
125. The Besançon Galaxy model

THE BESANÇON GALAXY MODEL is a stellar population synthesis model which played a key part in the preparation of the Gaia mission. It is now being used, by comparison with the latest data releases, as a probe of properties such as our Galaxy's stellar initial mass function, star formation rate, and gravitational potential.

POPULATION SYNTHESIS MODELS, in general, aim to describe a galaxy's observed properties as arising from their constituent stellar population(s), evolving according to well-defined physical processes.

The star formation history of a distant galaxy, for example, determines its integrated light. In population synthesis, assumed initial mass function(s) and star formation rate(s) are adjusted to match the observed integrated spectrum. Starting with the work of Tinsley (1972), and later Bruzual (1983) and others, these models have long been successfully used in the interpretation of galaxy colours and spectra.

FOR OUR OWN GALAXY, star counts as a function of magnitude, colour, and direction can be compared with models in which stars are created following an initial mass function and star formation rate, and evolved according to theoretical evolutionary tracks. For each simulated star, photometry, metallicity, and kinematics can be computed. Results can be compared with observations to improve the model's initial assumptions.

The development of this sort of Galaxy star count model has its origins in the early 1980s with the need for star count predictions, versus magnitude, for operation and observations with the Hubble Space Telescope. Starting with assumptions on density laws and luminosity functions, these early Bahcall-Soneira models had numerous applications to studies of Galactic structure, halo modelling, and quasar evolution (Bahcall & Soneira, 1980; Bahcall, 1986; Bahcall, 1999).

In a similar way to the preparations for HST 40 years ago, population synthesis models played a valuable part in preparing for Gaia, and are playing a similar role in preparations for the Vera C. Rubin Observatory, embracing stars as faint as $r = 27.5$ mag (Dal Tio et al., 2022).

BEFORE LOOKING further at the Besançon galaxy model, and its applications to Gaia, let me put it in the context of other recent Galaxy models.

Amongst these, TRILEGAL (Girardi et al., 2005; Girardi, 2016) is based on a theoretical stellar luminosity function as a function of absolute magnitude, Galactic position, and passband, derived from a set of evolutionary tracks. It includes five distinct Galaxy components: the thin and thick disks, the halo, the bulge, and a disk extinction layer. It has been calibrated against various observational star counts, including Hipparcos.

Just & Jahreiss (2010) used dynamical constraints to create a local Galaxy model. Although it only accounts for main sequence disk stars, it gave specific constraints on the local star formation history and initial mass function. More recently, it has been compared with the astrometric data from Gaia DR1 and radial velocities from RAVE DR5 (Sysoliatina et al., 2018), as well as Gaia DR2 and APOGEE (Sysoliatina et al., 2021).

Another recent development is GalMod, a star-count model featuring an asymmetric bar/bulge, as well as spiral arms and associated extinction (Pasetto et al., 2018).

THE BESANÇON Galaxy model is an axisymmetric approximation comprising the four main stellar populations (thin disk, thick disk, halo, and bulge), each with its own star formation history and stellar evolutionary models. The objective was both to simulate reasonable star counts, but also to test the assumptions on the rate of star formation, initial mass function, and stellar evolution (Robin et al., 2003; Robin et al., 2012).

AMONGST OTHER Gaia related applications, Perryman et al. (2014) used TRILEGAL to construct a star count model as a function of magnitude, populating them with planets (according to known dependencies on spectral type, planet mass, and orbits), and then used this to predict the number of exoplanets detectable with Gaia astrometry over a projected 5- or 10-yr mission.

Holl et al. (2022) similarly used the Besançon model to predict Gaia's brown dwarf detection rates around FGK stars in astrometry, radial velocity, and transits.

FROM THE early Gaia concept definition phase in the 1990s, the Besançon Galaxy model was at the heart of the work of the Simulation Working Group, which itself developed into Gaia DPAC Coordination Unit 2.

A key component of the resulting Gaia Simulator is its Universe Model, used to create catalogues down to its magnitude limit. For stellar sources (both single and multiple stars), the Universe Model is based on the Besançon ‘Galaxy’ (with nebulae, star clusters, diffuse light, planets, satellites, asteroids, comets, (un-)resolved galaxies, quasars, and supernovae also included). It yields object distances, magnitudes, spectral characteristics, and kinematics, as well as observation errors.

The complete Gaia Simulator actually comprises three data generators: this Gaia Object Generator, GOG (Luri et al., 2014); the Gaia Instrument and Basic Image Simulator, GIBIS, generating pixel-level images (Babusiaux, 2005); and the Gaia System Simulator, GASS, generating the telemetry stream (Masana et al., 2010).

The Gaia Simulator was essential for predicting the numbers of stars observed as a result of the two superimposed viewing directions and the (ecliptic-based) scanning law. This was, in turn, crucial for optimising the CCD readout strategy, the on-board data handling requirements, the on-board memory sizing, and the required downlink data rate from its L2 orbit, along with various other aspects of the scientific payload design.

It was also used for tests of the astrometric global iterative solution, providing star distributions for large-scale simulations, choice of primary stars and the effects of binaries, tests of object matching, and so on.

WITH THE SUCCESSIVE Gaia data releases have come progressive model improvements and insights.

A significant disagreement with true bright star counts had already been illuminated by the Tycho 2 catalogue data, which provided homogeneous all-sky results complete to $V \sim 11$. Czekaj et al. (2014) showed that A–F dwarfs, constituting a large fraction of the bright stars, are very sensitive to the star formation rate history.

In the process, they developed an improved generation strategy for thin disk stars, treating the initial mass function, star formation rate, and evolutionary tracks as free parameters, along with a more consistent generation of binary stars. They constrained the slope of the initial mass function at high masses to close to 3.

Initial comparisons of the Besançon model with Gaia DR1 were given by Arenou et al. (2017). More comprehensive results from DR2 were used to construct a revised model and, in turn, a ‘mock stellar catalogue’ to compare with EDR3. This used the PARSEC evolutionary tracks (Bressan et al., 2012), and also included white dwarfs, the Magellanic Clouds, and a number of open clusters with internal rotation, along with reddening according to new 3d extinction maps (Rybizki et al., 2020).

WITH THE AVAILABILITY of Gaia EDR3, Smart et al. (2020) constructed a star catalogue within 100 pc, the Gaia Catalogue of Nearby Stars. As part of a much more extensive study, they used a comparison of their catalogue with the simulations of the Besançon model to derive constraints on the contribution of high-velocity halo stars, the Sun’s height above the Galaxy mid-plane, and the solar motion.

In another wide-ranging paper based on Gaia EDR3, Robin et al. (2022) used the Besançon model to construct the implied gravitational potential of the Galaxy, and the resulting stellar distribution functions of the thin/thick disk components. These were adjusted to agree with the kinematics and density distributions from Gaia.

Their model produces densities and kinematics consistent with EDR3, over 6–12 kpc in Galactocentric radius, and ± 2 kpc in z . It also results in a thin disk comprising seven age components each with its own velocity ellipsoid; a tilt of the velocity ellipsoid varying with age, R , and z ; a thin disk population density exhibiting a significant flare in the outer regions, arising naturally from the variation of the vertical force with R ; significant differences between the young thick-disk and old thin-disk properties; and different variations with R for the mean azimuthal velocity at the solar position, supporting the idea of a different formation for the thin and thick disks.

Despite good fits assuming an axisymmetric potential, discrepancies are seen particularly towards the anti-centre (where disk substructures have been highlighted), towards the north Galactic pole (where a vertical wave is seen), and in the model of the stellar halo.

SIMILAR COMPARISONS are being made for TRILEGAL. Dal Tio et al. (2021) used Gaia DR2 to construct an almost complete sample within 200 pc, and for Galactic latitudes above 25° . Improved modelling of the observed binary star population in DR2, and optimising the assumed star formation history and the initial binary mass fraction, led to three main results: a binary fraction of ~ 0.4 derived from the lower main sequence, a factor 2 larger than implied by the upper part of the HR diagram; predictions of the observed numbers of hot subdwarfs to within a factor of 2; and a star formation rate peaking at $1.5 \times 10^{-4} M_\odot \text{ yr}^{-1}$ at ages slightly above 2 Gyr, decreasing to $0.8 \times 10^{-4} M_\odot \text{ yr}^{-1}$ at very old ages.

A FINAL POINT to mention in the context of applications of the Besançon model is its use in the problem of constructing unbiased distance estimates from the observed parallaxes, where the reciprocal of the observed parallax is known to be a poor estimate of the distance when the relative parallax error exceeds 10–20% (e.g. Bailer-Jones, 2015; Luri et al., 2018). The distance estimate can be improved by adding prior information about the Galaxy (Bailer-Jones, 2015).