SF2A 2016
C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse and I. Vauglin (eds)

THE WEAVE DISK DYNAMICS SURVEY

B. Famaey[1], T. Antoja[2], M. Romero-Gomez[3], A. Siebert[1], C. Babusiaux[4], P. Di Matteo[4], F. Figueras[3], F. Fragkoudi[4], F. Garzon-Lopez[3], C. Gonzalez-Fernandez[5], I. Martinez-Valpuesta[6], G. Monari[1], R. Mor-Crespo[3], V. Hill[7] and the WEAVE Survey Consortium

Abstract. WEAVE is the next-generation wide-field survey facility for the William Herschel Telescope. It consists of a multi-object fibre spectrograph with a 2°-diameter field of view that can obtain ~ 1000 spectra simultaneously. The "WEAVE Galactic Archaeology survey" is the survey focused on the Milky Way, as a complement to the Gaia space mission, and will start operating in early 2018. This survey is subdivided in four sub-surveys, among which the "WEAVE disk dynamics survey". This survey plans to measure the radial velocities (and abundances as far as possible) of $\sim 10^6$ stars with magnitude $15 < V < 20$ in the Milky Way disk to unravel the detailed features of its gravitational potential. In particular, the non-axisymmetric perturbations such as the bar and spiral arms, are among the main drivers of the evolution of the Galactic disks. Questions (i) about their nature – e.g., are these features transient, quasi-stationary, or do both types co-exist? – (ii) about their detailed structure and dynamics – e.g., is the bar short or long, what is its pattern speed? –, as well as (iii) about their influence on secular processes such as stellar radial migration are essential elements for a better understanding of the chemo-dynamical evolution of our Galaxy, and of galaxies in general. This survey is designed to answer these questions.

Keywords: Galaxy: kinematics and dynamics – Galaxy: evolution

1 Introduction

The Milky Way is a unique laboratory in which to test our models of galaxy formation, structure, and evolution. The story of the efforts to obtain stellar kinematic data in the solar neighbourhood during the XXth century has culminated with ESA's Hipparcos astrometric catalogue (Perryman et al. 1997), and with the complementary ground-based spectroscopic surveys that have provided the missing information on the line-of-sight velocities (e.g., Nordström et al. 2004; Famaey et al. 2005). Now, ESA's Gaia satellite (Gaia Collaboration 2016) will perform astrometry and photometry of more than 1 billion objects up to a magnitude $V \sim 20$, as well as spectrosocopy for some 150 million objects up to $V \sim 16$. In order to get six-dimensional phase-space information for fainter stars, the mission will have to be completed with ground-based spectrosocpic surveys. Such a ground-based survey is precisely what WEAVE is (Dalton et al. 2014). It consists of a multi-object fibre spectrograph with a 2°-diameter field of view. The spectrograph measures 1000 spectra simultaneously at a spectral resolution of $R \sim 5000$ over an instantaneous wavelength range $370 - 1000$ nm. In high-resolution mode, it reaches $R \sim 20000$ over two more limited wavelength regions.

The "WEAVE Galactic Archaeology survey" is the survey focused on the Milky Way, as a complement to the Gaia space mission, and will start operating in early 2018. This survey is divided into 4 sub-surveys focusing on

[1] Observatoire astronomique de Strasbourg, Université de Strasbourg, CNRS UMR 7550, 67000 Strasbourg, France
[2] Directorate of Science, ESA-ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
[3] Dept. dAstronomia i Meteorologia, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC, Martí i Franquès 1, E08028 Barcelona, Spain
[4] GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France
[5] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
[6] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[7] Laboratoire Lagrange, Université de Nice Sophia-Antipolis, Observatoire de la Côte d'Azur, CNRS, Bd de lObservatoire, CS 34229, 06304 Nice cedex 4, France

Galactic open clusters, the Galactic halo, the chemical labelling of Galactic populations (HR chemodynamical survey), and the disk dynamics.

The latter "WEAVE disk dynamics survey" is intended to be complementary to Gaia (and a Northern complement to the spectroscopic survey 4MOST in the South) and competitive with APOGEE. This survey therefore needs to be continuous in terms of spatial coverage, and to comprise of the order of 10^6 stars. We proposed to observe red clump stars with high priority, for $V > 15$. We therefore will cover a significant fraction of the Galactic disk to a depth well suited for gaining new insights on the disks structure and history.

We divide the WEAVE disk dynamics survey into four goals and two sub-surveys. The four goals are:

i) Global phase-space structure of the disk (see Sect. 2);

ii) Nature and dynamics of the bar and spiral arms (see Sect. 3);

iii) Radial migration (see Sect. 4);

iv) Interface between thin, thick disk and halo (see Sect. 5).

These goals can be achieved through measuring and studying:

a) The global phase-space distribution function of disk populations, including the spatial disk structure, mean velocity field and the velocity dispersion;

b) The substructure in phase-space associated to the distinct processes acting on the disk (mergers and/or resonances of non-axisymmetric perturbations);

c) The distribution of abundances and its relation to the aforementioned dynamical constraints.

The constraints set by the answers to our goals should ultimately help to determine the relative importance and actual efficiency of the various processes acting on the disk.

This science case is divided into two sub-surveys with different observing strategies to cover the different goals (see Sect. 6):

1) The Inner Milky Way LR disk (IMWD),

2) The Outer Milky Way LR-HR disks (OMWD) surveys.

The IMWD survey consists in the coverage of the inner Galactic disk ($20° < l < 135°$) at latitudes lower than 6°. It will consist fully of red clump stars for which photometric distances will be obtained even when Gaia parallaxes will be very uncertain at large distances. The innermost part of the disk ($20° < l < 90°$) will have continuous coverage. The main motivation of the survey is a detailed understanding of the effects of the bar and spiral arms on stellar dynamics in the inner Galaxy, which is essential to better understand the secular evolution of the disk. This will be complemented by a slightly sparser coverage of the disk between $90° < l < 135°$, in order to follow the effects of the bar and spirals beyond the suspected location of the bar's Outer Lindblad Resonance.

On the other hand, the effects of mergers and interactions of satellites or dark matter clumps on the disk is expected to become more important in the outer Galaxy. There these processes can lead to flaring, corrugation waves, the presence of accretion debris, etc, at the interface between the thin, thick disk and the halo. Studying the detailed dynamics of the outer disk is thus going to be of tremendous importance to understand the build-up history of the Galaxy. The interface between the disk and the halo is particularly important there, hence higher Galactic latitudes should be probed than in the inner disk. The OMWD survey plans to observe giant stars in the longitude range $135° < l < 225°$ at latitudes up to 10°. High latitude fields with relatively low extinction down to $b = 5°$ will be probed in HR mode while the lower latitude fields will be observed in LR mode.

2 Global phase-space structure of the disk

We need to know the radial and vertical kinematical structure of the Galactic disk in order to disentangle various kinematical subpopulations, and to measure the scale-length of the Galactic disk dynamically. This is particularly important in view of testing predictions of the standard cosmological model and of alternatives (e.g. Bienaymé et al. 2009; Bovy & Rix 2013), and in order to determine the shape of the putative dark matter halo around the Galaxy (e.g., Binney & Piffl 2015), as well as the possible existence of a dark disk. This main objective will be achieved through dynamical models of the Galaxy relying on the 0th order assumptions of axisymmetry and equilibrium. These very legitimate assumptions allow us to make use of Jeans' theorem constraining the phase-space distribution function to depend only on three isolating integrals of motion. In this context, the action integrals are the best suited, since they are adiabatically invariant and are, with their conjugate angle variables, the natural coordinates of perturbation theory. By constructing distribution functions depending on these action integrals, one can, e.g., disentangle the various stellar populations such as the thin and thick disk in a much more reliable way than with naive kinematic decomposition. One can then iterate the fits with different gravitational potentials until the best-fitting potential is found, giving access to the underlying mass distribution including dark matter. It will also be important to determine the extension of the Milky Way disk and the location of the break in the disk surface density in the outer Galaxy, as well as the characteristics of the warp and flare.

3 Nature and dynamics of the bar and spiral arms

With the approach presented in the previous section, the consequences of assuming axisymmetry and equilibrium when it is not actually the case might bias the results. In this respect, it will be extremely useful to test this type of modelling on non-equilibrium models from simulations. But the WEAVE data themselves will actually allow us to characterize the first-order perturbations of the global non-axisymmetric components, including the central bar and main spiral arms. These non-axisymmetries drive the position of the main mode of the velocity distribution in the radial direction (Siebert et al. 2011). This will be measured at all positions inside the inner Galactic disk thanks to the IMWD survey, and can leave a signature from line-of-sight velocities and photometric distances for red clump stars alone, as illustrated in Monari et al. (2016a, their Fig. 12). Starting from an axisymmetric equilibrium distribution function in action space, one can then apply linear perturbation theory to analytically determine the perturbed distribution function in terms of actions and angles in the presence of a single main perturber (Monari et al. 2016b). This technique breaks down close to first-order resonances, where stellar populations should rather be modelled in terms of new action and angle variables obtained from a well-chosen canonical transformation suited to the given resonance. Such equilibrium distribution functions in the presence of a main perturber such as the bar can then be themselves perturbed with the technique outlined in Monari et al. (2016b) in the presence of secondary non-axisymmetric perturbers such as spiral arms. Data allowing measurement of the mean radial and vertical motions as a function of position, combined with more local determinations of the positions of resonantly generated moving groups in velocity space (e.g., Antoja et al. 2011), will then place stringent constraints on the form of the perturber potentials themselves. Different models of spiral arms can e.g. be tested through comparison between accurate line-of-sight velocities together with astrometry from Gaia and existing spiral models (e.g., Lin et al. 1969; Romero-Gomez et al. 2011; Antoja et al. 2011; Grand et al. 2012). This will also allow the disentangling of the dynamical effects of a bar as measured with COBE/DIRBE (see e.g. Monari et al. 2016c) versus those with a slowly-rotating bar, like the one suggested by Wegg et al. (2015) and Portail et al. (2015). The WEAVE disk dynamics survey is particularly well-suited for this task as it will nicely cover the region of the Galactic disk where the tip of the bar and its long flat extension - whose nature remains to be determined with certainty - are located, and the region ahead of it in terms of rotation contrary to surveys based in the Southern hemisphere which will rather probe the region behind the bar in term of its rotation.

4 Radial migration

In classical chemical evolution models, stars are postulated to live their entire lives at the same radius. Even when heating is taken into account, the range of radii which individual stars in the disk explore was generally thought to be small, of the order 1.5 kpc. This seemingly natural assumption was shattered when Sellwood & Binney (2002) showed that stars can migrate over large distances while retaining essentially circular orbits. The mechanism governing this migration is the trapping of stars at the co-rotation resonance of transient spirals. This can be enhanced if the spirals are co-rotating in a large radial range (Grand et al. 2012). Migration is also triggered where the resonances of the bar and the spiral pattern overlap: stochasticity can force stars to rapidly migrate radially away from their place of birth (Minchev & Famaey 2010; Weinberg 2015). Radial migration is a key component driving the secular evolution of the disk, and has important consequences for understanding galactic evolution (e.g., Minchev et al. 2014), including issues such as the age-metallicity relation and the G-dwarf problem. There are several probes of radial migration. First, a direct dynamical probe is the dynamics in the Scutum-Crux window at $l = +27°$, which samples the overlap region between the suspected co-rotation of the bar and the 4:1 inner resonance of an inner spiral. This resonance overlap could cause stellar migration, as suggested by Minchev & Famaey (2010), which would lead to specific streaming along the spiral arm, and could be directly compared to other proposed processes such as trapping by a transient co-rotating spiral (Grand et al. 2012). The outer disk of the Milky Way is another important stellar repository reflecting the history of any migration that may have occurred in our Galaxy. Do we find that stars there are on nearly circular orbits (favouring either an in situ or a spiral migration mechanism) or are they on elongated orbits (favouring heating by satellites or the bar)? The chemistry will also be important to distinguish the processes: is the chemistry of the outer disk vastly different from that of coeval stars in the inner disk? (e.g., Haywood et al. 2013). A strong age-metallicity relation will be very suggestive of in situ star formation, which can help distinguish this scenario from migration. Different mechanisms causing the radial migration would leave drastically different signatures in the elemental abundance pattern of stars and in the age-metallicity relation across the disk, reflecting the variation in star-formation history and chemical evolution across the region of migration. The combination of dynamics and chemistry of stars in the disk, which for the foreseeable future is only possible in the Milky Way, will provide important new constraints on the evolution of disk galaxies. WEAVE is the ideal instrument to probe this important effect on disk evolution, as metallicities, alpha-element abundances and stellar kinematics at high precision can be obtained simultaneously.

5 Interface between thin, thick disk and halo

Recent studies have shown that several processes that were traditionally thought to act on the different Galactic components are, in fact, influencing also the whole Galaxy. For instance, there has been a debate on whether the non-axisymmetric components can influence or even cause the formation of the thick disk (Schönrich & Binney 2009; Minchev et al. 2012; Solway et al. 2012), with an emerging consensus that non-axisymmetries alone cannot induce the appropriate thickening (Minchev et al. 2012; Aumer et al. 2016). But in any case, it has been demonstrated that non-axisymmetries have at present non-negligible effects on the thick disk stellar populations (Monari et al. 2013; Antoja et al. 2015) and not only on the thin disk as traditionally believed. Another example: the study of the effects of the external perturbations by satellites has been traditionally focused on the thick disk. However, such interactions can also cause non-axisymmetric patterns in the outer disk. Moreover, the interplay between these and the vertical imprint of the external perturbations can create complex combinations of breathing modes (from the non-axisymmetries, Williams et al. 2013; Faure et al. 2014) and bending modes (from the impact of satellites themselves, Widrow et al. 2012; Gomez et al. 2013; Carlin et al. 2013; Laporte et al. 2016) of the thin disk populations. There is, thus, a complex interface between the thin, thick disks, and halo, and the mechanisms acting on them. This is particularly visible in the outer disk (Slater et al. 2014), where the density of stars exhibits a complex morphology with both stream-like features and a sharp edge to the structure in both the North and the South. This has been interpreted both in terms of tidal streams and a distorted disk structure creating stream-like features close to the disk, but none of these models seem satisfactory yet. Studying velocity gradients in combination with North-South density asymmetries (corrugation patterns) should allow us to disentangle these various effects. The outer disk directions covered in the OMWD sub-survey is an especially suitable place to test and measure all the above-mentioned effects. It is in this last goal of our sub-survey that the objectives of the whole Galactic archeology survey mix and become a single one: understand the formation and evolution history of our Galaxy as a whole.

6 Footprint

The footprint of the WEAVE disk dynamics survey is presented in Figure 1. Targets will now be selected essentially from IPHAS and VPHAS photometry, as well as Gaia. Selection of red clump stars in the magnitude range $15 < V < 20$ will be prioritized. The stars will be selected using the simplest criteria possible to allow for an easy estimation of the target selection bias a posteriori. The aim is to follow the red clump extension locus on the colour- magnitude diagram induced by correlated increase of distance and extinction. Additional criteria based on the Gaia DR2 will later on be used to remove close red dwarfs that could fall in some fields in this locus depending on the extinction.

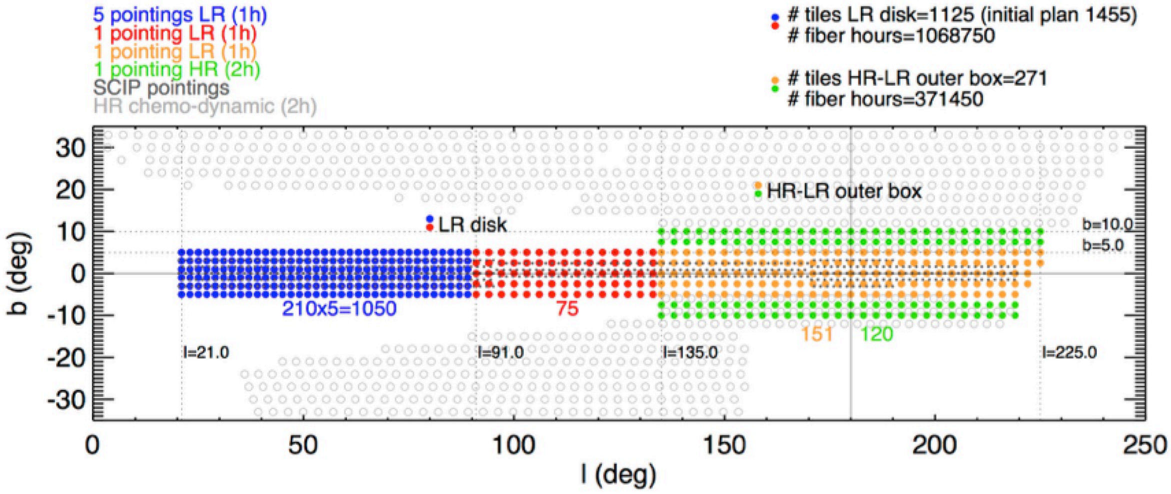

Fig. 1. The WEAVE disk dynamics survey footprint. IMWD 5 pointings: blue; IMWD 1 pointing: red; OMWD LR: orange; OMWD HR: green. Open circles are the original lines-of-sight for the HR chemodynamical survey.

References

Antoja T., et al., 2011, MNRAS, 418, 1423

Antoja T., et al., 2015, ApJ, 800, L32

Aumer M., et al. MNRAS, 459, 3326

Bienaymé O., et al., 2009, A&A, 500, 801

Binney J., Piffl T., 2015, MNRAS, 454, 3653

Bovy J., Rix H.-W., 2013, ApJ, 779, 115

Carlin J. L., et al., 2013, ApJ, 777, L5

Dalton G., et al., 2014, SPIE, 9147, 0L

Famaey B., et al., 2005, A&A, 430, 165

Faure C., et al., 2014, MNRAS, 440, 2564

Gaia Collaboration, et al., 2016, eprint arXiv:1609.04172

Gomez F., et al., 2013, MNRAS, 429, 159

Grand R. J. J., et al., 2012, MNRAS, 426, 167

Haywood M., et al., 2013, A&A, 560, A109

Laporte C. F. P., et al., 2016, eprint arXiv:1608.04743

Lin C. C., et al., 1969, ApJ, 155, 721

Minchev I., Famaey B., 2010, ApJ, 722, 112

Minchev I., et al., 2012, A&A, 548, A127

Minchev I., et al., 2014, A&A, 572, A92

Monari G., et al. 2013, eprint arXiv:1306.2632

Monari G., et al., 2016a, MNRAS, 461, 3835

Monari G., et al., 2016b, MNRAS, 457, 2569

Monari G., et al., 2016c, eprint arXiv:1609.02557

Nordström B., et al., 2004, A&A, 418, 989

Perryman M., et al., 1997, A&A, 323, L49

Portail M., et al. 2015, MNRAS, 448, 713

Romero-Gomez M., et al., 2011, MNRAS, 418, 1176

Schönrich R., Binney J., 2009, MNRAS, 399, 1145

Sellwood J., Binney J., 2002, MNRAS, 336, 785

Siebert A., et al., 2011, MNRAS, 412, 2026
Slater C. T., et al., 2014, ApJ, 791, 9
Solway M., et al., 2012, MNRAS, 422, 1363
Wegg C., et al., 2015, MNRAS, 450, 4050
Weinberg M. D., 2015, eprint arXiv:1508.06855
Widrow L. M., et al., 2012, ApJ, 750, L41
Williams M. E. K., et al., 2013, MNRAS, 436, 101