

Action-based Modelling of the Milky Way Disk with *RoadMapping* and our Imperfect Knowledge of the “Real World”

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1. Introduction

Stellar dynamical modelling can be employed to infer the Milky Way’s gravitational potential from the positions and motions of individual stars (Binney & Tremaine 2008; Binney 2011b; Rix & Bovy 2013) [TO DO: other / better references???]. Observational information on the phase-space coordinates of stars is currently growing at a rapid pace, and will be taken to a whole new level by the upcoming data from the Gaia mission (Perryman et al. 2001). Yet, rigorous and practical modelling tools that turn position-velocity data of individual stars into constraints both on the gravitational potential and on the distribution function (DF) of stellar orbits, are scarce (Rix & Bovy 2013) [TO DO: more references] [TO DO: References that explain that the modelling is scarce, or previous modelling approaches???] [TO DO: Hans-Walter suggested a Sanders & Binney reference, but I’m still not sure to what kind of paper: modelling approach or review of scarce modelling tools...]

The Galactic gravitational potential is fundamental for understanding the Milky Way’s dark matter and baryonic structure (Rix & Bovy 2013; McMillan 2012; Strigari 2013; Read 2014) and the stellar-population dependent orbit distribution function is a basic constraint on the Galaxy’s formation history (Rix & Bovy 2013) [TO DO: more references].

In the era of big Galactic surveys all of this could soon be within our reach [TO DO: rewrite to fit shorter intro]. Not only will there be full 6D stellar phase-space coordinates for a thousand million of stars measured by Gaia (Perryman et al. 2001) to unprecedented precision by the end of 2016. But already with existing surveys (e.g., SEGUE (Beers et al. 2006), RAVE (Steinmetz et al. 2006), LAMOST (Newberg et al. 2012), APOGEE (Majewski 2012), Gaia-ESO (Gilmore et al. 2012), GALAH (Freeman 2012) [TO DO: I just

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copied this from Melissas Cannon paper. Should I reference all of them??? Not in reference list yet.]) and sophisticated machine-learning tools (e.g. *The Cannon* by Ness et al. (2015)) to combine them, we will soon have huge data sets at our disposal.

In this work we present a rigorous, robust and reliable dynamical modelling machinery, strongly building on previous work by Binney & McMillan (2011); Binney (2012); Bovy & Rix (2013); Bovy (2015) and explicitly developed to exploit and deal with these large data sets in the future.

There is a variety of practical approaches to dynamical modelling of discrete collisionless tracers, such as the stars in the Milky Way (e.g. Jeans modelling: Kuijken & Gilmore (1989), Bovy & Tremaine (2012), Garbari et al. (2012), Zhang et al. (2013), Büdenbender et al. (2015); action-based DF modelling: Bovy & Rix (2013), Piffl et al. (2014), Sanders & Binney (2015); torus modelling: McMillan & Binney (2012, 2013); Made-to-measure modelling: Syer & Tremaine (1996), De Lorenzi et al. (2007) or Hunt & Kawata (2014); [TO DO: What kind of modelling is Xiangxiang doing?]: Xue et al. (2015)). Most of them – explicitly or implicitly – describe the stellar distribution through a distribution function. Actions are good ways to describe orbits, because they are canonical variables with their corresponding angles, have immediate physical meaning, and obey adiabatic invariance (Binney & Tremaine 2008; McMillan & Binney 2008; Binney 2010; Binney & McMillan 2011; Binney 2011b).

Recently, Binney (2012) and Bovy & Rix (2013) [TO DO: are these the correct references??] proposed to combine parametrized axisymmetric potentials with DF’s that are simple analytic functions of the three orbital actions to model discrete data. Binney (2010) and Binney & McMillan (2011) had proposed a set of simple action-based (quasi-isothermal) distribution functions (qDF). Ting et al. (2013) and Bovy & Rix (2013) showed that these qDF’s may be good descriptions of the Galactic disk, when one only considers so-called mono-abundance populations (*MAP*), i.e. sub-sets of stars with similar $[\text{Fe}/\text{H}]$ and $[\alpha/\text{Fe}]$ (Bovy et al. 2012b,c,d).

Bovy & Rix (2013) implemented a modelling approach that put action-based DF modelling of the Galactic disk in an axisymmetric potential in practice. Given an assumed potential and an assumed DF, they directly calculated the likelihood of the observed (\vec{x}, \vec{v}) for each sub-set of *MAP* among SEGUE Gdwarf (Yanny et al. 2009). This modelling also accounted for the complex, but known selection function of the kinematic tracers. For each *MAP*, the modelling resulted in a constraint of its DF, and an independent constraint on the gravitational potential, which members of all *MAP*s feel the same way.

Taken as an ensemble, the individual *MAP* models constrained the disk surface mass density

over a wide range of radii ($\sim 4 - 9$ kpc), and proved a powerful constraint on the disk mass scale length (~ 2 kpc) and on the disk to dark matter ratio at the Solar radius [TO DO: quote number??].

Yet, these recent models still leave us poorly prepared with the wealth and quality of the existing and upcoming data sets. This is because Bovy & Rix (2013) made a number of quite severe and idealizing assumptions about the potential, the DF and the knowledge of observational effects (such as the selection function). All these idealizations are likely to translate into systematic error on the inferred potential or DF, well above the formal error bars of the upcoming data sets.

In this work we present *RoadMapping* ("Recovery of the Orbit Action Distribution of Mono-Abundance Populations and Potential INference for our Galaxy") - an improved and refined version of the original modelling machinery by Bovy & Rix (2013), making extensive use of the *galpy* python package (Bovy 2015). *RoadMapping* relaxes some of the restraining assumptions Bovy & Rix (2013) had to make, is more flexible and more adept in dealing with large data sets. In this paper we set out to explore the robustness of *RoadMapping* against the breakdowns of some of the most important assumptions of DF-based dynamical modelling. What is it about the data, the model and the machinery itself, that limits our recovery of the true gravitational potential?

In the light of Gaia we explicitly analyze how well the modelling machinery behaves in the limit of large data. For a huge number of stars three statistical aspects become important, that are hidden behind Poisson noise for smaller data sets: (i) We have to make sure that our modelling is an un-biased and asymptotically normal estimator (§??). (ii) Numerical inaccuracies in the actual modelling machinery start to matter and need to be avoided (§??). (iii) Parameter estimates become so precise, that we start to be able to distinguish between similar models. We therefore want more flexibility and more free fit parameters in the potential and DF model. The modelling machinery itself needs to be flexible and fast in effectively finding the best fit parameters for a large set of parameters. The improvements made to the machinery used in Bovy & Rix (2013) are presented in §??.

Different characteristics of the data might influence the success of the parameter recovery. (i) In an era where we can choose data from different MW surveys, it might be worth to explore if different regions within the MW (i.e. differently shaped or positioned survey volumes) are especially diagnostic to recover the potential (§??). (ii) What happens if our

knowledge about the selection function, specifically the completeness of the data set within the survey volume, is not perfect (§??)? (iii) How to account for measurement errors in the modelling (§??)?

One of the strongest assumptions is to restrict the dynamical modelling to a certain family of parametrized models. We investigate how well we can hope to recover the true potential, when our potential and DF models deviate from the true potential and DF. For the DF we specifically investigate two of our assumptions in §??: First, what would happen if the stars within *MAPs* do intrinsically not follow a single qDF as assumed by Ting et al. (2013); Bovy & Rix (2013). Second, and assuming *MAPs* do indeed follow the qDF, what would be the effect of pollution of *MAPs* through stars from neighbouring *MAPs* in the $([\text{Fe}/\text{H}], [\alpha/\text{Fe}])$ plane due to too big abundance errors or bin sizes. And last but not least we test in §?? how well the modelling works, if our assumed potential family deviates from the true potential.

For all of these aspects we show some plausible and illustrative examples on the basis of investigating mock data. The mock data is generated from galaxy models presented in §??-?? following the procedure in §??, analysed according to the description of the machinery in §??-?? and the results are presented in §?? and discussed in §??.

The strongest assumption that goes into this kind of dynamical modelling might be the idealization of the Galaxy to be axi-symmetric and being in steady state. We do not investigate this within the scope of this paper but strongly suggest a systematic investigation of this for future work.

[TO DO: Check if all references are actually used in paper. ???]

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