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RECONSTRUCTING THE SFH OF THE MILKY WAY

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Abstract. Recent galactic archaeology results suggest that the stellar mass budget of the Milky Way requires reassessment, particularly regarding the mass of the thick disc. Our results imply a massive thick disc and are in agreement with the results of redshift surveys of Milky Way-type galaxies. We report our previous work on recovering the SFH of the Milky Way from solar vicinity data and discuss how recent and future surveys will refine our understanding.

Keywords: Milky Way, star formation history, chemical evolution

1 Introduction

There are two main approaches to recovering the evolution of the Milky Way from observations. We can use Galactic Archaeology to reconstruct the behavior of the Galaxy, using the characteristics of different stellar populations, such as the chemical and dynamical properties of stars (a recent example being Bovy et al. 2012). The alternative is to study the properties of Milky Way-like galaxies at different redshifts, using large statistically significant samples of galaxies (e.g. van Dokkum et al. 2013). Here, we will discuss our method for recovering the star formation history (SFH) of the Milky Way (presented in detail in Snaith et al. 2014b), which mainly follows the Galactic Archaeology approach. We do, however, compare our results with the work of van Dokkum et al. (2013), who use the other method (see Snaith et al. 2014b, for further details.).

The Milky Way has, historically, been thought to consist of a dominant thin disc, with a less massive thick disc and much smaller stellar halo. However, recent results, (van Dokkum et al. 2013; Haywood et al. 2013; Snaith et al. 2014b) have called this into question, and suggest that the thick disc is substantially more massive than implied by the previous orthodoxy. A massive thick disc has been discussed before (e.g Fuhrmann et al. 2012; Gilmore & Wyse 1986) but has not, historically, been favoured.

Haywood et al. (2013) supported an alternative model of the Milky Way, based on solar vicinity data, which we explored in Snaith et al. (2014a,b) and Snaith et al. (2014b). In Snaith et al. (2014b) we reassessed the mass budget of the Milky Way by recovering the SFH that best replicates the chemical evolution of solar vicinity stars.

2 Data & Interpretation

We used a sample of 365 stars in the solar vicinity, with very precise abundances, kinematics and ages. These stars were selected by Haywood et al. (2013) from 1111 stars observed by Adibekyan et al. (2012). The ages were then calculated, taking into account the alpha abundances of the stars. Only stars with well defined ages were included in the Haywood et al. (2013) sample. Formal errors on the ages are 1-1.5 Gyr (increasing with age), due to uncertainties in stellar physics and atmospheric parameters.

The stars were divided into three subsamples. A first cut was made according to the metallicity-[α/Fe] distribution. At low metallicity ([Fe/H]<-0.2 dex) there are two parallel sequences. The lower alpha sequence was attributed in Haywood (2008) and Haywood et al. (2013) to stars from the outer thin disc which contaminate

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the solar vicinity (green symbols on Fig. 1 panel a). The status of these objects has been confirmed on larger surveys (see Bovy et al. 2012, their figure 7).

Haywood et al. (2013) further labeled the stars not included in the outer disc as either thick disc or inner thin disc stars. This was done according to the distinct behavior of the alpha-age relation for stars older and younger than 8 Gyr, (blue and red points for Silicon in Fig. 1, panel b), reflecting the distinct SFR regimes at these two epochs.

We calculated the orbits of the stars in an axisymetric potential from Allen & Santillan (1991), using the velocity and position data observed by Adibekyan et al. (2012). The thick disk stars in the local vicinity have pericenters and apocenters which span from less than 2 kpc to about 10 kpc, and so cover the whole disc (Snaith et al. 2014a). With stars coming from across the disc, we assume that stars trace out the locus of the chemistry and age distribution representative of the entire disc.

3 The Model

We used a simple galactic chemical evolution (GCE) code, without any gas infall or outflows, to model the Milky Way (see Snaith et al. 2014a, Snaith et al. 2014b, Haywood 2014). The model assumes: (1) all gas which can form stars is present throughout the evolution, but makes no assumptions as to whether the gas is cold star forming gas, warm circumgalactic gas or hot halo gas. This assumption is equivalent to saying the accretion of gas is not significantly delayed and does not introduce any dependency of the SFR on the gas accretion (2) the gas is initially primordial. (3) The gas is homogeneous at all times. No a priori shape is given to the SFH, which is used as a free parameter to fit the data.

The ingredients into the model are: Nomoto et al. (2006), Iwamoto et al. (1999) and Karakas (2010) stellar yields, the Kroupa (2001) IMF, and the stellar lifetimes of Raiteri et al. (1996). The only input into the model is the SFH.

We then use a χ^2 fitting algorithm to match the chemical evolution of the model to the data by fitting the stellar age-[Si/Fe] distribution and recovering the best-fit star formation history. We fit the inner thick and thin discs with a single star formation history. The outer disk is the result of a different chemical evolution history, as suggested by Haywood et al. (2013), and shown in Snaith et al. (2014a). Here, we will only discuss the inner disc, see Snaith et al. (2014a) for a discussion of the outer disc.

4 Galactic Archaeology

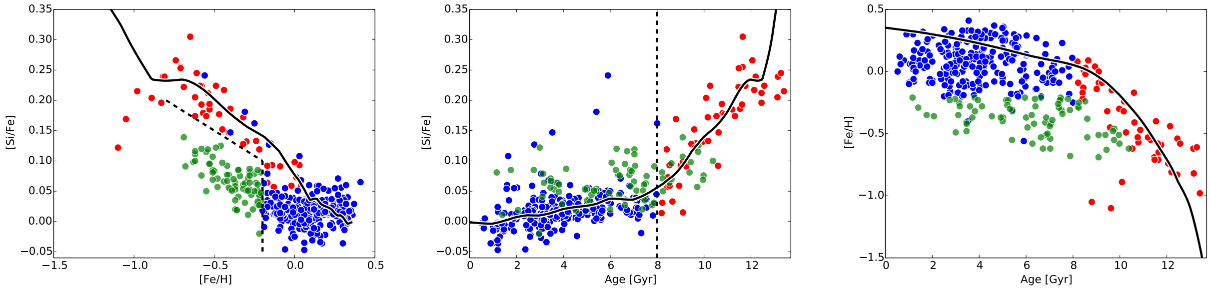
Using the model outlined in the previous section, we identified the SFH which produced the age-[Si/Fe] distribution that best matches the data, (see Snaith et al. 2014a,b).

The chemical evolution track which results from the best fit SFH is shown in Fig. 1, and clearly fits the age-[Si/Fe] distribution (panel b), as well as the metallicity-[Si/Fe] distribution (panel a) of the inner discs. The track does, however, follow the upper limit of the age-metallicity distribution (panel c). The SFH itself (Fig. 2, panel a) shows four particular features: (1) the SFR during the thick disc phase is three times that of the thin disc, (2) the thick disc phase falls sharply at a lookback time 8 Gyrs, (3) the interface between the thick and thin discs shows a 1 Gyr dip in the star formation rate, (4) star formation in the thin disc is relatively constant.

Although the thick disc formation only lasts between 13-8 Gyr it is characterised by a considerably higher SFR than the thin disc. During the thick disc phase the Galaxy assembles $\sim$50% of its total stellar mass (Fig. 2, panel b). This makes a considerable change from models where the thick disc is small, or not explicitly included (e.g. Chiappini et al. 1997). Our SFH leaves us with a very massive thick disc, in tension with the canonical model of the Milky Way.

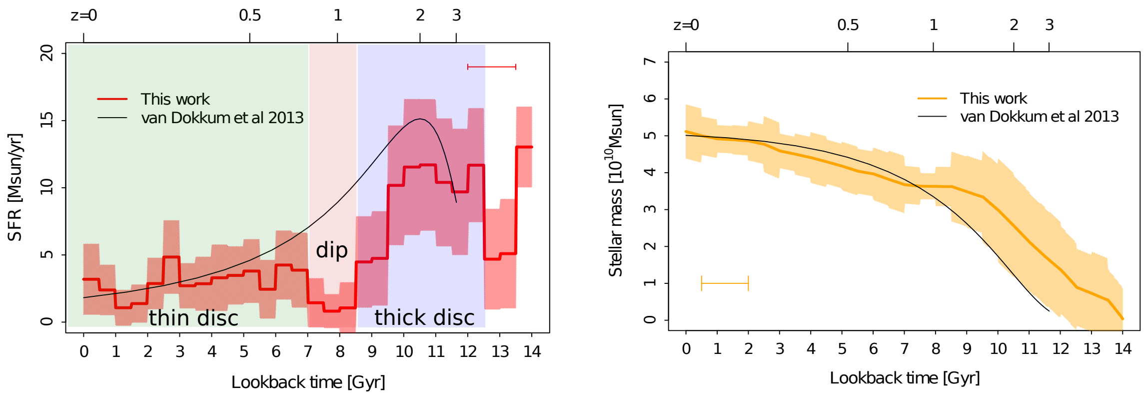
Using SEGUE data Bovy et al. (2012) found that the thick and thin stellar discs have different radial scale lengths. These are given as 1.8 kpc for the thick disc, and a mean of 3.6 kpc for the thin disc (the thin disc scale length is found to vary with metallicity in Bovy et al. 2012).

If we model the Milky Way as two exponential discs, using the radial scale length provided by Bovy et al. (2012), and take into account the standard surface density of thick and thin disc stars in the solar vicinity, then, a massive thick disc, comparable in mass to the thin disc, is implied. This lends considerable weight to the massive thick disc model of the Galaxy.



(a) (b) (c)

Fig. 1. The best fit chemical evolution tracks for the GCE model (black line) of Snaith et al. (2014a) and Snaith et al. (2014b). Panel (a) gives the metallicity-[Si/Fe] distribution, panel (b) gives the [Si/Fe] evolution with time and panel (c) gives the metallicity evolution with time. The red, blue and green points are stars assigned to the thick, inner thin and outer thin discs. The dashed line in panel (a) defines the outer thin disc while vertical dashed line in panel (b) is the split between the thick and thin discs . The data are taken from Haywood et al. (2013)



(a) (b)

Fig. 2. Left: The SFH recovered for the inner disc of the Milky Way (from Snaith et al. 2014b) and the SFR evolution of Milky Way type galaxies (from van Dokkum et al. 2013). The coloured area shows the error due to bootstrapping the data. **Right:** The stellar mass assembly history (from Snaith et al. 2014b) of the Milky Way against that recovered by van Dokkum et al. (2013) for Milky Way type galaxies. This figure was taken from Snaith et al. (2014b).

5 Milky Way-type galaxy evolution

van Dokkum et al. (2013) explored the evolution of Milky Way-type galaxies out to z=2.5, and derived empirical expressions for their mass assembly and star formation rate.

It is clear from Fig. 2, taken from Snaith et al. (2014b), that much of the mass in Milky Way-type galaxies was assembled before a lookback time of 8 Gyrs (the black curves). With appropriate scaling this produces a mass assembly history similar to our recovered SFH (Snaith et al. 2014b).

It is clear that the van Dokkum et al. (2013) data implies a considerable fraction of the stellar mass in a Milky Way type galaxy forms before z=1, thus demonstrating that a massive thick disc for the Milky Way is unsurprising.

6 The Future

Gaia will produce a vast sample of Milky Way stars, covering a sizable fraction of stars in the disc and bulge. This mission will provide unparalleled data on the astrometric properties of stars. Spectroscopic surveys will be combined with distance measurements from Gaia, and will allow us to calculate much more accurate ages for stars. They will also provide alpha element abundances far beyond the solar vicinity.

We have illustrated in Snaith et al. (2014a) and Snaith et al. (2014b) that it is possible to reconstruct the star formation history of the Milky Way from solar vicinity data, if we assume that the solar vicinity contains stars representative of the entire disc. This is expected to be true (Snaith et al. 2014a) for old stars, but becomes less so for younger stars. The immense sample of stars, over a wide range of radii, expected in the future, will allow us to test that our results are valid beyond the solar vicinity.

Fuhrmann et al. (2012) and Gilmore & Wyse (1986) envisioned that the thick disc might have an important role in the history of the Milky Way. Our evidnce suggests that this is indeed the case. With this reappraisal it is important to discuss this in the context of idealized simulations (e.g. Di Matteo et al. 2014). A large thick disc has previously been neglected in many idealised models. It is essential to understand the features in a galaxy that are the result of a massive thick disc, so that such models can be tested by forthcoming observations.

7 Conclusions

Recently, highly precise observations have led to tension with the canonical model of a low mass thick disc. For example: (1) Haywood et al. (2013) interpret exquisite observations of the solar vicinity, and find that they imply a massive thick disc, (2) Snaith et al. (2014b) fit the Adibekyan et al. (2012) and Haywood et al. (2013) data using a GCE code and return a thick disc containing 50% of the Galaxy's stellar mass, (3) Bovy et al. (2012) utilize SDSS data to calculate local densities, and disc scale lengths. A massive thick disc arises from the geometry of the system. (4) van Dokkum et al. (2013) explore large scale surveys out to high redshifts, and find that a substantial fraction of the stellar mass of Milky Way type galaxies forms before z=1.

With the current and forthcoming Milky Way surveys providing ever larger and more precise data on Milky Way stars, it is important to improve our theoretical understanding of the Galaxy, including a massive thick disc, in order to interpret new data.

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