Abstract. The body of photometric and astrometric data on stars in the Galaxy has been growing very fast in recent years (Hipparcos/Tycho, OGLE-3, 2-Mass, DENIS, UCAC2, SDSS, RAVE, Pan Stars, Hermes, ...) and in two years ESA will launch the Gaia satellite, which will measure astrometric data of unprecedented precision for a billion stars. On account of our position within the Galaxy and the complex observational biases that are built into most catalogues, dynamical models of the Galaxy are a prerequisite full exploitation of these catalogues. On account of the enormous detail in which we can observe the Galaxy, models of great sophistication are required. Moreover, in addition to models we require algorithms for observing them with the same errors and biases as occur in real observational programs, and statistical algorithms for determining the extent to which a model is compatible with a given body of data.

JD5 reviewed the status of our knowledge of the Galaxy, the different ways in which we could model the Galaxy, and what will be required to extract our science goals from the data that will be on hand when the Gaia Catalogue becomes available.

Keywords. Galaxy: stellar content, Galaxy: evolution, Galaxy: dynamics
The challenge raised by Gaia

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Abstract. Gaia will perform an unprecedented high quality survey of the Milky Way. Distances, 3D kinematics, ages and abundances will be obtained, giving access to the overall mass distribution and to the Galactic potential. Gaia data analysis will involve a high level of complexity requiring new and efficient multivariate data analysis methods, improved modelling of the stellar populations and dynamical approaches to the interpretation of the data in terms of the chemical and dynamical evolution of the Galaxy.

Keywords. Galaxy: stellar content, Galaxy: evolution, Galaxy: dynamics

The Gaia instruments will perform accurate photometry and astrometry up to magnitude 20 and spectroscopy up to 16th magnitude. The astrometric accuracy is expected to be at the level of 10, 20, 100 μas for stars at $G = 10, 15, 20$ resp. (Brown, 2008). This astrometric accuracy will permit measurement of parallactic distances up to the Galactic center at the level of 10%. The photometry will be accurate at the level of the 0.2 mmag at G=15 and 2.5 millimag at G=20. From the RVS, the radial velocity errors will be better than 1 km s$^{-1}$ for bright and cool stars, and at the end of the mission 30 km s$^{-1}$ for stars at V = 16. Gaia will also provide astrophysical parameters from the BP/RP, such as, for a star at $G = 15$, effective temperature at the level of 1 to 5%, gravity to 0.1 – 0.4 dex, metallicity to better than 0.2 dex. Extinction will be measured on hot stars from RVS with an accuracy of 0.05 – 0.1 mag. Thus, Gaia provides full characterization for populations to $G = 15$ (accurate distance, age, abundances, 3D velocities). Consequently, ages will be determined from the astrophysical parameters and stellar evolution models, as well as relative ages from the elemental abundances. This will enable us to trace the chemo-dynamical evolution of different populations. For example one expects to have about:

- 1.5 billion stars (∼ 0.5% of the stellar content of the Galaxy) with photometry, parallaxes and proper motions. Among them, about $9 \times 10^8$ stars belonging to the thin disc, $4.3 \times 10^8$ to the thick disc, $2.1 \times 10^7$ to the spheroid and $1.7 \times 10^8$ to the bulge.
- 200 million stars with spectroscopy ($G < 16$) (astrophysical parameters $T_{\text{eff}}$, log$g$, [Fe/H], radial velocity)
- 6 million stars with elemental abundances ($G < 12$)
- Variabilities and binarity.

All populations in the Galaxy will be surveyed. Although a limited number of stars truly in the bulge will be measured with the spectrograph due to extinction and crowding, (Robin et al, 2005), most stars in the bulge region will have their parallaxes and proper motions measured.

In the meantime, complementary surveys are planned that will enhanced the Gaia outputs, among them LSST, RAVE, PanStarrs and JASMINE. All these surveys will efficiently complement Gaia, giving better accuracy on radial velocities for fainter stars, exploring deeper fields, furnishing denser light curves for variables, revealing dusty regions from the near infrared, etc.

Having data sets for billions of objects, covering large numbers of multi-epoch observ-
ables, the data analysis will be a real challenge. The experience with recent large scale surveys will be of some help but previous surveys have never reached this level of complexity. The question is: how to turn Gaia data into a clear understanding of Galactic dynamics and evolution?

A promising path is to use modelling as a tool for analysis, interpretation and confrontation between the data and scenarios of formation and evolution of the Milky Way. Various modelling options are pursued. Since Galactic evolution leaves traces both in the stellar kinematics and the abundances, both aspects have to be taken into account. For this reason, the stellar population-synthesis approach will be valuable, allowing us to compare scenarios of Galaxy formation and evolution with the Gaia data set by simulating catalogues with the same observables and comparable accuracies. The Besançon Galaxy model is such a project (Robin et al, 2003), constrained by already existing surveys like GSC2, DENIS, 2MASS, SDSS, etc., from multi-wavelength data (from X to infrared) and multivariate catalogues (photometric, astrometric and spectroscopic). It produces realistic simulations of the stellar content of the Galaxy with characteristics in agreement with our present knowledge of Galactic evolution and taking into account interstellar extinction. It is already used in Gaia preparation and is planned to be exploited for the data analysis.

Complementary to the synthetic approach, dynamical models allow the reconstruction of the Galactic potential from the space distribution and the kinematics of numerous stars or selected tracers. Several dynamical approaches are being pursued, like the Schwarzhchild approach, the torus method (Dehnen & Binney 1996), N-body simulations or adaptive N-body techniques such as the "Made-to-Measure" scheme (Syer & Tremaine 1996), or quadratic programming (Dejonghe, 1989). The drawback is that the data sets are biased with parameters generally not included in the dynamical analysis – the first bias being the limiting magnitude but more complex biases also exist, such as those generated by the fact that the accuracy depends on magnitudes, colours and position on the sky, and the bias coming from interstellar extinction. As a consequence, these dynamical modelling approaches will benefit from being coupled with the synthetic approach.

Using such tools for the interpretation of Gaia data will require us to develop efficient methods of multivariate data analysis and model fitting, like genetic algorithms, or Markov Chain Monte Carlo. Inverse methods will be attempted but are not easy to handle with the large parameter space furnished by Gaia.

A huge challenge is then raised by Gaia interpretation. One can expect that no simplistic model will straightforwardly fit the data. Complemented by other surveys, the Gaia catalogue will encompass any model view. Even though imperfect, the modelling will still be useful to i) understand the imperfections of our knowledge, ii) help to interpret the findings, iii) test physical scenarios of Galaxy formation and evolution, iv) describe the dynamics of the system, in relation with the dark matter content, and v) place the scenario of formation in the cosmological context and constraints cosmological models.

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Dynamics and history of the Milky Way

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Abstract. The structure and dynamics of the Galaxy contain information about both its current workings and its assembly history. I review our understanding of the dynamics of the disk and stellar halo, and sketch how these may be used to unravel how our Galaxy formed.

Keywords. Galaxy: dynamics, evolution

1. Dynamics of the disk(s)

The structure and kinematics of the Galactic components constrain the mass distribution and history of the Galaxy. For example the vertical dynamics of the thin disk:

- Puts limits on the distribution of mass in the disk, most of which is accounted for by the stars (Kuijken & Gilmore 1991; Holmberg & Flynn 2004). Their contribution to the circular velocity (which itself still has large uncertainties, McMillan & Binney 2009) is roughly half of that required and thus a rounder (dark) component is needed. Also the tilt of the velocity ellipsoid rules out very flattened oblate halos (Siebert et al. 2008).

- Its coldness has been used to constrain the amount of recent merger events (Toth & Ostriker 1992). Small dark satellites, which are so abundant in CDM simulations (Springel et al. 2008), do not induce much heating (Font et al. 2001), but mergers of 10-20% mass ratio can significantly increase the velocity dispersion of the stars.

Stewart et al. (2008) have found that 70% of dark-matter halos similar to that of the Milky Way ($\sim 10^{12} M_\odot$) have experienced a merger with an object of $\sim 10^{11} M_\odot$ (i.e. mass comparable to the thin disk’s) in the last 10 Gyr. This would therefore be a plausible origin for the thick disk (Kazanzidis et al. 2008; Villalobos & Helmi 2009), also if we take into account the age distribution of its stars (Bensby & Feltzing 2009). However, this merger rate does not account for possible environmental dependences – the Local Group is in a low density region of the Universe, which must imply a smaller chance of encounters. Note as well that this class of mergers are less damaging for gas-rich disks, which is the relevant case for those lookback times (Hopkins et al. 2008).

Other models, besides the minor-merger scenario, have also been proposed for the formation of the thick disk. Abadi et al. (2003) suggest that it may result purely from the accretion of satellites on low inclination orbits, while Brook et al. (2004) find that a thick component might form early on during gas rich mergers (a different but also gaseous formation scenario has been put forward by Bournaud et al., 2008). Recently Schönrich & Binney (2009) have proposed that the thick disk is composed by stars which have migrated radially via resonant mechanisms from the inner thin disk.

The dynamics of thick-disk stars encode which of these mechanisms has been dominant in the formation of this component. Recently, Sales et al. (2009) have shown that the eccentricity distribution is a particularly powerful discriminant. In all scenarios where the majority of the stars are formed in-situ (minor merger, gas rich mergers or migration), the distribution has a prominent peak at low eccentricity. On the other hand, when the whole disk is built by accretion, the eccentricity distribution is predicted to be flatter, reflecting the range of orbital eccentricities of satellites found in cosmological simulations.
2. Dynamics of the stellar halo

The dynamics of halo stars, and especially of those in streams, can be used to constrain:
i) the total mass of the Galaxy and its spatial distribution (e.g. density and shape of the
dark matter halo); and ii) the merger history of the Galaxy, as accreted objects will often
deposit their debris in this component.

Models of the Sgr streams have yielded conflicting results favouring spherical, oblate
or slightly prolate shapes for the Galactic dark halo depending on the set of observations
used (Helmi 2004; Johnston et al. 2005; however see Law et al. (2009) who suggest it
may be triaxial). Narrow streams are arguably better-suited to derive the gravitational
potential in the region probed by their orbits (e.g. Eyre & Binney 2009). Koposov et
al. (2009) have modelled GD-1 and been able to constrain the circular velocity at the Sun
to be $\sim 224 \pm 13 \text{ km s}^{-1}$, and the shape of the potential (including disk and halo) to have
a global flattening $q_\phi \sim 0.87$.

Very high-resolution cosmological CDM simulations in combination with semi-analytic
models of galaxy formation may now be used to make detailed predictions on the prop-
erties of the stellar halo (and in particular the accreted component, De Lucia & Helmi
2008; Cooper et al., in prep.). The most recent such studies show good agreement with
observations, revealing the presence of broad streams such as those from Sgr (typically
originated in massive recently objects), and very narrow features, akin the Orphan Stream
(Belokurov et al., 2007). Furthermore, in these simulations the very chaotic build up char-
acteristic of the hierarchical structure formation paradigm endows the stellar halo near
the Sun with much kinematic substructure (Helmi et al., in prep).

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Non-equilibrium Dynamical Processes in the Galaxy

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Abstract. Dynamical models have often necessarily assumed that the Galaxy is nearly steady state or dynamically relaxed. However observed structure in the stellar metallicity, spatial and velocity distributions imply that heating, mixing and radial migration has taken place. Better comprehension of non-equilibrium processes will allow us to not only better understand the current structure of the galaxy but its past evolution.

During a Hubble time the Milky Way disk at the radius of the Sun has only had time to rotate 40 or 50 times. There is little time for dynamical relaxation. As larger and more precise surveys are conducted we expect even more structure to be revealed in the stellar abundance and phase space distributions. As there is little time for relaxation, structure in the phase space distribution depends on the evolution of the Galaxy.

Resonances with a bar or spiral structure cause stars to move in non-circular orbits. Libration times in Lindblad resonances can be long so evolution could take place in the non-adiabatic limit. Minchev et al. (2009b) proposed that the division between the Pleiades and moving groups in the solar neighborhood is associated with librations in the 2:1 Lindblad resonance with the Galactic bar (see Figure 1). These oscillations are also seen as long lived R1/R2 asymmetric ring structures in test particle simulations of bar growth (Bagley et al. 2009).

If pattern speeds vary, then either particles are trapped into resonance or heated as they cross the resonance. When particles are trapped into resonance their eccentricity depends on the total pattern speed change after capture. When particles cross the resonance their eccentricity can be predicted from the resonance strength and order. Bagley et al. (2009) suggested that the morphology of ring structures associated with a bar depends on bar pattern speed variations since growth. Peanut shaped bulges can also be modeled with a resonant trapping model (Quillen 2002). When there is more than one perturbation, chaotic heating occurs in resonances (Quillen 2003, Minchev & Quillen 2006).

Since resonances are often narrow, they can be used to place tight constraints on their pattern speed. Their location in the galaxy could be used to measure the pattern speed of a distant spiral pattern with a deep radial velocity survey (Minchev & Quillen 2007). Resonances occur when the sum of integer multiple of a star’s orbital frequencies is equal to an integer multiple of a perturbing frequency such as a planet’s mean motion or the pattern speed of a bar. In the Galaxy the orbital period is estimated from the tangential or v velocity component at a particular location. Thus resonances can be located on a u, v plane velocity distribution. Divisions between streams can be used to estimate bar or spiral pattern speeds (Dehnen 1999, Quillen & Minchev 2005). By matching both the velocity distribution in the solar neighborhood and simulated Oort function measurements (that depend on velocity gradients) Minchev et al. (2007) placed an even tighter constraint on the bar pattern speed.
Differences between orbital frequencies cause the velocity and spatial distribution of stars in a narrow region in phase space to spread. This process is called “phase wrapping” and can be used to estimate the time since a merger occurred (Gomez & Helmi 2009). Uneven distributions in phase space could also be caused by large scale perturbations to the disk. The timescale for them to wrap places constraints on the time since perturbation (Minchev et al. 2009). These scenarios are proposed explanations for high velocity streams in the thick disk of the Galaxy. Both mergers (Quillen et al. 2009) and resonances (Sellwood & Binney 2002) cause radial migration. Future work can better explore the relation between structure in the phase space and abundance distributions.

In summary, dynamical structures and events leave signatures in the stellar distributions. Precise measurements can be made as observations and associated models become more comprehensive. Unveiling the current and past structure and evolution of the Galaxy will be increasingly exciting in the coming decade.

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Star-formation histories, metallicity distributions and luminosity functions

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Abstract. A selection of topics was discussed, but given the limits of space, I discuss here only the IMF in any depth, with only a brief supplementary comment on the bulge.

1. The Stellar Initial Mass Function

The stellar Initial Mass Function is a fundamental aspect of star formation. Variations in the IMF are predicted in many theories, particularly those that invoke the Jeans mass, and associated dependences on cooling rates and pressure. The environment of the Galactic Center is rather different from the solar neighbourhood, and the dense, massive, young star clusters there provide an interesting test of the variation, or not, of the massive-star IMF. Indeed, early star-count observations had suggested a flatter IMF in the Arches star cluster, some 25 pc in projection from the Galactic Center and with age \( \lesssim 3 \) Myr, than in the solar neighbourhood (Figer et al. 1999). However, the most recent data, obtained with the NACO Adaptive Optics imager on the VLT, are entirely consistent with a standard, Salpeter (1955), slope to the IMF above \( 10 M_\odot \) (Espinoza, Selman & Melnick 2009), modulo a level of mass segregation in the inner regions.

The level of variation in generations of massive stars that have since exploded as core-collapse supernovae can be constrained through analysis of the elemental abundances in low-mass stars that they pre-enriched. In general, if the massive-star IMF is biased towards more massive stars, the predicted ratio of alpha-elements to iron will be higher, due to the dependence of the nucleosynthetic yields on progenitor mass, within the range of core-collapse progenitors, \( \sim 10 M_\odot \) to \( \sim 50 M_\odot \) (e.g. Kobayashi et al. 2006). Stars formed early in the history of self-enrichment of a system will show signatures of only core-collapse supernovae, and when these stars can be identified, they show remarkably little scatter in most elemental abundance ratios, even down to very low levels of \([\alpha/Fe]\) (e.g. Cayrel et al. 2004). This constancy, within estimated errors, implies not only an invariant massive-star IMF, but also efficient mixing so that IMF-averaged yields are achieved (e.g. Wyse & Gilmore 1992; François et al. 2004). It should be noted that the conclusion of the invariance of the IMF from the lack of scatter is not dependent on the details of the supernova models, nor on a chemical evolution model, but is a robust conclusion. Of course, determination of what the IMF is from the value of the elemental ratios would be sensitive to models.

These conclusions hold for stars in diverse environments such as the old, metal-rich bulge (e.g. Fulbright, McWilliam & Rich 2007) and metal-poor halo. Even in the metal-poor dwarf spheroidals, where the bulk of the member stars show lower values of \([\alpha/Fe]\) (e.g. Venn et al. 2004), consistent with their broad internal spread of ages and likely self-enrichment by Type Ia supernovae (see Unavane, Wyse & Gilmore 1996), the most metal-poor – and presumably oldest – stars show the same enhanced ratio as in the field halo (e.g. Koch et al. 2008).

Extending this analysis to larger samples of extremely metal-poor stars is possible.
through exploitation of the database from the RAVE moderate-resolution spectroscopic survey of bright stars \((I < 12; \text{see Steinmetz et al. 2006 for an introduction to the survey})\), for which 4–8m-class telescopes suffice for follow-up high-resolution data. Preliminary results (Fulbright, Wyse, Grebel et al., in prep) are very encouraging. Extremely metal poor stars, with \([\text{Fe/H}] < -3\) dex, have also been identified in dwarf spheroidal galaxies (e.g. Kirby et al. 2008; Norris et al. 2008), predominantly in the ‘ultra-faint’ systems discovered by analysis of the imaging data of the Sloan Digital Sky Survey (e.g. Belokurov et al. 2006, 2007).

As noted below, the ages of the bulge and halo stars are equal to look-back times corresponding to redshifts of 2 and above, implying constancy of the massive star IMF back to these early stages of the Universe, in a wide range of physical conditions.

The low-mass luminosity function can be determined in most systems by straightforward star counts, and again the constancy or otherwise of the IMF can be tested in systems that probe a wide range of physical parameters: the high-metallicity, old, dense stellar bulge; the low-metallicity, old, diffuse, dark-matter dominated dwarf spheroidals; the low-metallicity, old, dense Globular star clusters; and lastly the young disk star and open clusters. Again, all is consistent with an invariant low-mass IMF (e.g. Wyse 2005).

In terms of modelling the Galaxy, the IMF should be held fixed.

2. The Bulge

The conclusion that the bulge consists of exclusively old stars – at least those regions probed by low-reddening windows – is not new, but has been given considerably more weight by a recent HST-based analysis by Clarkson et al. (2008) in the Sgr low-extinction window. These authors used multi-epoch observations to identify foreground disk stars, through their proper motions. After removal of these younger stars, the colour-magnitude diagram remaining is that of an old, metal-rich population. However, much more data are required to map the stellar population in the bulge, and understand how it connects to the stellar halo, and to the inner thin and thick disks.

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Structure and evolution of the Milky Way: the interstellar medium perspective

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Abstract. The Herschel and Planck satellites have started imaging the sky at far-IR to mm wavelengths with an unprecedented combination of sky and spectral coverage, angular resolution, and sensitivity, thus opening the last window of the electromagnetic spectrum on the Galaxy. Dedicated observing programs on Herschel and the Planck all-sky survey will provide the first complete view at cold dust across the Galaxy, opening new perspectives on the structure and dynamical evolution of the Milky Way relevant to Gaia. The analysis and modelling of these observations will contribute to our understanding of two key questions: how do stars form from interstellar matter? how are the interstellar medium and the magnetic field dynamically coupled? The comparison with Gaia observations will contribute to build a 3D model of the Galactic extinction taking into account dust evolution between ISM components.

Keywords. Interstellar medium, Star formation, Magnetic field, Interstellar dust

1. Introduction

The Gaia mission will produce an extraordinary stellar database and we have to consider how the data may be used to build a dynamical model of the Milky Way that will unravel its past history. To understand the evolution of the Galaxy, we need a model that describes physically how star formation proceeds from the chemical and thermodynamical evolution of interstellar matter. This is a vast field of research. At the meeting I highlighted the prospect of imminent advances made possible by the successful launch of the Herschel and Planck satellites. Here I focus on two main topics related to star formation: the inventory of the cold interstellar medium across the galaxy, and the structure of the Galactic magnetic field and its coupling to interstellar matter.

2. Cold interstellar matter across the Galaxy

Herschel and Planck surveys will provide the small-scale (down to the detection of individual pre-stellar cores) and global views of the distribution of cold interstellar matter in the Galaxy. Both missions will image the far-IR emission from large (> 10 nm) grains that account for the bulk of the dust mass. The spectral coverage will allow us to determine the dust temperature and thereby infer dust column densities and masses. With an empirical determination of the dust-to-gas mass ratio, the infrared brightness becomes a tracer of interstellar gas. It complements usual interstellar matter tracers, like the HI and CO line emission, in a unique way because the dust emission is independent of the chemical composition and physical conditions of the gas. For the first time we will have access to a complete inventory of cold interstellar matter in the Galaxy. This step forward opens several key perspectives.

The dust temperature may be used to identify the cold infrared emission from dense condensations within molecular clouds. In doing this, we will quantify the mass and distribution of matter that is presently susceptible to collapse into stars. The data will
be sensitive enough to look for dust emission from High Velocity Clouds, the Magellanic Stream and the outer disk. This will help us to quantify the mass-inflow rate available to sustain star formation over the past history of the Galaxy. The dust seen in emission by Herschel and Planck is the dust that makes the extinction at optical and near-IR wavelengths. The data analysis will involve the characterisation of dust evolutionary processes that may account for the observed variations in the optical and near-IR dust extinction curve. The outcome of these dust studies will need to be taken into account to build the 3D model of extinction for Gaia.

3. The Galactic magnetic field

The Galactic magnetic field and cosmic-rays are tied to the interstellar gas. Their dynamical coupling is a prime facet of interstellar-medium physics, and many questions remain quantitatively open due to the paucity of data on the small-scale structure of the magnetic field. Planck will map the polarisation of the dust and of the synchrotron emission. The two emissions provide complementary perspectives on the structure of the Galactic magnetic field. Dust grains, unlike relativistic electrons, are coupled to the interstellar gas. Thus, the dust polarisation traces the magnetic field within the thin Galactic disk where matter is concentrated and within interstellar clouds, while the synchrotron polarisation probes the field over the whole volume of the Galaxy up to its halo. The novelty of upcoming observations ensures major progress in our understanding of the magnetised Galactic interstellar medium.

Polarisation of the dust emission results from the presence in the ISM of elongated grains with a preferred orientation. Several alignment mechanisms have been proposed. They are expected to work through interstellar clouds even if their efficiency may depend on the gas density and radiation field. It is thought to be generally true that the magnetic field acts on elongated grains so they spin with their long axes perpendicular to the field. In this case, the direction of polarisation in emission is perpendicular to $B_\perp$, the magnetic field component in the plane of sky. The degree of polarisation depends on dust properties (e.g. which grains are aligned), the efficiency of the alignment mechanism and the structure of the magnetic field within the beam.

Measurement by Planck of the polarisation of the thermal emission from aligned grains provide an unprecedented means to map continuously the orientation of the magnetic field within the ISM, from diffuse clouds to dense molecular gas. The Galactic magnetic field is commonly described as a vector sum of a regular and a random component. A first goal will be to complement existing models of the regular component. To fully describe the ordered field, we will face two open questions: (i) what is the impact of nearby bubbles powered by massive star associations on the field structure? (ii) how is the field within the thin Galactic disk, where gas and star formation is concentrated, connected to the thicker disk and the Galactic halo? The turbulent component results from the dynamical interaction between the field and interstellar turbulence. The data will also allow us to study the geometry of the magnetic field in relation to the density structure and kinematics of interstellar clouds derived from dust and gas maps. The degree of randomness in the magnetic field orientation may be combined with Doppler measurements of the turbulent gas velocity to measure the magnetic field intensity and quantify the dependence on gas density. These investigations will test theoretical and numerical studies, stressing the importance of the magnetic field in the dynamical evolution of the interstellar medium and the regulation of the star-formation efficiency.
The Milky Way Halo and the First Stars: New Frontiers in Galactic Archaeology

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Abstract.
We discuss plans for a new joint effort between observers and theorists to understand the formation of the Milky Way halo back to the first epochs of chemical evolution. New models based on high-resolution N-body simulations coupled to simple models of Galactic chemical evolution show that surviving stars from the epoch of the first galaxies remain in the Milky Way today and should bear the nucleosynthetic imprint of the first stars. We investigate the key physical influences on the formation of stars in the first galaxies and how they appear today, including the relationship between cosmic reionization and surviving Milky Way stars. These models also provide a physically motivated picture of the formation of the Milky Ways “outer halo,” which has been identified from recent large samples of stars from SDSS. The next steps are to use these models to guide rigorous gas simulations of Milky Way formation, including its disk, and to gradually build up the fully detailed theoretical “Virtual Galaxy” that is demanded by the coming generation of massive Galactic stellar surveys.

Keywords. astronomical data bases: surveys, Galaxy: halo, structure, methods: data analysis, n-body simulations, stars: abundances

The explosion of detailed astrometric, photometric, and spectroscopic data for stars in the Milky Way (and Local Group galaxies) that is coming upon us both now (e.g., SDSS/SEGUE, RAVE), and in the near future (PanSTARRS, SkyMapper, Gaia, LSST, SIM Lite) will fundamentally change our vision of galaxy formation and evolution. Full exploitation of this wealth of new information requires the development of sophisticated numerical models capable of producing testable predictions against which the observations can be compared. We have initiated one such effort, foreshadowed by the work of Tumlinson (2006), and continued by Tumlinson (2009). The new models predict the locations, kinematics, and chemistry of the stars in the Galactic halos, with different assumptions concerning the nature of the first stars and their effects on subsequent stellar generations. We are also exploring new methods for visualizing both the predictions and the existing databases. The first efforts will compare expectations with observed differences in the inner- and outer-halo populations, e.g., as in Carollo et al. (2007).

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Physics and Structure of the Galactic disc(s)

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Abstract. The model of Schönrich & Binney (2009) offers new ways to understand the chemo-kinematic structure of the solar neighbourhood in the light of radial mixing. The combination of chemical information with rich kinematic data reveals a still hardly explored abundance of interconnections and structures from which we can learn about both the physics and history of our Galaxy. Large upcoming datasets can be used to improve estimates of central parameters, to shed light on the Galaxy’s history and to explore the unexpected way of understanding the well-known division of the Galactic disc yielded by the new model.

Keywords. Galaxy: structure, Galaxy: evolution, Galaxy: abundances, Galaxy: kinematics and dynamics

Radial mixing has been a vastly neglected process in modelling galactic discs until it was shown to be crucial for disc evolution from a theoretical point of view by Sellwood & Binney (2002). Schönrich & Binney (2009) demonstrated that under regular assumptions about star formation and disc structure, a perfect fit to the metallicity distribution of the Geneva-Copenhagen Survey (Nordström et al. 2004, Holmberg et al. 2007) was possible if radial mixing was allowed for, and that no acceptable fit could be achieved without it. This new model of chemical evolution gives a completely different history of the disc compared to classical approaches. Since a large range of different galactocentric radii contribute their populations to local datasets, there is no need for the local star-forming interstellar medium to have followed the observed density ridges in the $[\alpha/Fe], [Fe/H]$ plane. Among the most important differences between classical modelling without radial mixing and models including radial migration are the predicted correlations between chemistry and kinematics along the thin-disc ridge line. In larger datasets containing $[\alpha/Fe]$ ratios, such as that of Borkova & Marsakov (2005), thin-disc stars can be picked out from stars belonging to the thick disc and halo by selecting for low $[\alpha/Fe]$ and dropping obvious halo stars. In this subsample one finds a highly significant increase of rotational velocity along the thin-disc ridge line moving from higher to lower metallicities, in nice concordance with the SB09 model. In the classical models the metal-poor stars should be the oldest thin-disc stars, so the increase in rotational velocity should be associated with an increase in velocity dispersion. The data do not show a significant increase towards lower metallicities, so the classical view is in conflict with the data.

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Gas flows within the Galaxy

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Abstract. In the recent years, more and more sophisticated models have been proposed for the gas distribution and kinematics in the Milky Way, taking into account the main bar, but also the possible nuclear bar, with the same or different pattern-speed. I review the success and problems encountered by the models, in particular in view of the new discovery of a symmetrical far-side counterpart of the 3 kpc arm. The inner part, dominated by the bar, and the outer parts, dominated by the spiral arms, can be observed from a virtual solar position, and the errors coming from kinematical distances are evaluated. The appearance of four arms could be due to a deprojection bias.

Keywords. Galaxy, dynamics, interstellar medium, bars, kinematics

1. Introduction
Reconstruction of the Galaxy’s spiral arms is difficult given our internal perspective. Distances of the various features or objects are derived through a kinematical model, with near-far ambiguities inside the solar circle. One of the most successful models is that from Georgelin & Georgelin (1976) of four tightly-wound arms, traced by OB associations, optical or radio HII regions and molecular clouds. The best tracer of the Galaxy structure is the gas, atomic (HI, Liszt & Burton 1980) and molecular (CO surveys, Dame et al 2001), because of its low velocity dispersion, and its confinement to the plane.

Position-velocity (P-V) diagrams are particularly instructive, revealing the high-velocity ($\Delta V = 560$ km s$^{-1}$) Central Molecular Zone (CMZ) near zero longitude, with a molecular ring, connecting arm, 3 kpc arm, etc. The existence of a bar has long been suspected from non-circular motions towards the center, and has been directly confirmed by COBE and 2MASS (e.g. Lopez-Corredoira et al 2005). Near-infrared images show clearly the peanut bulge, which is thought to be formed through vertical resonance with the bar (e.g. Combes et al 1990). The CMZ has a peculiar parallelogram shape in the P-V diagram (Bally et al 1988), that has been first interpreted in terms of cusped $x_1$ and almost circular $x_2$ periodic orbits, and associated gas flows, by Binney et al (1991). Then Fux (1999) carried out fully self-consistent N-body and hydrodynamical simulations of stars and gas to form a barred spiral, and fit the Milky Way. He succeeded remarkably to reproduce the HI and CO P-V diagrams with a bar pattern speed of about 40 km s$^{-1}$ kpc$^{-1}$, implying corotation at 5 kpc, and an ILR producing the $x_2$ orbit inside 1 kpc. The spiral structure has essentially 2 arms starting at the end of the bar.

2. More recent developments
Both external galaxies and simulations frequently show evidence for several pattern speeds in the disk and a spiral is expected to rotate slower than the bar (Sellwood & Sparke 1988). For example, by modelling gas flow in a fixed potential Bissantz et al (2003) conclude that in the Galaxy $\Omega_p = 60$ km s$^{-1}$ kpc$^{-1}$ and 20 km s$^{-1}$ kpc$^{-1}$ for the bar and spiral, respectively. Amores et al (2009) notice that there is a ring gap in the
HI distribution at about 8.3 kpc, outside the solar circle at 7.5 kpc, and propose that it corresponds to the corotation (CR) of the spiral, which will then have a pattern speed of $\sim 25 \text{ km s}^{-1} \text{ kpc}^{-1}$. Simulations of gas in a barred spiral do not show ring gaps at CR, but depopulated regions at the corresponding Lagrangian points, which could correspond to the observations; there is no gap in the azimuthally averaged HI and CO gas surface density.

In the 2MASS star counts, a nuclear bar has been found by Alard (2001), and there is a corresponding CO nuclear bar (Sawada et al 2004). New simulations of gas flow in a two-bar models have been done by Rodriguez-Fernandez & Combes (2008), who find a best fit when the two bars are nearly perpendicular, and the bar-spiral pattern is about $35 \text{ km s}^{-1} \text{ kpc}^{-1}$ (similar to Fux, 1999). The model shows the far-side twin of the 3 kpc arm, which has just been discovered in the CO P-V diagram (Dame & Thaddeus 2008). It reproduces also the connecting arm (characteristic leading dust lanes along the bar). No evidence is found of lopsidedness in the stellar potential, and the CO lopsidedness must be a purely gaseous phenomenon.

3. Remaining problems

New reconstruction of the spiral structure in the galactic plane have been attempted in the HI gas (Levine et al 2006), and in the CO gas (Nakanishi & Sofue 2006, Englmaier et al 2009). The best fit could be two arms, starting at the end of the bar, with a pitch angle of 12°, although four arms are still possible. Pohl et al (2008) have tried novel deprojections, by simulating the gas flow with SPH in a bar potential, and obtaining distances with a kinematic model derived from the non-circular velocity field obtained. A test of the procedure with a 2 arms+bar fiducial model, with only one pattern speed, retrieves after deprojection a four arms spiral. These recent efforts demonstrate further the difficulty of disentangling distances and dynamical effects. It is still possible that several patterns exist in the Galaxy. Other prominent features have not yet been interpreted, such as the warp or tilt of the nuclear structure, or its lopsidedness.

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Mapping the Milky Way with SDSS, Gaia and LSST

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Abstract. We summarize recent work on the Milky Way “tomography” with SDSS and use these results to illustrate what further breakthroughs can be expect from Gaia and the Large Synoptic Survey Telescope (LSST). LSST is the most ambitious ground-based survey currently planned in the visible band. Mapping of the Milky Way is one of the four main science and design drivers. The main 20,000 deg² survey area will be imaged about 1000 times in six bands (ugrizy) during the anticipated 10 years of operations, with the first light expected in 2015. Due to Gaia’s superb astrometric and photometric accuracy, and LSST’s significantly deeper data, the two surveys are highly complementary: Gaia will map the Milky Way’s disk with unprecedented detail, and LSST will extend this map all the way to the halo’s edge.

Keywords. Surveys, atlases, catalogs, astronomical data bases, astrometry, photometry

1. The Milky Way Tomography with SDSS

With the SDSS data set, we are offered for the first time an opportunity to examine in situ the thin/thick disk and disk/halo boundaries over a large solid angle, using millions of stars. In a three-paper series, Jurić et al. (2008), Ivezić et al. (2008a) and Bond et al. (2009) have employed a set of photometric parallax relations, enabled by accurate SDSS multi-color measurements, to estimate the distances to tens of millions of main-sequence stars. Photometric metallicity estimates based on the $u-g$ colors are also available for about six million F/G stars, and proper motions based on a comparison of SDSS and the Palomar Observatory Sky Survey positions are available for about 20 million stars.

With these distances, accurate to $\sim 10\%$, the stellar distribution in the multi-dimensional phase space can be mapped and analyzed without any additional assumptions. The adopted analytic models and a computer code ($galfast$†) that summarize these results, can be used to generate mock catalogs for arbitrary depths and photometric systems (including kinematic quantities). They also enable searches for substructure by subtracting the smooth background distributions. Indeed, a lot of substructure is seen in the data in all projections of the parameter space (spatial distributions, kinematics, metallicity distribution).

The extension of observations for numerous main-sequence stars to distances up to $\sim 10$ kpc represents a significant observational advance, and delivers powerful new constraints on the dynamical structure of the Galaxy. For example, most stars observed by the Hipparcos survey are within $\sim 100$ pc (Dehnen & Binney 1998). In less than two decades, the observational material for such in situ mapping with main-sequence stars has progressed from first pioneering studies based on only a few hundred objects (Majewski 1993), to over a thousand objects (Chiba & Beers 2000), to the massive SDSS data set.

These new quantitative results enable fairly robust predictions for the performance

† See http://hybrid.mwscience.net.
of new surveys, such as Gaia and LSST (Eyer et al., in prep.). Due to Gaia’s superb astrometric and photometric measurements, and LSST’s significantly deeper data, the two surveys will be highly complementary: Gaia will map the spatial, metallicity and kinematic distributions of stars in the Milky Way’s disk with unprecedented detail, and LSST will extend these maps all the way to the halo’s edge, and will obtain large local samples of intrinsically faint sources such as L, T and white dwarfs. We briefly describe LSST in the next section.

2. Brief Overview of LSST

LSST will be a large, wide-field ground-based system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The LSST design is driven by four main science themes: constraining dark energy and dark matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way. The current baseline design, which envisages an 8.4 m (6.7 m effective) primary mirror, a 9.6 deg$^2$ field of view, and a 3,200 Megapixel camera, will allow about 10,000 square degrees of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The survey area will include 30,000 deg$^2$ with $\delta < +34.5^\circ$, and will be imaged multiple times in six bands, $u$g$\text{rizy}$, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe a 20,000 deg$^2$ region about 1000 times in the six bands during the anticipated 10 years of operations. These data will result in databases including 10 billion galaxies and a similar number of stars, and will serve the majority of science programs. The remaining 10% of the observing time will be allocated to special programs such as Very Deep and Very Fast time domain surveys. More information about LSST can be obtained from www.lsst.org and Ivezić et al. (2008b).

Each 30-sec observation will be about 2 mag deeper than SDSS imaging, and the repeated observations will enable proper-motion and trigonometric parallax measurements to $r = 24.5$, about 4-5 mag fainter limit than to be delivered by Gaia, and the coadded LSST map will reach $r = 27.5$. Due to Gaia’s superb astrometric and photometric accuracy, and LSST’s significantly deeper data, the two surveys will be highly complementary. As shown by Eyer et al., in the range $19 < r < 20$ Gaia’s and LSST errors are fairly similar (within a factor of $\sim 2$). Towards brighter magnitudes, Gaia’s error significantly decrease (by about a factor of 10 already at $r \sim 14$), and towards fainter magnitudes, LSST will smoothly extend the Gaia’s error vs. magnitude curves by over 4 mag.

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Schwarzschild Models for the Galaxy

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Abstract.

Schwarzschild’s orbit-superposition technique is the most developed and well-tested method available for constraining the detailed mass distributions of equilibrium stellar systems. Here I provide a very short overview of the method and its existing implementations, and briefly discuss their viability as a tool for modeling the Galaxy using Gaia data.

1. Introduction

Models are used to relate observations to theoretical constructs such as the phase-space distribution function. A number of simplifying assumptions are required to make the modeling process tractable and these assumptions can have profound implications for the inferred mass distribution. A delicate balance must be struck between the available observations and the complexity of the models fitted to them.

The Gaia mission will require modeling techniques that are capable of handling huge numbers of measurements, while taking full advantage of the high precision of the data. Existing implementations of the orbit-superposition method already fulfill some of these requirements but do have limitations. For example, while an assumption regarding the geometry of the gravitational potential is inescapable, Schwarzschild models can be built that are completely free from assumptions regarding the detailed orbital structure, which generally have the largest impact on the derived mass distribution.

1.1. Schwarzschild’s technique

Given an orbit library for an assumed gravitational potential, the orbit-superposition technique (Schwarzschild 1979) finds the linear sum of those orbits that best reproduces the available observations. The success of the method relies on two aspects: (1) that the stellar system can be safely considered to be in equilibrium, and (2) that the orbit library is sufficiently comprehensive. If these two conditions are satisfied, the method is very general and free from most assumptions. Even the required assumption of a given geometry for the gravitational potential is in practice removed by the iterative nature of the technique, which calls for the construction of Schwarzschild models for an entire grid of potentials, with the final model the one that best fits the data. Of course a Schwarzschild model only provides a snapshot of the current dynamical state of the system, and the question of stability must be addressed by other means.

Schwarzschild models have been successfully used to constrain the dark-matter halos of galaxies (e.g., Rix et al. 1997, Thomas et al. 2005), to weigh supermassive black holes at the centers of both galaxies (e.g., van der Marel et al. 1998, Gebhardt et al. 2000, 2001) and globular clusters (Gebhardt, Rich, & Ho 2005). They have also been used to study the dynamics of star clusters (e.g., van de Ven et al. 2006). More relevant to the subject at hand, orbit-superposition models have also been used to study the dynamics of the Galactic bulge (Zhao 1996, Häfner et al. 2000). Existing implementations of the Schwarzschild method are usually classified/labeled according to the geometry of the
stellar systems they can be applied to (spherical, axisymmetric, triaxial), and to the type of dataset they are designed to handle (continuous or discrete; see Chanamé, Kleyna, & van der Marel 2008 for a review).

Points of weakness or controversy regarding Schwarzschild modeling include: the non-uniqueness of the initial conditions used to generate orbits; the amount of smoothing or regularization of the solution that is applied and its impact on the final results; possible over-interpretation of $\chi^2$ plots and indeterminacy of best solution; how to deal with incomplete positional sampling; and large computational costs.

2. Applicability of Schwarzschild’s method to Galactic surveys

We can consider the Galaxy to be composed of two kinds of structure: (1) a smoothly distributed and old Galaxy in steady-state equilibrium, and (2) a perturbed, inhomogeneous Galaxy that changes over relatively short timescales and is not in dynamical equilibrium. While the classical Galactic structures of bulge, disk(s), and halo belong to the first category, shorter-lived structures such as tidal streams, spiral arms, and disk warps, all fall into the second one. Only the background, steady-state Galaxy is susceptible to Schwarzschild modeling. Fortunately, most of the Galaxy’s mass lies in steady-state structures, so a Schwarzschild model should provide a useful first approximation to the data. However, even though the non-equilibrium mass fraction is small, this component is expected to hold clues to the history of the Galaxy, and means must be found to model it too.

Modeling data from current surveys such as SDSS and RAVE will prepare us for modeling the vastly superior Gaia data. Clever arguments such as those in Smith, Evans, & An (2009) can only benefit the applicability of Schwarzschild’s technique by narrowing down the range of possible shapes and geometries of the underlying gravitational potential, and could even shed light on the optimal choice of initial conditions for orbit integration.

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Connecting Moving Groups to the Bar and Spiral Arms of the Milky Way

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Abstract. We use test-particle orbit integration with a realistic Milky Way (MW) potential to study the effect of the resonances of the Galactic bar and spiral arms on the velocity distribution of the Solar Neighbourhood and other positions of the disk. Our results show that spiral arms create abundant kinematic substructure and crowd stars into the region of the Hercules moving group in the velocity plane. Bar resonances can contribute to the origin of low-angular momentum moving groups like Arcturus. Particles in the predicted dark disk of the MW should be affected by the same resonances as stars, triggering dark-matter moving groups in the disk. Finally, we evaluate how this study will be advanced by upcoming Gaia data.

Keywords. Galaxy: disk, kinematics and dynamics, structure, solar neighborhood, dark matter

The MW potential and initial conditions (cold, intermediate and hot disks) of our simulations are described in Antoja et al. (2009). Next figures show: a) left: the region of Hercules ($V = -40\text{ km s}^{-1}$) is crowded by the the spiral arms applied to the cold disk, b) middle: the bar with the hot disk creates groups at low angular momentum ($V = -100\text{ km s}^{-1}$) with long integration time, c) right: effects of a model with spiral arms and bar. We propose that a good fit between the observed velocity field – see Antoja et al. (2008) – and the simulations requires the combined model under IC1, IC2 and IC3, where the central and low angular momentum moving groups would appear simultaneously.

Gaia will revolutionize our knowledge of the Galactic disk. Accuracies in $U VW$ velocities are computed using the Gaia Universe Model Snapshot (GUMS), based on the Besançon Galaxy Model, and the current estimations of the Gaia errors. We find that we will be able to perform robust statistical analysis of the velocity distribution (with accuracies better than $2\text{ km s}^{-1}$ in all components $U VW$) up to $\sim 3\text{ kpc}$ from the Sun.

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Cosmological simulations of the Milky Way

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Abstract. Recent simulations of forming low-mass galaxies suggest a strategy for obtaining realistic models of galaxies like the Milky-Way.

Cosmological simulations of galaxy formation are powerful tools for confronting the ΛCDM model with observational datasets. The increase in mass and spatial resolution and the improvement of sub-grid algorithms for star formation and feedback processes have recently resulted in simulated galaxies with realistic disk size and angular momentum content (Mayer et al. 2008; Governato et al. 2009a). However, simulated galaxies hosted in halos with masses $\sim 10^{12} M_\odot$ exhibit prominent bulges and structural parameters reminiscent of Sa spirals rather than of Sb/Sc galaxies. Surface densities at the solar radius are larger than that of the Milky Way (MW) by factors of a few and the more massive bulge produces a steeper rotation curve compared to that of the MW (Read et al. 2009). At halo masses $M_{\text{vir}} > 2 \times 10^{12} M_\odot$ the predominance of hot-mode gas accretion counters the presence of a prominent star forming disk at $z = 0$, producing earlier-type objects resembling S0 galaxies (Brooks et al. 2009) and supporting recent estimates based on RAVE that yield $M_{\text{vir}} \sim 10^{12} M_\odot$ (Smith et al. 2007).

Yet the solution to forming a realistic MW analog could be at hand. Recently we have performed galaxy-formation simulations for mass scales $< 10^{11} M_\odot$. By sampling these low-mass galaxies with several millions of particles, we achieve a mass resolution better than $10^3 M_\odot$ in the baryons, thus resolving individual molecular clouds. Star formation can now be tied to gas at molecular cloud densities ($\rho > 100 \text{ cm}^{-3}$). A realistic, inhomogeneous interstellar medium is obtained that results naturally in stronger supernova outflows than when the standard star formation threshold ($\rho = 0.1 \text{ cm}^{-3}$) is adopted. Such outflows efficiently remove the low-angular momentum baryonic material from the central region, suppressing the formation of a bulge and producing an object with a slowly rising rotation curve in very close agreement with observed dwarf galaxies (Governato et al. 2009b; see also Ceverino & Klypin 2009). We argue that comparable resolution of MW-sized galaxies will yield rotation curves and bulge-to-disk ratios appropriate for Sb-Sc spirals at $z = 0$. This requires increasing the number of particles employed by more than an order of magnitude.

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Modelling the Galaxy with orbital tori

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Abstract. The principles and advantages of torus modelling are explained.

Keywords. Galaxy: dynamics, Galaxy: evolution

1. What is torus modelling?

Torus modelling (McMillan & Binney 2008 and references therein) is a modification of Schwarzschild modelling in which orbits are numerically constructed as three-dimensional surfaces in six-dimensional phase space rather than as time sequences. These surfaces are topologically equivalent to 3-tori: if we identify each point of the floor of a room with the point of the ceiling that is vertically above it, and similarly identify corresponding points on the front and back walls, and on the right and left walls, the room becomes a 3-torus. The “angle variables” $\theta_1, \theta_2, \theta_3$ are Cartesian coordinates for position in a room that has been thus made into a 3-torus: for example, as $\theta_3$ increments from 0 to $2\pi$, the point moves vertically from floor to ceiling. Remarkably, as a star orbits through the Galaxy, its angle variables increase linearly in time, $\theta_i(t) = \theta_i(0) + \Omega_i t$, so its point moves in a straight line through its room-like orbital torus. Unless the frequencies $\Omega_i$ are rationally related ($\Omega_1: \Omega_2: \Omega_3 = n_1: n_2: n_3$ for integer $n_i$) the star eventually comes arbitrarily close to every point of its torus.

The natural labels for a torus are the three actions $J_i = (2\pi)^{-1} \oint_{\gamma_i} v \cdot d\mathbf{x}$, where $\gamma_i$ is the path on which $\theta_i$ increments from 0 to $2\pi$ with the other two angle variables held constant. Indeed the set of six coordinates $(J_i, \theta_i)$ are canonical coordinates for phase space. In particular the Poisson bracket of any two angle variables vanishes, $[\theta_i, \theta_j] = 0$, so tori are null in the sense that the Poincaré invariant of any part of a torus vanishes ($\int dv \cdot d\mathbf{x} = 0$).

The idea of torus-modelling is to use software that returns an orbit in terms of $\mathbf{x}(\mathbf{\theta})$ and $\mathbf{v}(\mathbf{\theta})$ rather than $\mathbf{x}(t)$ and $\mathbf{v}(t)$ as a Runge-Kutta integrator does. Since in this picture the orbit is identified with the torus, it is labelled by the actions $\mathbf{J}$. The following benefits flow from expressing orbits in this way.

- Given a point in space $\mathbf{x}$ we can readily find the values of $\mathbf{\theta}$ at which the star reaches that point and read off the velocities $\mathbf{v}(\mathbf{\theta})$ with which the star passes through that point. By contrast, if we are given $\mathbf{x}(t)$, we will in general search in vain for a time when the star is precisely at the given point and will have to settle for times when it is near. It will not be clear whether we have found times that give approximations to all the possible values of $\mathbf{v}$ at the given point.

- When we integrate orbits in time, the orbit is characterised by its initial conditions. The same orbit corresponds to infinitely many different initial conditions, so it is not clear how to do a systematic survey of phase space to obtain a representative sample of orbits. This difficulty does not arise in torus modelling because the actions are essentially unique labels of orbits and the orbits with actions in the range $d^3\mathbf{J}$ occupy a volume $(2\pi)^3 d^3\mathbf{J}$ in 6-d phase space.
• Actions are adiabatic invariants so we can relate orbits in different potentials: orbits with the same actions will deform into each other if we slowly deform the potential from that of one model to that of another. No such identification is possible if orbits are characterised by their initial conditions. On account of adiabatic invariance, the distribution function (DF) of a system such as a globular cluster is invariant as, for example, loss of gas modifies the cluster’s density distribution and gravitational potential. Together with the previous item, adiabatic invariance make it straightforward to specify a galaxy model uniquely and to compare the orbital structures of models that have slightly differing potentials.

• Analytic formulae for $x(\theta)$ and $v(\theta)$ can be specified using much less data than are required to specify $x(t)$ and $v(t)$. Consequently tori greatly simplify manipulation of orbit libraries. Moreover, expressions for infinitely many tori can be obtained by interpolating between data for numerically obtained tori.

• There is a simple, intuitive connection between the functional form $f(J)$ of the DF and the real-space properties of the system it specifies (Binney & Tremaine 2008 §4.6). Moreover, given $f(J)$ there is a stable scheme for evaluating the self-consistent gravitational potential, which is not always the case when a DF of the form $f(E, \ldots)$ is specified.

• The orbit-averaged Fokker-Planck equation takes an exceptionally simple form in action space (Binney & Tremaine 2008 §7.4.2), which should facilitate modelling of secular evolution.

• A set of orbital tori specify an integrable Hamiltonian which is very close to the true Hamiltonian. Perturbation theory works wonderfully well when this Hamiltonian is used as the point of reference (Kaasalainen 1994).

2. How do we obtain tori?

Analytic potentials (principally the potentials of the isochrone sphere and the multidimensional harmonic oscillator) provide analytic tori $x(\theta)$, etc. We choose such a potential and refer to its structures as “toy” ones. A canonical transformation is used to map the toy torus with given actions $J'$ into the target phase space. The image torus is guaranteed to be null but in general it will not lie within a hypersurface on which the target Hamiltonian is constant, as an orbital torus must. We numerically adjust the coefficients that define the canonical transformation so as to minimise the rms variation $\Delta H$ in the target Hamiltonian over the image torus. Once $\Delta H$ is small enough, the target torus provides an excellent approximation to an orbital torus.

The canonical transformation $(J, \theta) \rightarrow (J', \theta')$ is specified by its generating function

$$S(J', \theta) = J' \cdot \theta + \sum_n S_n(J') e^{in\theta},$$

where the sum is in principle over all vectors with integer components. The first term on the right generates the identity transformation, and the machine has to choose the coefficients $S_n(J')$ which are characteristic of the given orbit. Typically, a good approximation to an orbital torus can be obtained with a few tens of non-zero $S_n$.

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In What Detail Can We Represent the Milky Way in a Conventional N-Body Model?

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Abstract. After a brief review of past N-body models of the Milky Way, I consider some of the difficulties that are inherent in the N-body approach to modelling any disk galaxy.

1. Past N-Body Models of the Milky Way

Modern efforts at modelling the Milky Way (MW) take into account that it is barred. The first large effort in this regard was carried out by Fux (1997), who ran simulations of initially axisymmetric disk+bulge+halo systems. He then compared regularly spaced outputs with a de-reddened COBE K-band bulge map. He scaled the kinematics of his model by requiring that the velocity dispersion matches that of Baade’s window. A number of models provided reasonable fits to the data. His best fit bar angle to the sun-center line, $\psi_{\text{bar}} = 28^\circ \pm 7^\circ$. Later he added SPH gas to his simulations and was able to fit a number of features in the CO gas $l-V$ diagram Fux (1999). He argued that the high-velocity connecting arm is due to the shocked gas within the near side of the bar. The gas distribution is also sensitive to the pattern speed of the bar, and he constrained this parameter to $\Omega_p \sim 50 \text{ km s}^{-1} \text{kpc}^{-1}$.

Widrow et al., (2008) modelled the Milky Way by matching observations (including the rotation curve, local force field, Oort’s constants, local and bulge velocity dispersions, surface density and total mass within 100 kpc) to a suite of axisymmetric models. N-body models of these then all produced bars. The time of bar formation depended on the Toomre $Q$ and $X$ parameters; in all cases $\Omega_p$ started declining after the bar formed and a dynamically young bar is required if $\Omega_p = 50 \text{ km s}^{-1} \text{kpc}^{-1}$. A problem with this approach is, however, that bar formation leads to the model departing from the observations.

N-body models are also very useful for testing models constructed using other methods. Zhao (1996) tested his Schwarzschild model of the MW bulge using N-body simulations, finding that its shape and mass distribution is stable.

2. Fundamental Limitations

Modelling the MW, or any other disk galaxy, by N-body simulations is complicated by a number of effects. Foremost, disk simulations in which a bar forms are subject to considerable stochasticity. Sellwood & Debattista (2009) show that disk simulations which differ only in the seed of the random number generator used to set up the disk particles evolve quite differently. They identified a number of sources of stochasticity, including multiple disk modes, swing-amplified noise, variations in the onset and strength of bending instabilities, metastability due to upward fluctuations in $\Omega_p$ (Sellwood & Debattista 2006), and intrinsic chaos. Stochasticity is weaker when the halo is very massive, but is never absent. Such stochasticity makes it hard to improve N-body models by iterating runs with varying parameters.
Modeling is also complicated by radial migration of stars caused by transient spirals (Sellwood & Binney 2002). Roškar et al. (2008) show that this migration leads to significant mixing of stellar populations so that the age distribution of stars at any given radius does not reflect the star formation history at that radius. In the solar neighborhood, Roškar et al. (2008) estimate that as much as half the stars formed elsewhere. Since the incidence of spirals is chaotic, matching the stellar populations in simulations requires a certain degree of luck.

A third difficulty with modeling the MW is the somewhat weak constraints that kinematics of the bulge region impose on models. In order to demonstrate this, in Figure 2 I present an arbitrary disk-galaxy simulation, scaling its velocities to produce a rotation velocity of 220 km/s. The density distribution is a rather poor match to models of the MW [e.g. Bissantz & Gerhard (2002), López-Corredoira et al. (2005)]. However, comparing the kinematics of particles selected to lie in the bulge using selection functions that match those in observations of Rangwala et al. (2009) results in distributions of stellar velocities that are not substantially different from those observed.

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Made-to-Measure N-body Modeling of the Milky Way Galaxy

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Abstract. In this talk a brief introduction is given to made-to-measure particle methods and their potential use for modeling the Milky Way Galaxy.

1. Made-to-Measure N-body models

The term “Made-to-Measure” (M2M) for a dynamical model reproducing a set of observational data for a galaxy was coined by Syer & Tremaine (1996) (hereafter ST). M2M models can be based on distribution functions, moments, orbits, or particles, but in particular ST described an algorithm for constructing N-body equilibrium models, based on the idea of adjusting the masses or weights of the particles until the system agreed with a prescribed density distribution. The central part of their algorithm is the “force-of-change” (FOC) equation through which the particle weights are adjusted according to the mismatch of model and target density observables. Other important ingredients include a time smoothing to reduce particle noise and an entropy term to reduce large fluctuations in the weights.

As a first practical application of this method Bissantz, Debattista & Gerhard (2004) constructed a dynamical model for the Milky Way’s barred bulge and disk, constraining the projected density map. However, the ST algorithm is not well-suited for mixed density and kinematic observables, and it does not allow a proper treatment of observational errors. A modified $\chi^2$M2M algorithm which resolved both these problems was introduced by De Lorenzi et al. (2007) (DL+07) who also demonstrated the potential of the method by constructing particle models for spherical, axisymmetric, triaxial and rotating target systems. Their implementation NMAGIC has since been used by De Lorenzi et al. (2008,2009) (DL+08, DL+09) to construct dynamical models of elliptical galaxies based on photometry, Sauron, slit and planetary-nebula velocity data, and thus to explore the distribution of dark matter in these galaxies. For modeling the discrete velocities, De Lorenzi et al. (2008) introduced a likelihood scheme into the FOC equation, and they also added a separate equation for adjusting the mass-to-light ratio of the stellar system simultaneously with the observables.

A modified M2M method was introduced by Dehnen (2009). Rather than time-averaging the moments of the N-body system as ST and DL+07, he considered time-averaging the merit function, resulting in a second-order equation for adjusting the particle weights. This contains a linear damping term that acts to maximize the merit function. Writing the equations in dimensionless time (in units of orbital period) also made it possible to achieve a uniform adjustment rate per orbital time for the particle weights, despite the large range of orbital time-scales inherent in an N-body system. Dehnen (2009) used this algorithm to construct triaxial equilibrium target systems.
2. Comparisons with Schwarzschild and direct N-body methods

M2M particle models include aspects of both Schwarzschild orbit superposition metho ds and direct N-body simulations. When the gravitational potential of the target system is held fixed, the process of finding a distribution of particle weights to match a prescribed density field or set of kinematic observables for a galaxy, is closely related to the process of finding a distribution of orbital weights in Schwarzschild’s method to fit the same constraints. Conversely, when the adjustment of particle weights is switched off and the potential is allowed to evolve, M2M particle codes reduce to N-body methods. E.g., in the work of DL+07 several equilibria are found in the first limit, while the stability of the final galaxy models in DL+08 and DL+09 is tested in the second limit. Of course, the strength of the M2M particle methods is to self-consistently evolve the particle weights and their potential simultaneously while approaching the target data (see applications in DL+08). This is perhaps the greatest advantage over Schwarzschild and N-body techniques. However, this is most useful when the particles trace the mass. Because there is no direct connection between observables and the global gravitational potential, external dark-matter potentials have still to be explored one by one. Compared to Schwarzschild and N-body techniques, M2M modeling is still in an early stage, and improvements of both the techniques and the efficiency of the method are needed.

3. M2M modeling for the Milky Way

The goal of dynamical models for the Milky Way is to uncover the fossil record of its assembly history, as described by, for example, the orbital distribution of stars of different metallicities or other population parameters. Because of the enormous detail expected from future observations, particularly from Gaia, it is likely that interesting (sub)structure in the models would be visible in the data. Thus techniques with a minimum of simplifying assumptions such as M2M may be well-suited to understand what these data will be telling us.

M2M work to date has been confined to the inner Galaxy; see Bissantz, Debattista & Gerhard (2004) and Debattista et al. (in preparation). These models have successfully re-produced as diverse observables as densities, radial velocity histograms and microlensing event time-scale distribution, but a comprehensive bulge model is still pending.

Modeling the nearby Galactic disk has not been tried yet. This has the problem that only a small fraction of the particles from any such model will be seen in magnitude limited surveys; see e.g., Brown et al. (2005). However, this may actually not be such a large problem for M2M methods such as NMAGIC. The time averaging of the observables allows suppressing the particle noise in the model observables by a factor 10-100, which eases the comparison with solar neighbourhood data.

In conclusion, made-to-measure modeling for the Milky Way has little history, but a lot of promise, and so there is a lot of work to do!

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How to build a 3D extinction model of the Galaxy

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Abstract.
We show that anomalous extinction (deviations from the traditionally adopted $R_V = A_V / E(B-V) = 3.1$ introduces large uncertainties in the distances of stars, for distances larger than 1-2 kpc. We argue that for such distances and for directions close to the galactic plane, the use of extinction models based on the gas distribution in the Galaxy is safer, for the moment, than the use of extinction maps.

Keywords. interstellar extinction, galactic structure

1. Introduction
It is usually believed that all that we need to derive the photometric distance of a star, taking into account extinction, is the color excess $E(B-V)$. In reality the existence of anomalous extinction seriously challenges this belief. Besides this, there are two opposite views concerning the possibility of corrections for interstellar extinction based on models. One is that the dust distribution is clumpy and random. Consequently, it does not make any sense to produce models; only empirical extinction maps or tables are useful. The other idea is that the proportionality between gas and dust column densities is well established. Simple models of the gas distribution can be constructed, based on HI and CO surveys, so that extinction is predictable to some extent. Amôres & Lépine (2005) made an extensive comparison of an extinction model based on the gas distribution with a large sample of stars with known extinctions (the sample of Neckel & Klare 1980). The comparison proved that the extinction is largely predictable. Interestingly, Neckel & Klare themselves produced extinction maps based on their sample of stars, which constitutes an opportunity for a comparison between the two approaches.

2. The problem of anomalous extinction, and discussion
Neckel & Klare (1980) in a famous work, determined the spectral type and color excess for more than 7000 O and B stars situated near the galactic plane. They plotted the interstellar extinction $A_V$ as a function of distance for many directions, and obtained some unexpected results. In many cases, one can observe in those plots a low extinction up to a distance of the order of 1 kpc (see eg. the direction $l = 128$, $b = 0$), followed by a step in the extinction up to $A_V = 2-3$, and then $A_V$ remains constant up to about 5 kpc, the maximum distance investigated. It is not surprising to see steps in $A_V$, as they are explained by the presence of dense clouds along the line-of-sight. What is surprising is that there are paths of many kpc without steps, as if all the clouds were close to the Sun. Another surprising result, noted by Neckel & Klare, is that the clouds situated close to the Sun are bigger than the more distant ones.

The explanation for the two unexpected results is that the distances of the more distant stars (and clouds) are overestimated. The clouds contain dense cores in which $R_V$...
OB stars in the plane of the Galaxy. The distances from the Sun are indicated in parsecs, the centre of the Galaxy is outside the figure, at $(0, -7500)$. The line segments point to examples of directions of alignments of stars or “fingers of God” caused by anomalous extinction.

can be much larger than the classical value 3.1. As a consequence, the extinction is underestimated and the distances are overestimated. The existence of anomalous extinction is not a new result, we only call attention to the fact that the anomalous extinction is so widespread that it affects strongly our understanding of the local structures.

We present in Figure 1 the photometric distances of the sample of OB stars of the solar neighborhood taken from the Hipparcos catalog. We first computed the distances based on the absolute magnitudes expected from their spectral class, with the extinction estimated using $R_V = 3.1$. We also computed the distances based on the infrared H magnitudes taken from 2Mass and the relation $A_H = 0.18E(V - H)$ derived from the extinction relations by Koornneef 1983. The distances using V and H bands are not different, the ones based on H magnitudes are shown in Figure 1. Since the extinction in band H is smaller than in V, we would expect that the anomalous extinction would also be smaller. However, it can be seen in the figure that elongated structures like fingers of God are present. The elongated structures cannot be the result of any kind of calibration errors. They are the result of an unpredictable scattering in the values of $R_V$.

The distance of the first interstellar cloud found along a line-of-sight is correct, since the stars are still unaffected by extinction, but the next clouds have distances overestimated. Extinction maps, to be useful for a 3D description of the extinction in the Galaxy, would have to give the distances of all the steps in $A_V$, which is not possible at the moment.

How to correct for anomalous extinction? Of course when the data from Gaia become available we will be able to place real distances to the molecular clouds which are responsible for steps in the extinction, up to much larger distances. Meanwhile, it is possible that the approach of Fitzpatrick & Massa (2009) which describes $R_V$ in terms of two color indices could be a good solution.

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A New Approach to the Construction of Dynamical Structure of our Galaxy

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Information about positions and velocities of stars that will be gained in the era of GAIA is crucial for determining dynamical structure in our Galaxy. The distribution function of all component objects in our Galaxy is fundamental for describing its dynamics. However, only the distribution function of observable stars is obtained from space astrometry observations, and it is therefore necessary to develop theoretical studies of how to construct the distribution function of all matter including dark matter and unobservable stars using astrometric data of observable stars. This procedure falls into three categories.

1) Torus Fitting: In the first step, we find action variables \( J \) in any gravitational potential (Hamiltonian) whose system is almost integrable and considered to be a representation of our Galaxy. Concretely, we find the coordinate transformation between action variables and the Cartesian coordinates \((x, p)\) in a model of our Galaxy. Although the action-angle variables \((J, \theta)\) provide the most compact representation of a regular orbit, it is impossible to get analytically the coordinate transformation \((J, \theta) \leftrightarrow (x, p)\) in an arbitrary potential. We therefore propose a new approach that numerically obtains action variables \( J \) and coordinate transformations \((J, \theta) \leftrightarrow (x, p)\). It is called a “Torus Fitting method” and is an alternative of the Torus Construction method proposed by Binney and his collaborators.

2) Determination of a theoretical distribution function by M2M: In the second place, we construct the distribution function \( f_{\text{matter}}(J_1, J_2, J_3) \) of all matter in the system, using action variables from the first step. We do this using the made-to-measure algorithm for constructing an \( N \)-body realization of an equilibrium stellar system (please refer to Yano’s presentation for details).

3) Determination of a model of our Galaxy from the distribution function of observed stars, \( f_{\text{obs}}(x, p)\): Finally, we have to determine a model of the gravitational potential (Hamiltonian) of our Galaxy. Hence we need to construct the distribution function of all matter including dark matter and unobservable stars using astrometric data that include the error in distance measurements and selection biases. In this procedure a technique that utilizes Hermite polynomials is used.

From the above procedure we obtain the distribution function of all matter using space astrometry observations.
An iterative method for constructing stellar systems models: how far does it work?

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Abstract. We present a new method for constructing equilibrium phase models for stellar systems. Applications of the iterative method include both modelling of observational data and the construction of initial condition for N-body simulations.

Keywords. stellar dynamics methods: N-body simulations galaxies: kinematics and dynamics galaxies: structure

The aim of the iterative method (IM) is to construct an equilibrium N-body model with prescribed parameters, or constraints. Setting a given mass distribution and almost arbitrary velocities of particles, we start the iterative procedure, by letting the system go through a sequence of self-consistent evolutionary steps of short duration (iterations). At the end of each step, and before the new step is started, we transfer the new velocity distribution from a bit evolved system to a system with the initial density distribution. At this stage we need to correct individual particle velocities in accordance with imposed kinematic constraints (see details in Rodionov et al. 2009). We stop iterations when the velocity distribution ceases to change, which implies that the system has reached equilibrium.

We managed to construct equilibrium systems of various types – from spherical to triaxial, from one-component to multi-component, from isotropic to anisotropic (Rodionov & Sotnikova (2006); Sotnikova & Rodionov (2008); Rodionov et al. (2009)). Successful reconstruction of the distribution function of a model disc galaxy from its line-of-sight kinematics encouraged us to use the IM to derive the 3D kinematics of edge-on galaxies from observational data. Now we have all IR photometric parameters (for a bulge and a disc) of an edge-on galaxy NGC 4111 and obtained stellar LSVD of this galaxy at the 6-m telescope. Preliminary interpretation of kinematic and photometric observations of this galaxy in terms of its 3D structure and 3D velocity distribution showed that the IM may be very powerful method to reconstruct phase-space models of real galaxies (Sotnikova et al., 2010, in preparation).

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