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GAIA CONSTRAINTS ON THE GALACTIC THICK DISC

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Abstract. The Gaia mission, with its unprecedented astrometric and photometric precision, combined with its Radial Velocity Spectrometer, will provide to the astronomical community a wealth of necessary constraints to disentangle between the different formation scenarios of the Galactic thick disc. The aim of this review is to present some of the recent results obtained spectroscopically concerning this Galactic structure, and highlight the open questions that still remain to be answered under the Gaia era. These concern mainly the measurement of the chemo-dynamical properties of the Milky Way at the inner and outer parts, which allow us to determine the total accreted mass from the mergers with satellite galaxies, and will give us an estimate of the strength of the radial migration phenomena to form such a structure.

Keywords: Surveys: Gaia, Techniques: spectroscopy, Galaxy: structure, stellar content, evolution

1 Introduction

Surveys of external galaxies seem to suggest that thick discs are inherent structures in most (if not all) disc galaxies (Yoachim & Dalcanton 2008; van der Kruit & Freeman 2011). Although the existence of such a structure for the Milky Way has been highlighted for almost thirty years now (Yoshii 1982; Gilmore & Reid 1983), its origin is still uncertain, and many scenarios have been proposed to explain it. These can be separated into those involving internal mechanisms or those requiring external accretion or trigger in order to form the thick disc (e.g.: Abadi et al. 2003; Brook et al. 2004; Villalobos & Helmi 2008; Loebman et al. 2011, and references therein).

Most of the stellar spectroscopic and photometric surveys of stars in the Milky Way have shown that the Galactic thick disc is mainly composed by old stars ($\sim$ 10 Gyr, Fuhrmann 2008), of intermediate metallicity ([M/H] ~ -0.5 dex, e.g.: Bensby et al. 2007; Kordopatis et al. 2011b) and with hotter kinematics compared to the thin disc stars (e.g.: Casetti-Dinescu et al. 2011). In addition, the thick disc stars inside the solar cylinder ($7< R <9$ kpc) have a ratio of α-element abundances over iron ([α/Fe]) which is enhanced compared to the [α/Fe] ratio of the thin disc stars (e.g.: Fuhrmann 2008; Navarro et al. 2011). This property suggests that the thick disc has been formed in relatively short timescales ($\sim$ 1 Gyr), and hence the understanding of its formation offers us the possibility to decipher the merging history of our Galaxy back to redshifts of $z \sim 1.5-2$ (Freeman & Bland-Hawthorn 2002). This exploration of the origins of the Milky Way is widely known as Galactic archaeology.

Most of the models and simulations which have been proposed in order to explain the formation of the thick disc manage to successfully reproduce the locally measured properties of this structure. Nevertheless, this success has been preventing us to really disentangle between the models, since the community was lacking large observational datasets far from the solar neighbourhood, where the models differ the most.

The advent of multi-object spectrographs (such as VLT-FLAMES), combined with the part-time dedication of large telescopes in order to make deep and statistically significant stellar surveys (e.g.: Gaia-ESO Survey, RAVE, SEGUE) has already changed our view of the Milky Way. The simplistic approach consisting to consider that the thick disc has formed only by one mechanism is most probably out of date. The true question that one would like to answer now, is what is the relative importance of each of these processes. In that sense, the Gaia mission (Perryman et al. 2001) will be a goldmine, in order to extract all the necessary information, since

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the satellite will map the 3D positions and kinematics, and obtain estimations of the chemical compositions of several hundreds of millions of stars.

In the following section (Sect. 2) we will briefly review the most commonly cited formation mechanisms of the thick disc. Then, in Sect. 3 we will see how these scenarios have been constrained, by enumerating the latest results that have been obtained in terms of orbits, metallicity and kinematic gradients. This section will end up with the open questions that are still remained to be answered, and show how Gaia will help to decipher the formation history of the thick disc (Sect. 4).

2 Formation of the thick disc: *in situ* versus external mechanisms

One of the first scenarios that has been proposed to explain the difference in kinematics and chemistry of the stellar population composing the thick disc is the co-planar accretion of all the necessary stellar content from dwarf satellites (Statler 1988; Abadi et al. 2003). Such a scenario is mainly defended by the hierarchical formation history of the galaxies in the ΛCDM paradigm, where the dwarf galaxies are thought to be the building blocks of larger galaxies like ours. The direct accretion scenario predicts the absence of radial or vertical chemical gradients for the thick disc, since only one population is composing this structure. In addition, the kinematics of the stars, especially at the outskirts of the Galaxy, will depend on the inclination angle of the merger as well as on the total mass of the satellite.

Nevertheless, the numerical simulations of such accretions have shown difficulties in the preservation of the existence of the thin disc after the merger. Models involving multiple minor mergers of satellites, which would heat dynamically the pre-existent thin disc in order to form the thick disc have hence been developed (Quinn et al. 1993; Villalobos & Helmi 2008). In that case, the stellar population composing the thick disc is in majority the one of the thin disc at the epoch of the bombardment ($z \sim 1.5$) and chemical or kinematical gradients could have persisted in the thick disc only if the initial thin disc had any of those.

Similarly, in order to explain the presence of the thin disc despite the massive accretion, Jones & Wyse (1983) and Brook et al. (2004, 2007) have proposed that the accretion consisted of a gas-rich merger, from the collapse of which the stars forming the existent thick disc will have formed. In that configuration, the stars are born *in situ*, but using the accreted extra-galactic gas. The orbital and chemical properties of the thick disc stars, such as radial and vertical gradients, could then be explained by the time-scale of the cloud collapse and the accretion parameters of the merger.

Finally, the last family of scenarios require no external trigger at all. Here, the stars composing the thick disc are formed entirely in the thin disc or in the bulge and are moved afterwards far from the Galactic plane due to internal mechanisms. Such a mechanism is presented for example by Bournaud et al. (2009), where it is suggested that at high redshift the turbulent primordial discs would had scattered far from the plane part of the gas and stars, forming in that way the thick discs of external galaxies as we see them today. Like for the direct accretion or the gas-rich merger, it is predicted in such a scenario that the thick disc is chemically homogeneous. More interestingly, the inside-out evolution of the thin disc will have as a consequence to form a thick disc with a shorter scale-length than the one of the thin disc.

Another evoked internal mechanism in order to create a thick disc is the radial migration of the stars due to resonances with the spiral structure or the bar of the Milky Way (e.g.: Schönrich & Binney 2009; Minchev & Famaey 2010; Loebman et al. 2011; Bird et al. 2012; Minchev et al. 2012). In such scenarios, the thick disc stars inside the solar cylinder would had come in majority from the inner radii of the Galaxy, gaining vertical velocity due to the lower Galactic potential at the outskirts, keeping a chemical signature of the interstellar medium of the regions where they have been formed. Nevertheless, the assumed dynamical evolution of the disc implies that the information concerning the origin of the stars is blurred because of the radial migration, and hence that there is no distinctive thin and thick disc components: the disc is characterised by smooth changes in its chemo-dynamical properties.

3 The observational constraints at the pre-Gaia era: The unlike scenario of a single mechanism

The advent of spectroscopic surveys either dealing with hundreds of stars (e.g. Fuhrmann 2008; Bensby et al. 2007; Kordopatis et al. 2011b), or the ones organised around big collaborations with few hundreds of thousand stars (e.g.: SEGUE, RAVE) have already brought a wealth of information in order to claim nowadays that the formation history of the Milky Way's thick disc is very likely a combination of most of the above cited scenarios.

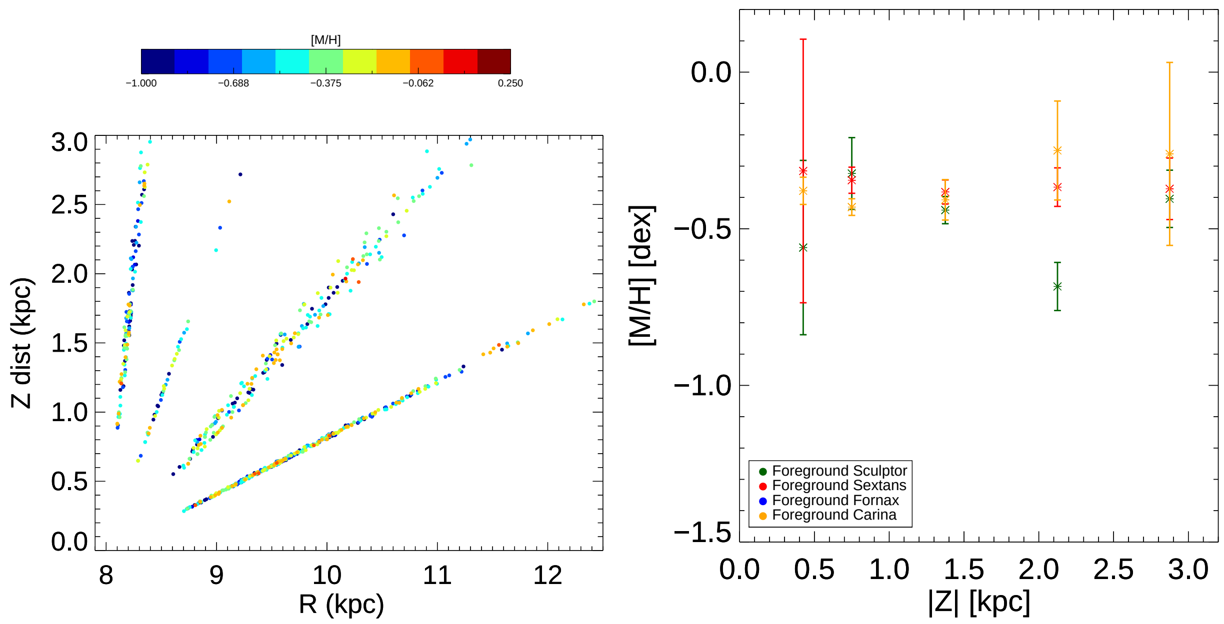

Fig. 1. Preliminary results of the study of ∼1200 foreground stars observed towards the line-of-sights of the dwarf spheroidal galaxies of Sculptor, Fornax, Sextans and Carina (Kordopatis et al. 2012, in prep.). **Left:** Metallicity of the surveyed stars at different distances above the Galactic plane and different galatocentric radii. **Right:** Measured vertical metallicity gradients towards the line-of-sights for which enough stars were available (Sculptor in green, Sextans in red, Carina in yellow). The preliminary results seem to suggest a chemically homogeneous thick disc in the studied directions.

For instance, Cheng et al. (2012b) used SEGUE data of $\sim$ 7000 stars to measure the radial metallicity gradients of the thin and thick discs, at different distances above the Galactic plane, up to $|Z| \sim 1.5$ kpc. They have shown that the farther from the plane, the flatter the gradient, suggesting that the thick disc population is chemically homogeneous, in agreement with the scenario of Bournaud et al. (2009), the one of Abadi et al. (2003) or with a radial migration mechanism (provided a strong migration rate). In a complementary approach, the analysis of ∼1200 foreground stars of several spectroscopic surveys towards the line-of-sights of the dwarf spheroidal galaxies of Sculptor, Fornax, Sextans and Carina (Kordopatis et al. 2012a, in prep) has yielded to the measurement of the vertical chemical gradient for the thick disc stars towards these four directions. The preliminary results of this study also seem to point towards a chemically homogeneous thick disc (see Fig. 1), in agreement with the result of Cheng et al. (2012b).

Nevertheless, a pure radial migration scenario as being the fundamental one in order to form the thick disc seem to be ruled out when analysing the eccentricity distribution function of the thick disc stars. The RAVE results (Wilson et al. 2011), the SEGUE ones (Dierickx et al. 2010; Lee et al. 2011) as well as the independent ones of Kordopatis et al. (2011b), obtained far from the solar neighbourhood, have shown that the thick disc stars have a peak at intermediate values ($\epsilon \sim 0.3$), with a tail going towards higher values, where merger scenarios predict that the accreted stars are found (Sales et al. 2009). In addition, Lee et al. (2011) have shown that there is a strong correlation between the metallicity and the eccentricity of the stars, a characteristic which does not seem to be existent for the thin disc stars, hence suggesting that radial migration played a less important role for the thick disc than for the thin one.

Similarly, the strong correlation between the rotational velocity and the metallicity measured by Kordopatis et al. (2011b); Lee et al. (2011); Schlesinger et al. (2011) ($\partial V_\phi / \partial$[M/H] ~ 45 km s^{-1} dex^{-1}) seem to decrease again the relative importance of the radial migration in the formation of the thick disc[i]. This correlation, combined with the measurement of the vertical metallicity gradient of more than -0.1 dex kpc^{-1} (Kordopatis et al. 2011b; Ruchti et al. 2011), as well as the similarity of the [α/Fe] ratio of the metal-poor thick disc stars with the [α/Fe] ratio of the halo stars (Ruchti et al. 2010), also rules-out the pure accretion scenario.

[i]We note, however, that recently Curir et al. (2012) suceeded to simulate such a strong correlation using radial migration in a barred disk Galaxy

With such a reasoning, and using a sample of $\sim 12 \times 10^3$ G-dwarfs, Liu & van de Ven (2012) have suggested that the thick disc could be decomposed into a radial migrated population being $\alpha-$old and having circular orbits, and another one formed from extra-galactic material, composed with the most metal-poor stars ([M/H]<-0.6 dex) on eccentric orbits. Worth mentioning are also the studies of Bensby et al. (2011) and Cheng et al. (2012a) who found no $\alpha-$enhanced stars at the outskirts of the galaxy, at the distances above the plane where the thick disc should be the dominant population. Whereas both studies rely on relatively poor statistics at these radii, both of them have suggested a smaller scale-length for the $\alpha-$enhanced thick disc. In particular, Cheng et al. (2012a) proposed as an explanation that the inner part of the thick disc could be consistent with a scenario in which the thick disc forms during an early gas-rich accretion phase. Furthermore, the stars far from the plane in the outer disc could have reached their current locations through heating by minor mergers. The precise measurement of the thick disc properties at these radii could hence impose important constraints on the strength of radial migration in the thin disc.

4 The Gaia legacy: determining the relative importance of each formation scenarios

The Gaia satellite is planned to be launched in September 2013. During its five year mission, the survey will aim for completeness to $V \sim 20 - 25$ mag, depending on the colour of the object, with astrometric accuracies of about 20 μas at $V \sim$15 mag. Within a radius of 10 kpc from the Sun, the 3D motions and positions of several hundreds of millions of stars will be known with accuracies better than 10%. The onboard Blue (BP) and Red (RP) spectro-photometers will deliver broadband photometry for roughly a billion stars, up to the 20th magnitude. For the brightest targets ($V \leq 17$ mag, $\sim 350 \times 10^6$ stars), these data will be complemented by the intermediate resolution spectra ($R \sim 11\,500$) gathered at the near-infrared, around the ionised Calcium triplet ($\lambda\lambda$ 847 $-$ 874 nm) from the Radial Velocity Spectrometer (RVS). The analysis of these spectra, will allow to obtain the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), overall metallicity and $\alpha-$abundances for the stars stars brighter than $V \sim 14$ mag. In particular, Kordopatis et al. (2011a) have estimated that accuracies of 100 K, 0.17 dex and 0.1 dex for the $T_{\rm eff}$, $\log g$ and [M/H], respectively, could be achieved for typical thick disc stars at a signal-to-noise ratio of 50 pixel^{-1} using their automated stellar spectra parameterisation pipeline.

The first astrometry data release is likely to be in 2016, with spectrophotometry and stellar parameters to follow later, and 2021 for the final catalogue. This wealth of data, will of course shed some light on the relative contribution of each of the previously cited mechanisms, revealing the relation between the thick disc and the other Galactic structures (thin disc, bulge and halo). In addition, the volume and the magnitudes that are going to be surveyed by Gaia, will minimise the effects of specific spatial and stellar mass sampling at the solar cylinder from which suffered previous surveys, and which according to Bovy et al. (2012), can bias the interpretation of the distinctive nature of the thick disc. More precisely, the constraints that Gaia will bring on the formation scenarios of the thick disc are the followings:

- The observation of the outskirts of the galaxy ($R > 8$ kpc) will allow to obtain estimations of the scale-length of the thick disc, both in terms of star counts, but also using a Jeans analysis. The measurement of a flaring for the thick disc will be possible, which will give valuable information about the total accreted mass of the Milky Way (Qu et al. 2011). In addition, the strength of the radial migration processes will be characterised robustly, by analysing the chemical homogeneity at the outer parts of the thick disc with a statistically significant stellar sample.

- The comparison of the star counts towards the northern and the southern Galactic cap, the search of kinematic asymmetries compared to the Galactic plane, as well as the radial gradients at different heights above the plane, will allow to detect in the thick disc the possible remnants of satellite accretions, either as stellar streams or over-densities in the phase-space. In addition, the evolution of the ellipticity of the orbits, or the variations in the correlations between the circular orbital velocity and the metallicity at different radii, will determine if there is complete mixing in the thick disc stars (Loebman et al. 2011), and perhaps constrain the influence of the Galactic bar in the radial migration of stars.

- The observation the thick disc towards the Galactic bulge will be limited by the high extinction of these regions, as well as the crowding limit of the RVS (20 000 stars deg^{-2}). Nevertheless, the chemo-dynamical characterisation of the brightest thick disc giants in that direction will reveal if there is a relation between the bulge stars and the thick disc ones, which will be for the first time a direct proof of radial migration as one of the mechanisms forming the thick disc structure.

Finally, it should be noticed that the results of Gaia will be complemented by the already on-going Gaia-ESO public spectroscopic survey (Gilmore et al. 2012). This project employs the VLT-FLAMES instrument for high quality spectroscopy of some 100 000 Milky Way stars. Targets brighter than $V \sim 18$ mag will be observed with GIRAFFE at a resolution of $R \sim 20\,000$ whereas some 10 000 stars brighter than $V \sim 16$ will have UVES spectra at a resolution of $R \sim 45\,000$. At the end of this survey, it is estimated that roughly 20 000 stars belonging to the thick disc will be observed, complementing the Gaia mission with more precise stellar radial velocities and chemical abundances at the fainter magnitudes.

5 Conclusions

The understanding of the formation of the thick disc is directly linked with our understanding of the hierarchical formation of the galaxies in the Universe. This review presented the most commonly evoked scenarios to form the Galactic thick disc, and highlighted which are the most recent findings from the large spectroscopic surveys such as RAVE or SEGUE. The future Gaia mission will complement the advent of the future data releases from RAVE (Kordopatis et al. 2012b, to be submitted), SEGUE, APOGEE and Gaia-ESO survey, by mapping chemo-dynamically the regions of the thick disc in which the formation scenarios differ the most. The combination of all these projects will hence determine the relative importance of internal and external mechanisms for the origin and the evolution of the thick disc.

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