Galaxy formation and evolution: Dynamical model of the Milky Way disk

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1. Introduction

Less than a hundred years have passed since the time when people realized that the modern Universe is filled with galaxies - innumerable gravitationally bound stellar islands, structures of the same nature as the Milky Way. Investigations of their formation and evolutionary processes can, undoubtedly, be classified as one of the most exciting and difficult branches of the modern astrophysics. Huge distances separating us from other galaxies leave astronomers no choice but to carry out their studies from a rather anthropocentric point of view: being ourselves located in a spiral galaxy, we learn a lot by looking at this magnificent structure from the inside. High-quality data available for stellar populations in the Milky Way is of such value for galactic astronomy that its worth can hardly be overestimated.

Many galactic models rest on the concept of stability or equilibrium of the system. Though we know that no galaxy can be considered as having reached relaxation, we can describe some of them as stable systems when looking at short timescales. By using this idea, considerable and successful improvements were made during the last several decades. This led us from purely dynamical models for several isothermal populations of the Milky Way disk in the presence of a stellar halo (Bahcall, 1984) to such sophisticated machinery as the Besançon model (Czekaj, 2014). All previous studies demonstrate that the complexity of the problem leads to a large number of free parameters, often poorly constrained. As a result, global models of the Galaxy predict such observable properties as stellar density, kinematics and chemical abundances with relatively low accuracy.
In order to avoid the aforementioned problem we concentrate our attention on the thin disk only – a thin exponential stellar structure with a scale height of ~10% of its scale length, where most of the luminous matter of the Milky Way is confined. Since the morphology of our Galaxy convinces us of an absence of global cataclysms (e.g. major mergers) during its history, much information about the Milky Way formation and evolution should still be imprinted in the properties of the thin disk stellar populations. Revealing this information will push the horizon of our knowledge about Galactic nature further; we aim to contribute to this with a semi-analytic self-consistent dynamical model of the Milky Way thin disk.

We start with the model for the local solar cylinder, known as Just-Jahreiß model (or JJ-model), which proved to be competitive, having been recently compared to kinematic data from Hipparcos (Just&Jahreiß, 2010), SDSS star counts near the North Galactic Pole (Just et al., 2011) and used to constrain the initial mass function (IMF) again with Hipparcos data and the Catalog of Nearby Stars (Rybizki&Just, 2015). Also a non-constant SFR assumed in the JJ-model has been successfully tested in the frame of the Besançon Galaxy model (Czekaj, 2014).
Now we extend this local JJ-model to mid-galactocentric distances in order to explore thin disk properties through star formation rate function (SFR), age-velocity dispersion relation (AVR) and age-metallicity relation (AMR).

3. Results

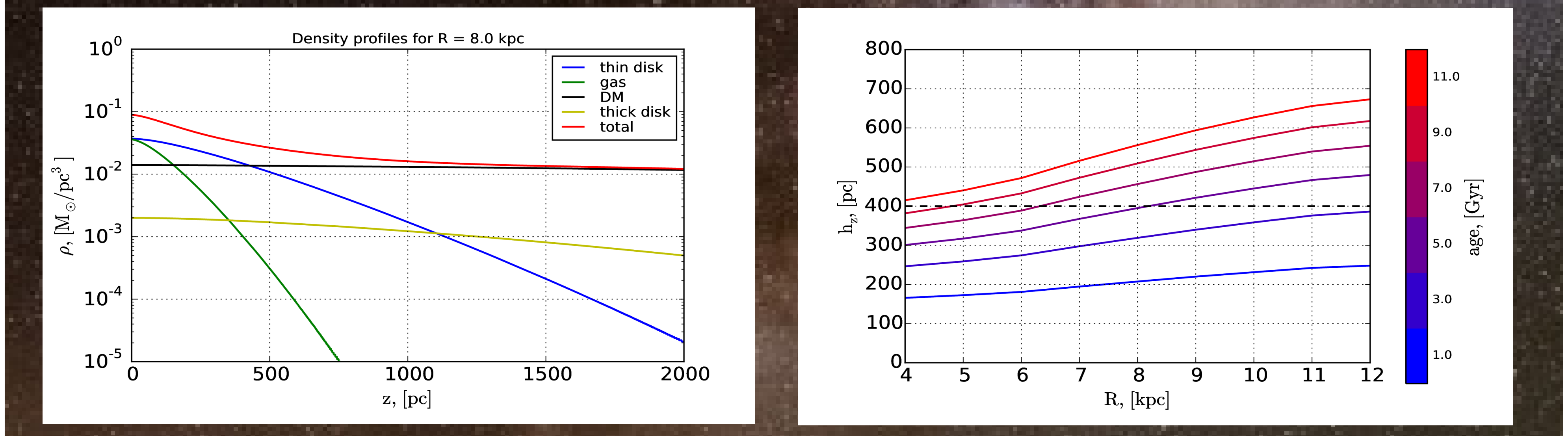

Fig. 2 Left: Vertical density profiles at solar distance R=8 kpc as output of the model with SFR from Fig.1. Right: Scale height versus distance for different ages of subpopulations. Thin disk effective thickness of 400 pc is overplotted with black dashed line.

With this model we are able to predict vertical density profiles for all included components (Fig.2, left) and for individual subpopulations of a specific age as well. Here we point out to the fact that the shape of profiles at Fig.2 is definitely more complex than a simple exponential law usually prescribed for vertical structure of the disk in the Milky Way and other galaxies. Our profiles have a core close to z = 0 - an outcome of the composite disk structure.

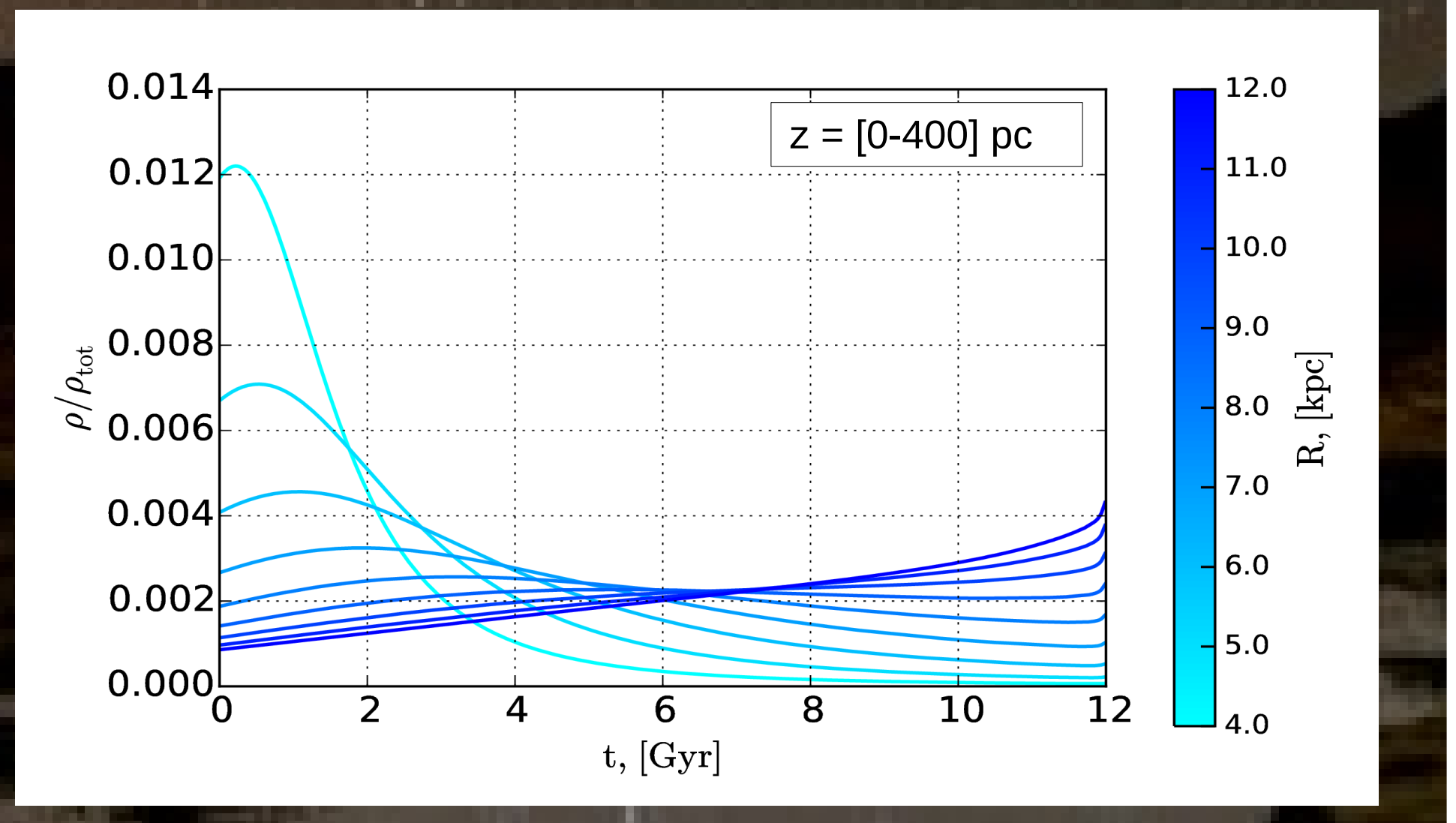

Fig. 3 Age distributions of the thin disk stars as derived from calculated vertical potential, AVR and assumed SFR.

Also two related effects arise naturally from the model: firstly, there is a clear positive age gradient towards the center of the Galaxy and secondly, though the effective thickness of the thin disk remains constant, subpopulations of different ages show flaring (Fig.2, right). The later fact is well-known and is often related to the impact of internal and external factors such as radial migration and satellites (Minchev, 2015). But we demonstrate here that it originates naturally even without any external influence as a result of inside-out disk growth, which is represented in our model by SFR with shifting peak of star formation intensity as we go outwards (Fig.1). Age distributions shown on Fig.3 contain a clue to this seemingly contradicting situation: they can be understood as relative weights one has to use while summing scale heights of all subopulations from Fig.2 in order to get an effective value of the thin disk thickness.

2. Extended Just-Jahreiß model

To construct a self-consistent Milky Way disk model we make two basic assumptions:

- disk is axially symmetric (no spiral arms)
- disk rests in dynamical equillibrium (is stationary on dynamical timescales).

We separate the horizontal and vertical dynamics of the disk. Keeping in mind that the thin disk dynamics is influenced by other components such as dark matter halo, thick disk and gas in the Galactic plane we include them in our model, but at the same time neglect stellar halo and bulge. Following one of the traditional approaches we assume that all this matter exists in a form of isothermal subpopulations of different ages. This implies that vertical density law of each subpopulation can be described by a simple exponential profile.

The full scheme includes two essential steps:
(1) we assume density distributions in the Galactic plain for the thin and thick disks, gaseous component (exponential laws with scale length of 2.5, 1.5 and 4.5 kpc respectively), and dark matter halo (power law profile given by thin-disk approximation (Just&Jahreiß, 2010)).
(2) for distances 4-12 kpc with a step of 1 kpc we iteratively solve combined Poisson-Boltzmann equation and by doing this we find self-consistent pair {vertical density-potential} that supports radial distribution of matter assumed in the previous step.

Following the local JJ-model, we construct thin disk of 480 isothermal subpopulations with ages in a range of 0-12 Gyr, which allows to reach high time-resolution of 25 Myr. Gaseous component is represented by 180 subpopulations. Thick disk and dark matter are modeled as single isothermal components. Effective thickness of thin and thick disks are assumed to be constant of 400 and 1200 pc respectively. Thickness of gas is 150 pc at solar position R=8 kpc and during iterations is allowed to change with galactocentric distance. The evolution and properties of the thin disk are governed by SFR and AVR as functions of time and galactocentric distance. SFR is given as a two-parametric analytic function and is a main instrument to change the model's predictions. AVR has only one free parameter – scaling factor, which value is calculated iteratively to fulfill the condition of constant effective thickness of the thin disk.

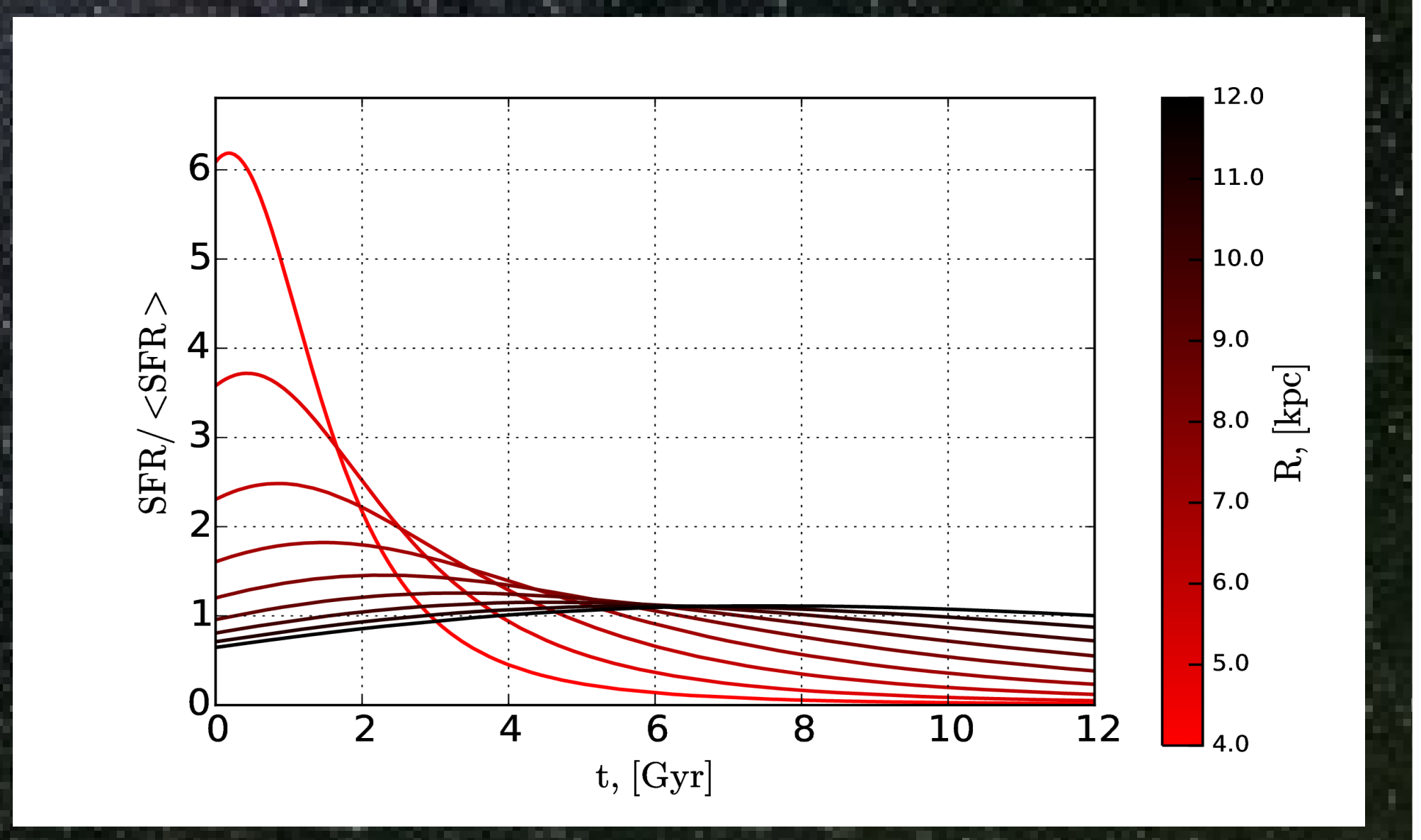

Fig. 1. SFR as a function of galactocentric distance for one of the model's realizations. Values of SFR parameters are chosen to represent an idea of inside-out disk growth.

4. Future of the model

Up to now this extended JJ-model remains theoretical and requires fitting to data. An extremely valuable sample for testing the model will be the first Gaia data release (Sept. 14, 2016) with ~ 2.5 million Tycho-2 stars with parallaxes and proper motions. We can compare our predictions to observed Gaia data in a form of star counts, CMDs or Hess diagrams. By looking at different distances we hope to pin down SFR parameters.

Another independent direction of improvement is to include radial and tangential velocity distribution functions in the model and compare kinematics to such catalogs as RAVE.
Up to now all the code is being developed on python 2.7. There is a possibility to integrate it in future with c++ Galaxia tool (Sharma, 2011) designed for creating mock catalogs of the Milky Way and based currently on the Besançon model.

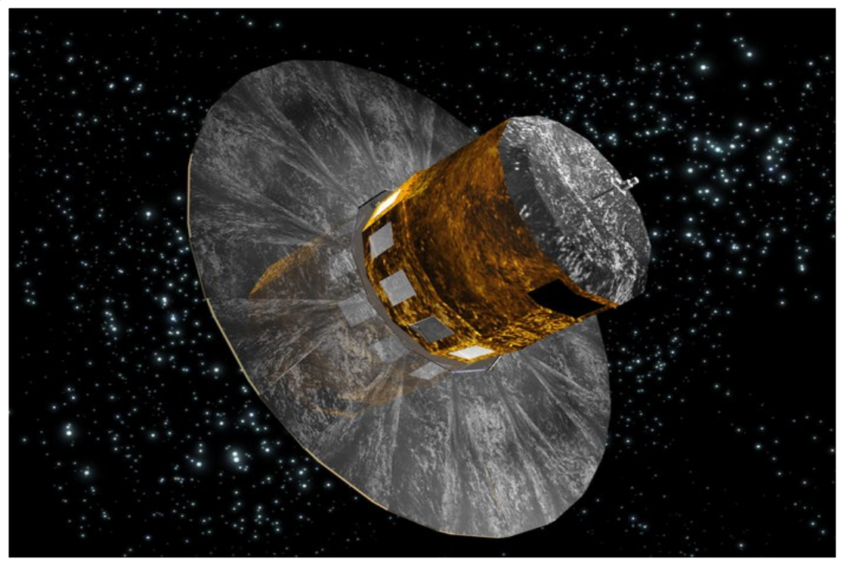

Fig. 4 Artist's impression of the Gaia satellite, ttp://www.esa.int

Acknowledgments

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Photo: night sky over northern Chilean highlands near San Pedro de Atacama, http://apod.nasa.gov/apod/ap160707.html