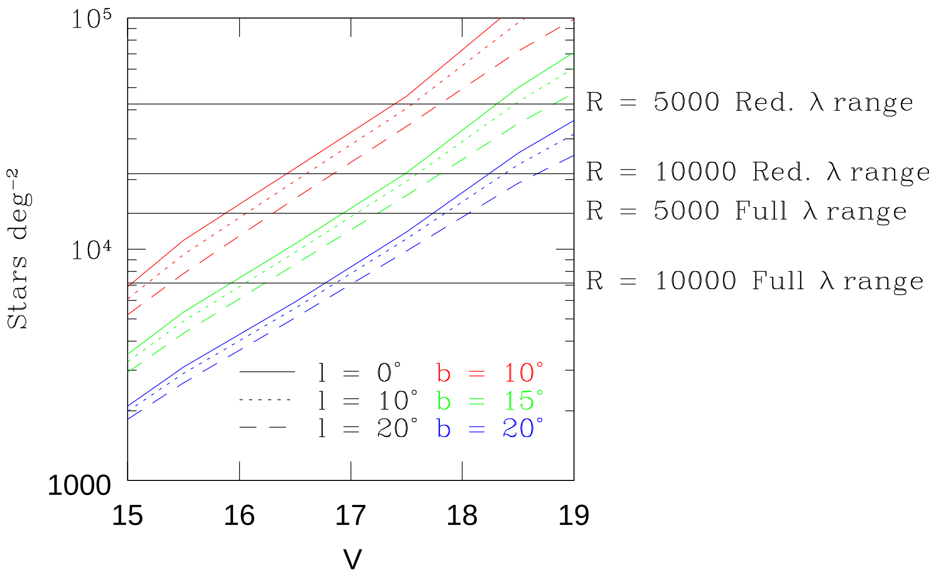

Figure 1: Estimated RVS performance for fields between $b = 10°$ and $b = 20°$. See text for details

ground-based follow-up program (e.g. RAVE, etc.) could conceivably map all the regions of interest in the Bulge, with a velocity accuracy significantly better than the RVS. It seems inadvisable to optimise the RVS to work at low latitudes if it will not be competitive with such programmes, particularly if this optimisation comes at the expense of other information of scientific interest (e.g. detailed spectral information such as abundances, etc.). Before taking such a decision, the following information is required:

1. Which regions of the sky are actually inaccessible to the RVS with the current specifications?
2. Can a ground-based program be initiated which will provide a publicly accessible data base of velocities on a similar timescale to the release of the GAIA proper motion data set?

Point 1 is the most urgent, and can be addressed in the coming months by applying the available RVS simulators to observed data fields. If, as appears likely, the RVS will be able to cover all regions except those towards the Galactic Centre, then reducing the priority of observing the Bulge may be the best course of action.

3 RVS limiting magnitudes

Fig 1 shows the cumulative numbers of stars brighter than a given V magnitude for fields between galactic latitudes of 10° and 20°. The data are taken from the Besancon galaxy model (supplied by Robin). The figure also shows the maximum number of stars per $\deg^{-2}$ which can be accommodated by the RVS for resolutions of 5000 or 10000 and assuming either the full spectral range proposed, or a reduced range covering only one third of the proposed spectral range (two of the calcium triplet lines). The limits displayed were calculated assuming that the limiting density of stars was reached when the CCD was uniformly covered with rectangular spectra. In generating this plot, no account was taken of the variation of performance for different spectral types and the stars were plotted only as a function of V magnitude. Bearing in mind the simplicity of the calculation, the figure illustrates the fact that a limiting magnitude of $V \sim 17$ is easily achievable with a resolution of 10000 outside 20° and even at $\sim 10°$ if the spectral range is reduced. Since the RVS is essentially observing in the I-band, the above limits become approximately $1-2$ mag brighter (assuming $V-I$ colours of $\sim 1-2$). While this means that the accuracy of the radial velocities will be more than sufficient, it also means that contamination due to background spectra may be more serious than Fig. 1 would suggest since if the limit of the RVS were $I \sim 17.5$ the stellar densities would correspond to those of $V \sim 19$.

In what follows, estimates of the kind described above were used to determine whether the RVS capabilities are appropriate for the various Galactic components. Realistic simulations of the performance of the RVS on actual observed fields are underway. These are essential to confirm that the approximate numbers presented here are reliable.

4 Requirements for Disk components

The data presented here combine information from Table 1.1 of the GAIA science case with more recent estimates of the performance of the RVS. They are given here to give an idea of the minimum requirements for modelling different disk components.

4.1 Thin Disk

- Typical tracer: gK
- Typical metallicity: [Fe/H] ~ 0.0.
- Typical extinction: $A_v = 1-5$
- Required magnitude limit: $V = 17$ ($14 < m_V < 19$)
- b values: $b < 15°$

- Typical (one dimensional) velocity dispersion: $10 - 40\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 2.5\mathrm{km\,s^{-1}}$ at $V \sim 16$ @ 10kpc ($l = 180^\circ$)
- Required v_r accuracy: $\sim 2 - 3\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy at V=$15 - 16$ (even without tilt mechanism).
- Low resolution allows limiting magnitude $V \sim 16.5$ at sufficiently low Δv_r and $V \sim 17$ with $\Delta v_r \sim 8\mathrm{km\,s^{-1}}$

4.2 Thick Disk

- Typical tracer: Miras, gK
- Typical metallicity: [Fe/H] $\lesssim -0.5 \implies v_r$ accuracies shift by $\lesssim 0.5$ magnitudes.
- Typical extinction: $\mathrm{A}_v \sim 2$
- Required magnitude limit: $\mathrm{V} = 17$ ($15 < \mathrm{m_v} < 19$)
- b values: $b < 30^\circ$
- Typical (one dimensional) velocity dispersion: $30 - 50\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 11.5\mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 8kpc ($l = 0^\circ$) $\sim 18\mathrm{km\,s^{-1}}$ at $V \sim 17$ @ 20kpc ($l = 180^\circ$)
- Required v_r accuracy: $10 - 20\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy (even without tilt mechanism) and limiting magnitude (except for low b)

4.3 Tracing Spiral Structure

- Typical tracer: Cepheids
- Typical metallicity: [Fe/H] $\gtrsim -0.5$
- Typical extinction: $\mathrm{A}_v = 3 - 7$
- Required magnitude limit: $\mathrm{V} = 17$ ($16 < \mathrm{m_v} < 18$)
- b values: $b < 10^\circ$
- Typical (one dimensional) velocity dispersion: $\sim 7\mathrm{km\,s^{-1}}$
- Typical tangential velocity errors: $\sim 3.5\mathrm{km\,s^{-1}}$ at $V \sim 16$ 10kpc
- Required v_r accuracy: $\sim 3\mathrm{km\,s^{-1}}$
- Both low and high resolution options give acceptable velocity accuracy and limiting magnitude (possibly except for high resolution at low b)

5 Halo stellar streams

According to the hierarchical model for the formation of the Milky Way, the stellar halo has built up via the accretion of a number of smaller satellite galaxies. As a result, the present-day halo consists of a large number of stellar streams which show up as correlations in phase space. The actual number of streams depends on the number of accretion events, and the stellar masses of the accreted objects: there are probably 300-500 individual streams in the solar neighbourhood (Helmi & White 2000). These streams provide vital clues to the history of the Milky Way, and probing their structure over as large a volume as possible is essential. As the summary below demonstrates, the key constraint is the limiting magnitude – a faint limit of $V \sim 18$ is strongly favoured.

- Typical tracer: K giant, $\mathrm{M_V} = 1$
- Typical metallicity: [Fe/H] $\sim -1.6 \implies v_r$ accuracies shift by ~ 1 mag.
- Required magnitude limit: V = 17.5 (though V= 18 strongly preferred)
- Allowed b values: $R = 5000 : b > 15°$
  $R = 10000 : b > 45°$
- Distance uncertainties dominate errors and lead to tangential velocity errors of $\sim 20\mathrm{km\,s^{-1}}$ at $V \sim 17.5$
- Required velocity accuracy: $15 - 20\mathrm{km\,s^{-1}}$ (< 5 $\mathrm{km\,s^{-1}}$ needed to observe internal structure of individual streams)
- Low resolution option allows deeper limit (V= 17.5 $\implies$ factor 2 increase in volume sampled) and greater coverage in b than high resolution.
- V= 18 limit may now be achievable – this increases the number of stars per stream and therefore improves identification of individual streams. Simulations (Helmi 2002) show that a limiting magnitude of $V = 18.5$ allows 2/3 of accretion events to be recovered.

6 Conclusions

The exact degree to which crowding will affect the GAIA RVS is still not fully known. However, it is clear that fields at low Galactic latitude ($b < 10°$, possibly even 15°) will be difficult or impossible. In view of the fact that proposed observational programmes (e.g. RAVE) will be able to obtain superior spectra for Bulge stars, and that covering the entire Bulge region from the ground will probably be feasible over the next decade, it is possible that the Bulge should be dropped from the priority target list of the GAIA RVS. Further simulations are required to obtain reliable estimates of how much of the sky will be inaccessible to the RVS.

Based on simulated data, it appears that all the main disk components can be satisfactorily observed using the current RVS specifications. Again, detailed modelling of observational data is urgently required to confirm that realistic thin/thick disk fields can be studied.

The role of the RVS in the study of stellar streams in the halo depends sensitively on the limiting magnitude achieved. A fainter limit ($V \sim 18 - 18.5$) allows a greater volume to be studied and increases the numbers of stars per stream.

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