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Data sets and population synthesis

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Abstract. The availability of new wide field survey opens the era of emphasizing our knowledge of large scale structure and evolution of the Galaxy. We describe the population synthesis approach used at Besancon Observatory which has led to a consistent description of the Galaxy, the way the model is constrained both by theoretical approach and by large scale surveys, from photometry, as well as from kinematics. We show recent progresses on large scale structure of dust in the galactic plane, and on the bulge structure linked with microlensing experiments.

Key words. Galaxy: stellar content – Galaxy: evolution – stellar populations

1. Introduction

Constraints on Galactic structure and evolution come from a wide variety of data sets, multi-wavelength photometry, kinematics, microlensing events, among others. Scenarios of Galaxy formation and evolution are inferred from these constraints. A ultimate test of these scenarios can be done by using these constraints piece by piece in order to built a population synthesis model which predictions can be directly compared with observations. This synthetic approach insures that biases have been correctly taken into account and that the scenario is compatible with that many kind of constraints. In the last years wide surveys have been obtained from optical and near-infrared photometry thanks to wide mosaic camera of CCDs, from spectroscopy, helped from the availability of dedicated telescopes and multi-object spectrometers, from the ground and from space. Astrometric accuracy has also been largely improved and catalogues with accurate proper motions are also available, well calibrated by Hipparcos and Tycho data. The homogeneity of these data sets is a great help for avoiding systematic bias and bad links from a set to the other, which have created troubles in data interpretation in the past. All these data sets benefit to Galactic evolution studies and provide constraints on the population synthesis approach. Here we report on the development of the Besançon Galaxy model based on this synthesis approach. We overview the basic scheme and inputs (sect. 2) and we describe new results obtained by analysis of large data sets like DENIS and 2MASS surveys, as well as predictions for microlensing optical depth (sect. 3). We conclude on future developments in sect. 4.

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2. Besancon Galaxy Model overall scheme

The population synthesis approach aims at assembling current scenarios of galaxy formation and evolution, theories of stellar formation and evolution, models of stellar atmospheres and dynamical constraints, in order to make a consistent picture explaining currently available observations of different types (photometry, astrometry, spectroscopy) at different wavelengths. The validity of any Galactic model is always questionable, as it describes a smooth Galaxy, while inhomogeneities exist, either in the disc or the halo. The issue is not to make a perfect model that reproduces the known Galaxy at any scale. Rather one aims to produce a useful tool to compute the probable stellar content of large data sets and therefore to test the usefulness of such data to answer a given question in relation to Galactic structure and evolution. Modelling is also an effective way to test alternative scenarios of galaxy formation and evolution.

The originality of the Besançon model, as compared to a few other population synthesis models presently available for the Galaxy, is the dynamical self-consistency. The Boltzmann equation allows the scale height of an isothermal and relaxed population to be constrained by its velocity dispersion and the Galactic potential. The use of this dynamical constraint avoids a set of free parameters quite difficult to determine: the scale height of the thin disc at different ages. It gives the model an improved physical credibility.

The main scheme of the model is to reproduce the stellar content of the Galaxy, using some physical assumptions and a scenario of formation and evolution. We essentially assume that stars belong to four main populations: the thin disc, the thick disc, the stellar halo (or spheroid), and the outer bulge. The modeling of each population is based on a set of evolutionary tracks, assumptions on density distributions, constrained either by dynamical considerations or by empirical data, and guided by a scenario of formation and evolution.

In Bienaymé et al. (1987a,b) we have shown for the first time an evolutionary model of the Galaxy where the dynamical self-consistency was taken into account to constrain the disc scale height and the local dark matter. Then Haywood et al. (1997) used improved evolutionary tracks and remote star counts to constrain the initial mass function (IMF) and star formation rate (SFR) of the disc population. The thick disc formation scenario has been studied using photometric and astrometric star counts in many directions, which also provided its velocity ellipsoid, local density, scale height, and mean metallicity. These physical constraints led to a demonstration that the probable origin of the thick disc is an accretion event at early ages of the Galaxy (Robin et al. 1996). Improved constraints on the spheroid (Robin et al. 2000) and the thick disc populations (Reylé & Robin 2001a) have also been obtained my comparing model simulations with a wide set of photometric data in different directions. The bulge populations has been studied extensively from analysis of near-infrared survey data, leading to constrains on its bar shape and the age of the population (Picaud & Robin 2004).

The Galactic model has been developed to return results in the near-infrared and visible filters, but has also been extended to predict the stellar content in the X-ray domain (Guillout et al. (1996)). More recently, the Hipparcos mission and large scale surveys in the optical and the near-infrared have led to new physical constraints improving our knowledge of the overall structure and evolution of the Galaxy. These new constraints are now included in the present version of the model described in Robin et al. (2003).

3. New results on disc and bulge large scale structure from large data sets analysis

Once the dynamical and stellar evolution constraints have led to a well defined distributions of stars near the sun and at high and medium latitude, interest have been put forward to the Galactic disc which contains most of the mass into stars of the Galaxy. The thin disc contains several know features which have however not been quantified enough due to the position of the sun in the Galactic plane and the high dust absorption at optical wavelength: the spiral structure, disc scale length, warp and flare are not known with sufficient accuracy from simple analysis of photometric data. Distances of the stars have uncertainties large enough that

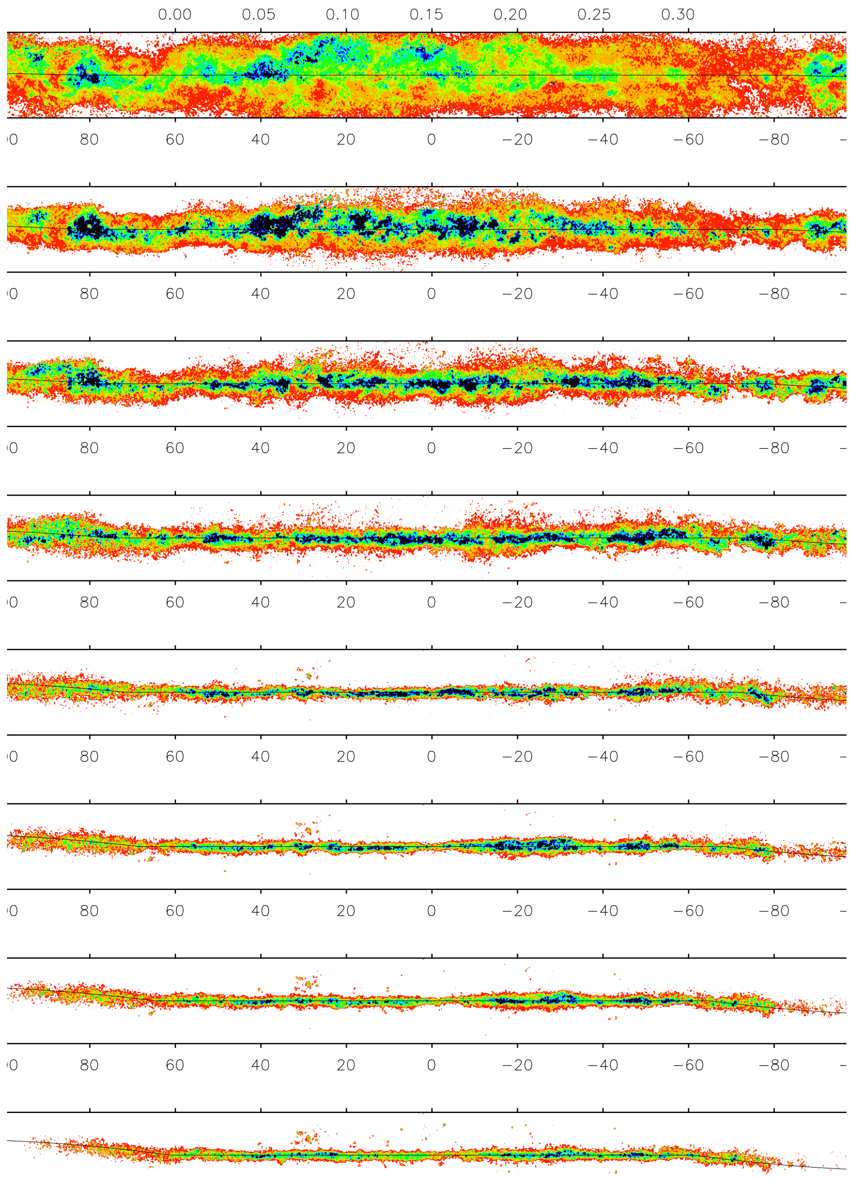

Fig. 1. Local extinction at different heliocentric distances. The uppermost image is at 1 kpc, the bottom one is at 8 kpc. The x axis is in Galactic longitude, the y axis in Galactic latitude. The warp is well visible in the last rows. The solid line indicates the warped mid-plane as used in the Galaxy model and is not a fit to these data.

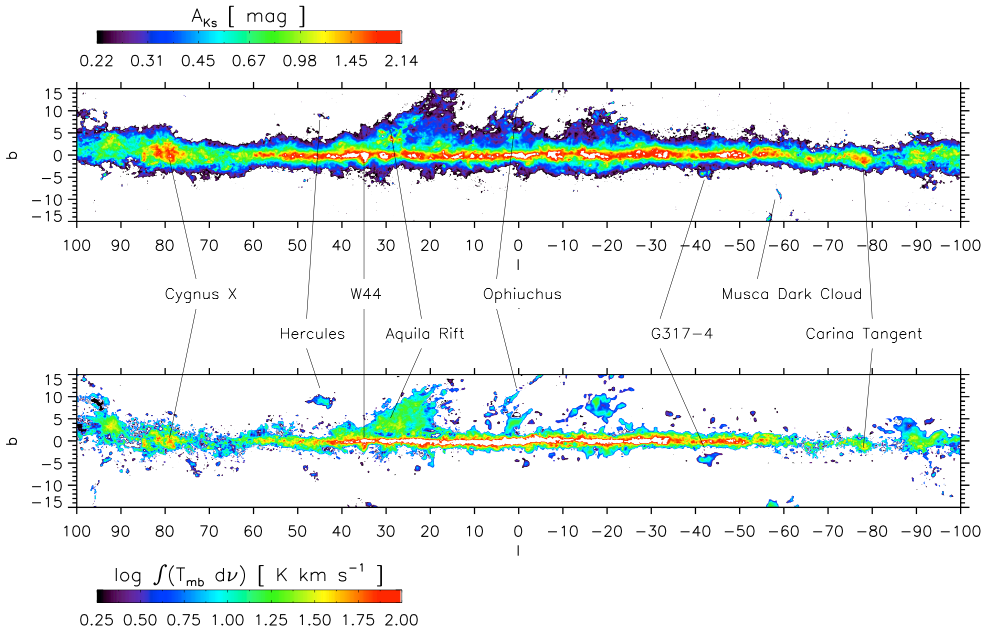

Fig. 2. Top: Total extinction integrated along the line of sight to 10 kpc. Bottom: CO velocity integrated spatial map by Dame et al. (2001). The units of the two maps are different; they are put here to compare their respective interpretation of the large scale structure of the Galaxy. The coordinates are expressed in degrees (l, b).

even the spiral structure is uncertain, being either 2-arm or 4-arm or even a mixing of both depending on the radius. The warp has been detected in stars only recently while it was detected in HI for several decades. The flare in stars is still subject to debate, as well as a possible hole in the center of the inner disc.

3.1. Dust extinction 3D distribution

The first effect visible in star density distribution near the Galactic plane is due to the dust, even at near-infrared wavelength. Extinction is so clumpy that it drives the number of stars more than any other large scale structure in the stars. Conversely, photometry and star counts contains the information about the dust extinction. Marshall et al. (2006) have shown that the 3D extinction distribution can be inferred from star counts and colour distributions from the 2MASS survey. Using stellar colours in J-K as extinction indicators and assuming that most of model prediction deviations from observed colours come from the variation of extinction along line of sights, they built a 3D extinction model of the galactic plane ($-10 < b < 10°$ and $-90 < l < 90$) with a resolution in longitude and latitude of 15 arcmin and variable resolution in distance between 100 pc to 1 kpc, depending on star density and dust density along the line of sight. Figure 1 shows the resulting extinction distribution at different distances from the sun. As expected close structures are spread over several degrees in latitude while farther ones are squeezed to the galactic plane, due to the projection effects.

The 3D extinction model furnishes an accurate description of the large scale structure of the disc of dust. It shows a scale height of 98 ± 21 pc. A big hole almost free of dust is identified around the Galactic center with a radius of $\sim 3.2 \pm 0.5$ kpc, but it also contains an elongated feature which ressembles a dust lane with an inclination with regard to the sun-

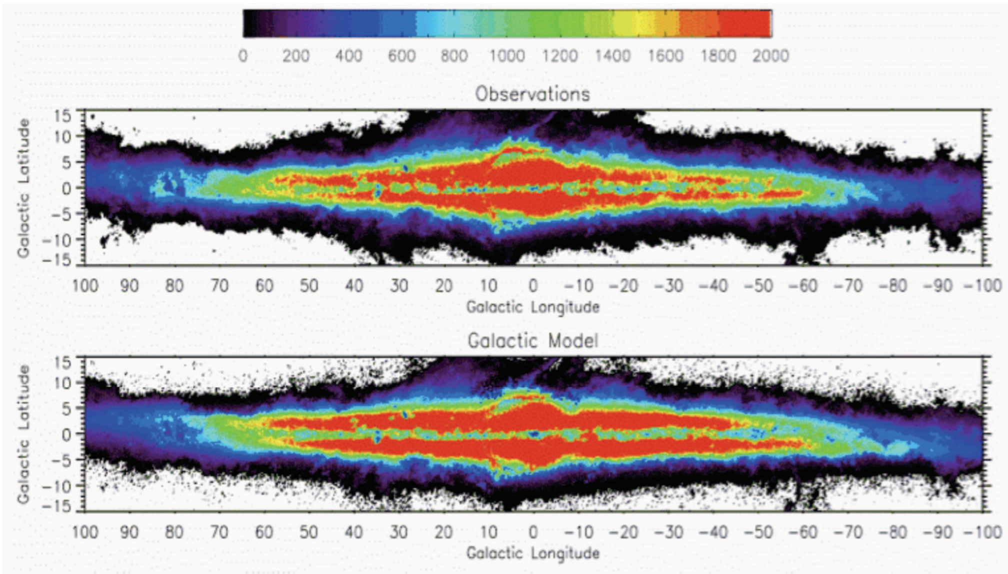

Fig. 3. Distribution of star counts in K magnitude up to the limit of completeness of the 2MASS survey (top panel) compared with Besancon Galaxy model prediction using 3D dust model described in the text (bottom panel). The stellar population model is completely smooth, with no spiral structure. Hence the clumpiness of the star counts in the 2MASS survey seems mainly due to the dust distribution. The simulated warp is symmetrical, while the warp in the data is not. The observed stellar warp appears stronger in the north than in the south, as in HI (see text). The model fit correctly the northern warp but should be revised in the south.

Galactic center direction of $\sim 32° \pm 10°$. This feature may trace the dust falling into the center along the stellar bar.

A test of the reliability of the features discovered by this original method of determining extinction is to compare it with other tracers of interstellar matter. Dame et al. (2001) have created a large scale CO survey of the entire Milky Way, using the rotational transition 1-0 of the CO molecule at 115 GHz, from new observations and existing CO surveys. Fig. 2 shows the total extinction integrated to a distance of 10 kpc from the Sun from the Marshall et al. extinction map, as well as the distribution of CO as presented in Dame et al. (2001), where the two maps overlap. The resolution of the extinction map is 15′x 15′; the resolution of the CO map varies from 9′to 30′, the region presented here is mostly at the higher resolution of 9′. The main structures that appear in both maps are indicated. The Musca Dark cloud, $(l, b) = (-59, -9)$, that appears in the extinction map is not in the Dame et al. (2001) map as this region was not observed in their composite survey. The overall very good agreement of the CO emission and dust extinction feature indicates a good correlation of these two components of the interstellar material as well as give confidence into the 3D extinction map.

3.2. Star counts in the galactic plane

Using this 3D extinction map, detailed predictions of the star density and luminosity can be produced in the Galactic plane and compared with observations. Figure 3 compares the star density per square degree up to completeness limit from the 2MASS near-infrared survey and from the Besancon Galaxy model predictions using the 3D extinction map described above. It should be noted that the stellar population model is completely smooth, with no spiral structure. Hence the clumpiness of the star counts in the 2MASS survey is only due to the dust distribution. The spiral structure is certainly not a prominent structure in our Galaxy, as seen from K giants which is the dominant population in this data set. This is due to the fact that K giants in the clump are mostly older than 1 gigayear and have lost most of the memory of their birth place (see also Amores et al. (2006)).

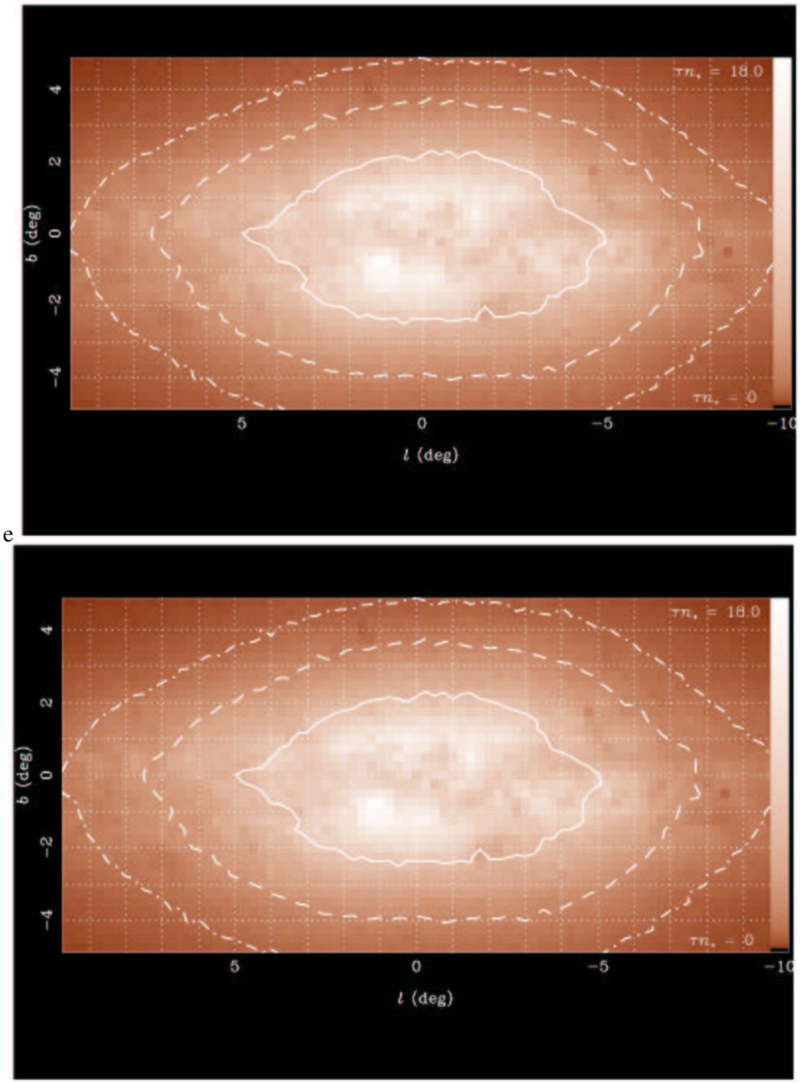

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Fig. 4. Comparison of I and K band maps of instantaneous microlensing event density, that is the product of the optical depth and source number density, as predicted by the Besancon Galaxy Model. The greyscale in both maps is normalised to a peak density of 20 events per square degree. Upper panel is for all sources brighter than I = 19 at baseline, bottom panel is for sources brighter than K = 17 at baseline. The greyscale range is given by the bar to the rights of each plot. Optical depth contours are also over-plotted : solid, dashed and dot-dashed indicate optical depths of 4, 2 and 1 $\times 10^{-6}$, respectively.

The overall structure of the model reproduces well the 2MASS star counts, while neither the scale length nor the warp have been adjusted onto these data. However looking carefully to this figure one can notice slight differences between model and data showing that better agreement could be obtained with slightly decreased scale length (smaller than

2.5 kpc) for the stellar population, and an asymmetric warp. The warp as simulated is symmetrical, while the warp in the data is not. The observed warp is stronger in the north than in the south. The model fits correctly the northern warp but should be revised in the south. In HI data, the southern warp does not go as high as the northern warp (Levine et al. 2006). 2MASS data seem to show the same feature. A quantitative analysis will be performed using 2MASS data as well as deeper data towards the external disc in order to better constrain the warp shape, its kinematics and its origin.

3.3. Microlensing optical depth towards the Galactic bulge

Several microlensing survey teams have been monitoring millions of stars over a large region of the Galactic bulge for more than a decade. These surveys have detected thousands of events and the combined detection rate of the OGLE-III and MOA-II surveys is expected to reach around 1000 events per year. The microlensing optical depth, that is the instantaneous number of ongoing microlensing events per source star, is a key measurable for these surveys and provides an important constraint on the bulge surface mass density. Its dependency upon direction provides, in principle, a unique and powerful probe of the three-dimensional geometry of the bulge stellar mass distribution.

Direct star counts and photometry also allow to derive the bulge stellar distribution based on the luminous population, mainly from K and M giants. Picaud & Robin (2004) have analysed DENIS data towards the galactic bulge in about hundred windows in order to adjust a bulge density model on (K,J-K) star counts. They show that the bulge ressembles a bar, with an inclination of about 10° from the sun-Galactic centre direction, and find a hole inside the thin disc. From the Galaxy model it is then possible to check that these two different data sets (photometric catalogues and microlensing events) are compatible with each other, given the uncertainties. Kerins et al. (2006) have computed the expected optical depth from the Besancon model in the bulge region. Figure 4 shows I and K band maps of instantaneous microlensing event density, that is the product of the optical depth and source number density, as predicted by the Besancon Galaxy Model. The map in I band is produced by sources having $I < 19$ at baseline and can be compared with events data sets. The high resolution of this map show how the optical depth varies from line of sight to line of sight due to extinction. The map in K band is produced by sources having $K < 17$ at baseline. It shows that surveys in the K band are much less affected by dust and would provide a substantial sensitivity increase over current I-band surveys and would reveal a significant microlensing signature towards the far side of the bar.

4. Conclusions

The population synthesis approach has been shown to be very useful for analysis of large data sets, like visible and near-infrared photometric surveys. The same approach can be used on other types of data sets, like microlensing optical depth maps, all-sky proper motions and radial velocity surveys like UCAC2, RAVE experiment, or deep surveys on restricted areas like Cosmos, CFHT-Legacy Surveys, GOODS, among others. These data sets must be combined in order to have combined information about stellar evolution stage, kinematics and metallicity. It allows to confirm global scenario of formation and evolution of the Galaxy, including kinematics, dynamical constraints and chemical evolution constraints. The main problem is still due to the large amount of data to manage. An accurate and efficient method of data fitting must be involved which would require anyhow large amount of computing time.

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