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PROBING THE THICK DISC FORMATION SCENARIOS OUTSIDE THE SOLAR NEIGHBOURHOOD

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Abstract. The origin and evolution of the Milky Way remains one of the key unanswered questions in astrophysics. From a sample of roughly 700 stars selected in order to probe the galactic thick disc outside the solar neighborhood, we investigate the radial scale length and scale height of this structure, based on the spectroscopic measurement of its star members. Estimations of the scale height and scale lengths for different metallicity bins result in consistent values, with $h_R \sim 3.4 \pm 0.7$ kpc and $h_Z \sim 694 \pm 45$ pc, showing no evidence of relics of destroyed massive satellites and challenging the radial migration mechanisms as being the most important processes of creation of the thick disc.

Keywords: Galaxy: evolution – Galaxy: kinematics and dynamics – stars: abundances – methods: observational

1 Introduction

The existence of a thick disc for the Milky Way (Gilmore & Reid 1983), and for other disc galaxies (Yoachim & Dalcanton 2006) is rather clearly established nowadays. Nevertheless, its creation mechanisms still remain a riddle in the paradigm of a cold dark matter dominated Universe. For instance, Abadi et al. (2003) propose that the stars forming the thick disc mostly come from disrupted satellites, whereas Villalobos & Helmi (2008) predict that the pre-existing thin disc has been heated rapidly from successive accretions. On the other hand, Brook et al. (2004) suggest that a gas rich merger brought the necessary gas to form *in situ* the thick disc stars, before the gas have had completely settled into a thin disc. Finally, the simulations of Schönrich & Binney (2009) manage to form a thick disc without any external stimulus: stars migrate to larger heights from the inner parts of the Galaxy, due to resonances with the spiral arms and the central bar.

Typical F, G and K main sequence stars are particularly useful to study galactic evolution, since they are both numerous and long-lived, and their atmospheres reflect their initial chemical composition. However, a direct measurement of their spatial distribution requires accurate estimates of stellar distances, which is a delicate step involving (if the parallax is not available) the determination of precise stellar parameters (effective temperatures $T_{\rm eff}$, surface gravities $\log g$, and metal content [M/H]).

In order to put more constraints on the thick disc properties, we explore spectroscopically the stellar contents outside the solar neighborhood, owing to an extensive use of the Ojha et al. (1996) catalogue in which are published the proper motions (μ_l, μ_b) and U,B,V colors of several thousand stars. Here, based on the spectroscopic observations of 700 of these stars towards the galactic coordinates $l \sim 277°$, $b \sim 47°$, we present a kinematic and chemical characterization of the thick disc.

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2 The star sample

The target stars were selected having $14 \leq m_V \leq 18.5$ mag in order to probe the galactic thick disc and an acceptable signal-to-noise ratio (S/N>20). According to the published values of Ojha et al. (1996), the magnitude precisions range from 0.02 mag for the brightest, to 0.05 mag for the faintest stars. Associated errors for the proper motions are estimated to be 2 mas/year.

The observations were obtained with VLT/FLAMES feeding the GIRAFFE spectrograph with the LR08 grating (8206-9400 Å, R$\sim$6500). This setup contains the Gaia/RVS wavelength range (8475-8745 Å), and is similar to its low-resolution mode. In that wavelength range, the IR CaII triplet is predominant for most of the spectral types and luminosity classes as well as for very metal-poor stars. In addition, these strong features are still detectable even at low S/N, allowing a good radial velocity ($V_{\rm rad}$) derivation and, combined with the other available lines, a good overall metallicity estimation.

Radial velocities have been derived by cross-correlating the spectra with a binary template of a K0 type star, reaching a mean estimated error of 4.7 km s^{-1}. We used the pipeline presented in Kordopatis et al. (2011a) to obtain the $T_{\rm eff}$, log g and [M/H] for our sample. This pipeline combines a local multi-linear regression method, MATISSE (Recio-Blanco et al. 2006), and an oblique decision-tree, DEGAS (Bijaoui et al. 2010) in order to normalize iteratively the spectra and derive accurately the stellar atmospheric parameters. The method has been tested on a set of 8×10^4 synthetic spectra, in order to establish the relative errors of our algorithm on the effects of the S/N and possible radial velocity shifts. We found that for an intermediate metallicity dwarf star, at S/N$\sim$50 pixel^{-1} (which is the mean S/N of our spectra), accuracies of $\sim$ 108 K, 0.17 dex and 0.12 dex are achieved for $T_{\rm eff}$, $\log g$ and [M/H], respectively. In addition, the algorithm has been applied on two observed stellar libraries, the S^4N (Allende Prieto et al. 2004) and the CFLIB one (Valdes et al. 2004), showing no particular biases according to the S/N, the spectral type of the star or the metallic content.

2.1 Derivation of the stellar distances and velocities

At least until the ESA/Gaia mission, stellar distances for FGK targets far from the solar neighborhood have to be determined spectroscopically or photometrically. For instance, the atmospheric parameters determined in the previous section can be projected on a set of theoretical isochrones to derive the absolute magnitudes of the stars. Then, the line-of-sight distances can be derived, using the distance modulus.

We generated our own set of isochrones by using the *YYmix2* interpolation code, based on the Yonsei-Yale models (version 2, Demarque et al. 2004) combined with the Lejeune et al. (1998) colour table. To obtain the absolute magnitude $M_{\rm v}$, the method of Zwitter et al. (2010) was used. This procedure consists in finding the most likely values of the stellar parameters, given the measured atmospheric ones, and the time spent by a star on each region of the H–R diagram.

The availability of the distances (D) then allows to estimate their galactic-centred cylindrical coordinates, which, combined with proper motions and radial velocities, provide the information required to calculate the full space motions of any star in the Galaxy. For our sample, the radial velocities are derived from the observed spectra, whereas magnitudes, colors and proper motions are taken from Ojha et al. (1996).

The errors on these kinematic data are estimated as follows: for each star, we make 5×10^3 Monte-Carlo realisations for D, μ_l, μ_b and $V_{\rm rad}$, assuming Gaussian distributions around their adopted values, with a dispersion according to their estimated errors. For every realization, 6d phase-space parameters are computed, taking as a final value the mean of all the realisations, and as an error the standard deviation (see Kordopatis et al. 2011b).

3 Derivation of the radial scale lengths and scale heights

In what follows, we considered as thin disc the stars below 800 pc from the galactic plane, and as thick disc the stars between 1 and 3 kpc, in order to avoid a strong contamination from the other components. Supposing that the thick disc and the thin disc are in equilibrium, the velocity ellipsoids that were derived (corrected from the observational errors as in Jones & Walker 1988), can be used with the Jeans equation in order to infer an estimation of their radial scale lengths (h_R) and scale heights (h_Z). In cylindrical coordinates, the radial and azimuthal components of the Jeans equation are:

$$v_c^2 - \overline{v_\phi}^2 = \sigma_{V_R}^2 \left(\frac{\sigma_{V_\phi}^2}{\sigma_{V_R}^2} - 1 - \frac{\partial ln(\rho \sigma_{V_R}^2)}{\partial lnR} - \frac{r}{\sigma_{V_R}^2} \frac{\partial \sigma_{V_{R,Z}}^2}{\partial Z} \right) \quad (3.1)$$

$$\rho K_Z \quad = \quad \frac{\partial \rho \sigma^2_{V_Z}}{\partial Z} + \frac{1}{R}\frac{\partial R \rho \sigma^2_{V_{R,Z}}}{\partial R} \tag{3.2}$$

where ρ is the density of the considered galactic component, $V_c = 220$ km s^{-1} is the circular velocity at the solar radius, $\overline{V_\phi}$ is the mean rotational velocity of the stars having the $\sigma_{V_R}, \sigma_{V_\phi}, \sigma_{V_Z}$ velocity dispersions, $\sigma^2_{V_{R,Z}} = \overline{V_R V_Z} - \overline{V_R}\ \overline{V_Z}$, and K_Z is the vertical galactic acceleration.

3.1 Radial scale lengths

We consider that $\rho(R) \propto \exp(-R/h_R)$, and that $\sigma^2_{V_R}$ has the same radial dependence as ρ (as in Carollo et al. 2010). Therefore, $\sigma^2_{V_R} \propto \exp(-R/h_R)$. In addition, one can assume that the galactic potential is dominated by a centrally concentrated mass distribution and that the local velocity ellipsoid points towards the galactic centre (Gilmore et al. 1989; Siebert et al. 2008). In that case, the last term of Eq. 3.1 becomes:

$$\frac{r}{\sigma^2_{V_R}}\frac{\partial \sigma^2_{V_{R,Z}}}{\partial Z} \approx 1 - \frac{\sigma^2_{V_Z}}{\sigma^2_{V_R}} \tag{3.3}$$

Equation 3.1 can then be re-written as follows:

$$\frac{\sigma^2_{V_\phi}}{\sigma^2_{V_R}} - 2 + \frac{2R}{h_R} - \frac{v_c^2 - \overline{v_\phi}^2}{\sigma^2_{V_R}} + \frac{\sigma^2_{V_Z}}{\sigma^2_{V_R}} = 0 \tag{3.4}$$

Each of the terms of Eq. 3.4 have been measured in our data, leaving as the only free variable, the radial scale length h_R of the discs. With the values derived for the thick disc of $(\sigma_{V_R}; \sigma_{V_\phi}; \overline{V_\phi}) = (66\pm5; 57\pm4; -167\pm 3)$ km s^{-1}, we find $h_R \sim 3.4 \pm 0.7$ kpc. This results is found to be the upper end of the values cited in the literature (ranging from 2.2 kpc (Carollo et al. 2010) up to 3.6 kpc (Jurić et al. 2008), or even 4.5 kpc in the case of Chiba & Beers (2001)).

As far as the thin disc is concerned, using $(\sigma_{V_R}; \sigma_{V_\phi}; \overline{V_\phi}) = (43\pm2; 33\pm1; -204\pm1)$ km s^{-1}, we find that it has a smaller, though comparable radial extent (within our uncertainties) as the thick disc, with $h_R = 2.9\pm0.2$ kpc. A smaller thin disc has been suggested by other recent observations (see Jurić et al. 2008), but once more, the value we derive is at the upper end of the previously reported values in the literature. Nevertheless, such an extended thin disc is plausible, since our data probe mainly the old thin disc, which is likely to be more extended than its younger part.

3.2 Scale heights

We assume that the last term of Eq. 3.2 is negligible, since we are far from the galactic centre, and that $\rho(Z) \propto \exp(-Z/h_Z)$. Equation 3.2 hence becomes:

$$\frac{\partial ln \sigma^2_{V_Z}}{\partial Z} - \frac{1}{h_Z} + \frac{K_Z}{\sigma^2_{V_Z}} = 0 \tag{3.5}$$

We use $K_Z = 2\pi G \times 71\ M_\odot pc^{-2}$ derived by Kuijken & Gilmore (1991) at $|Z| = 1.1$ kpc, but we note however, that this value of K_Z might differ at the distances where our targets are observed. We also use for the thick disc the value derived from our data of $\partial\sigma_{V_Z}/\partial Z = 15 \pm 7$ km s^{-1} kpc^{-1} and $\sigma_{V_Z} = 53 \pm 3$ km s^{-1}. Hence, for the thick disc, we find $h_Z \sim 694 \pm 45$ pc.

As far as the thin disc is concerned, we found that $\partial\sigma_{V_Z}/\partial Z = 19\pm10$ km s^{-1} kpc^{-1} and $\sigma_{V_Z} = 25\pm1$ km s^{-1}, resulting in $h_Z = 216\pm13$ pc. The derived values for both components are in good agreement with, for example, Jurić et al. (2008), who suggested a thin disc with $h_Z = 300$ pc, and a thick disc having $h_Z = 900$ pc.

4 Discussion

We computed the radial scale lengths and scale heights of the thick disc for different metallicity bins, using Eq. 3.4 and Eq. 3.5. The results are shown in Table 1, where the metallicity bins have been selected in order to include at least 30 stars each. Though we found that both h_R and h_Z increased with decreasing metallicity (except for the most metal poor bin), this trend is not strong enough to stand out significantly from the errors. We conclude that, within the errors, the same scale lengths and scale heights are found, which could be the

Table 1. Kinematic parameters, radial scale lengths and scale heights for different metallicity bins of the thick disc targets.

$[M/H]$ (dex)	N	$\overline{V_R}$ (km s^{-1})	σ_{V_R} (km s^{-1})	$\overline{V_\phi}$ (km s^{-1})	σ_{V_ϕ} (km s^{-1})	$\overline{V_Z}$ (km s^{-1})	σ_{V_Z} (km s^{-1})	h_R (kpc)	h_Z (pc)
-1.14	36	-5± 9	58± 11	-137± 11	61± 7	-7± 8	59± 7	1.9± 0.7	934± 166
-0.67	26	-3± 17	85± 17	-161± 11	54± 11	-4± 12	54± 8	4.0± 1.3	804± 181
-0.40	56	5± 8	81± 8	-168± 6	52± 5	-17± 6	45± 4	3.8± 0.9	610± 90
-0.11	37	6± 9	64± 8	-171± 7	50± 6	-18± 7	45± 5	3.1± 0.9	620± 97

signature of only one population. Indeed, if an important amount of relics of a destroyed massive satellite would exist in our line-of-sight, as suggested by Gilmore et al. (2002), one would expect them to have a different spatial distribution compared to the canonical thick disc, which we do not observe. Unless, of course, the satellite debris provides the dominant stellar population in the thick disc.

This result can also be discussed in the frame of a thick disc formed according to a radial migration scenario. In that case, the older stars being at the solar radius have come from the inner parts of the Galaxy, and are expected to have a higher vertical velocity dispersion and a different metallicity, and therefore, should exhibit scale heights dependent on metallicity. In particular, the model of Schönrich & Binney (2009) predicts a smaller scale height for the metal poor thick disc, compared to its metal rich counter part. Such a trend is not seen in our data (if it exists, it should be rather small), which challenges the migration scenario as being the most important process of creation of the galactic thick disc.

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