GAIA CENSUS AND COMPLETENESS

Annie C. Robin
Observatoire de Besançon, CNRS UMR 6091, BP 1615, 25010 Besançon cedex, France

ABSTRACT

The expected number of sources in the Gaia final catalogue is investigated and discussed with regards to uncertainties on interstellar extinction, assumed instrument sensitivity and overall characteristics, and model parameters. Numbers as a function of magnitude, of stars of different populations, spectral types, luminosity class are given. We explore the various uncertainties on these numbers and implications for understanding galaxy formation and evolution.

Key words: Gaia; Galaxy: structure; Galaxy: evolution; Stellar population.

1. INTRODUCTION

The Gaia mission preparation requires preliminary estimations of the stellar content of the Galaxy in order to assess the feasibility of the science case, to adjust the definition of the instruments to this science case and to the observational constraints, such as the crowding. Telemetry issues in particular requires reliable star counts in all the observable regions in order to find out the level of data compression needed in crowded regions. Star counts are also useful for testing on-board object detection and data handling (window strategy), and for defining the processing requirements.

Here we present estimations of stellar densities as a function of limiting magnitudes, stellar populations, galactic latitudes, spectral types, and luminosity classes. We emphasize the uncertainties on these estimates such as the G band definition, model parameters and assumed interstellar extinction. We also discuss the observability of major components for understanding galaxy formation and evolution, such as white dwarfs as age tracers, brown dwarfs as constraints on the local mass density, the bulge/bar population, and inhomogeneities in the thick disc and halo.

2. ESTIMATING THE GALAXY STELLAR CONTENT ACCESSIBLE TO GAIA

Estimates of the number counts that Gaia will detect can be made from observed star counts, such as the GSC2 catalogue (Drimmel et al. 2005). Assuming that the filters are not too far from Gaia G band, the stellar density should be a good estimate, useful for the mission preparation (Drimmel et al. 2005). However these counts may suffer from large uncertainties due to the correction of incompleteness in dense regions such as the galactic plane and bulge, and do not give ideas of the distribution of expected stars as a function of their types and populations. Hence we have used the Besançon model of population synthesis for the Galaxy to estimate the stellar content of the Gaia final catalogue, to evaluate the condition of detections and measurements of the galactic components, and implications for galactic structure and evolution.

2.1. The Besançon Galaxy Model

The Besançon Galaxy model is a simulation tool aimed at testing galaxy evolution scenarii by comparing stellar distributions implied by these scenarii with observational constraints, such as photometric star counts and kinematics. A complete description of the model inputs can be found in Robin et al. (2003, 2004a). We summarize here the ins and outs.

The model assumes stars are created from the gas following a star formation history and an initial mass function. To reproduce the overall galaxy formation and evolution we distinguish 4 populations of different ages and star formation histories.

The oldest one is the spheroid. It is assumed a short period of star formation (single burst) at early ages of the Galaxy, about 14 Gyr in the past, from the gas still in a spheroidal distribution. The density distribution of this population is described by a power law for which the power, the axis ratio and the local normalisation are constrained by remote star counts (Robin et al. 2000). The kinematics are also deduced from *in situ* velocity determinations.

Secondly, a population, called the thick disc, is formed of stars born about 11–12 Gyr ago in a short period of time (assumed single burst for simplicity) as implied by recent chemical abundance determinations for this population (Mashonkina & Gehren 2001). Star formation is supposed to have occured from the gas already settled in a disc. The kinematics, deduced from observational constraints (Ojha et al. 1999), imply that it has undergone a merging event shortly after the disc formation (Robin et al. 1996), enhancing the thickness and giving larger velocity dispersion and scale height. The density distribution and local normalisations were constrained from remote star counts (Reylé & Robin 2001a).

Thirdly, a bulge population is present in the centre of the Galaxy and extends to about 2 kpc. Its age is of the order of 10 Gyr, with no strong constraints on this value. This population reflects a triaxial distribution, as a bar (Picaud & Robin 2004)). Velocity dispersions are large, similar to the spheroid kinematics.

The disc population, which produces most of the brightness of the Galaxy, is assumed to have formed stars for 10 Gyr with a constant star formation rate (Haywood et al. 1997). The initial mass function is described by a two-slope power law, the values of which are constrained by the local luminosity function from Jahreiß & Wielen (1997). The evolutionary scheme allows to distinguish the ages of the stars in the disc. The velocity dispersions, metallicity distributions and scale heights are age dependent. Then the disc scale heights are self-consistently constrained using the Boltzmann equation: the potential is computed from the whole density distribution of the Galaxy model (adding the dark matter halo and the interstellar matter to the stellar populations), the vertical velocity dispersion is a function of the age, following Gómez et al. (1997) from Hipparcos data analysis. Hence for each age the vertical exploration of disc stars of a given age is deduced from the relation:

$$\frac{\rho(z)}{\rho(0)} = \exp(-\frac{(\Phi(z) - \Phi(0))}{\sigma_Z^2}) \qquad (1)$$

where $\Phi(z)$ and $\Phi(0)$ are the galactic potential at height z above the plane and at the solar position respectively, σ_Z^2 is the velocity dispersion perpendicular to the plane of the population considered as isothermal and relaxed, $\rho(z)$ and $\rho(0)$ are the density of this population at z and at the solar position respectively.

The number of stars of a given age at the galactic position (R, θ, z) is given by

$$\sum \phi(M_V, T_{\rm eff}, {\rm age}) \times \rho(z) \times \Omega \times r^2 \times dr$$

$\phi(M_V, T_{\rm eff}, {\rm age})$ being the number of stars of this age of absolute magnitude M_V and effective temperature $T_{\rm eff}$. The functions $\phi(M_V, T_{\rm eff}, {\rm age})$ are computed from the assumed constant star formation rate and Initial Mass Function and a set of evolutionnary tracks (Haywood et al. 1997).

Then these numbers are summed over ages and lines of sight. The model simulations also include a model of extinction (see below) and account for observationnal errors (photometric and astrometric). The outputs can be either a catalogue of simulated stars or statistics of the distribution of stars as a function of any given observable.

2.2. The Gaia Photometric System and Broad Band Definitions

In the Gaia reference book (ESA 2000), a number of estimations of stellar densities are given, sometimes in the V band, sometimes in a preliminary definition of the G band. Nowadays that the Gaia detectors are defined, the definition of the G band has significantly changed. We here consider the G band in the Astro focal plane, used also in the Broad Band Photometer (BBP) photometric system. In Figure 1, transformations between the Johnson V and the G band as a function of V–I colour are given. The transformations used in the new design show that the Gaia AF CCDs are more sensitive to the red than previously thought. Hence there is a difference of about 1 magnitude in the sensitivity in the G band compared to the 2000 estimation, for stars which are redder than about V–I = 1, the new G being more sensitive. This translates to the number of stars expected in Gaia to be as large as 1.5 billion compared to the previous estimation of 1 billion.

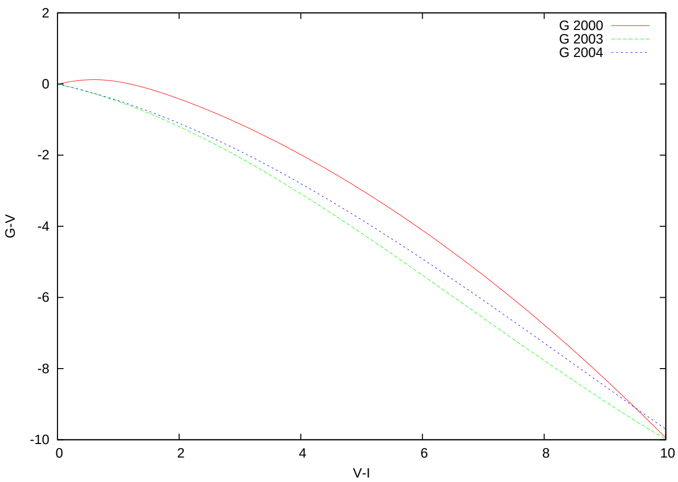

Figure 1. G–V magnitude transformation as a function of V–I colour. The solid line: 2000 G–V transformation; dashed-dotted: 2003; short-dashed line: new CCD transformation 2004.

3. STELLAR DENSITY ESTIMATIONS

3.1. Overall Densities

Even if there are a number of uncertainties in the following estimations, coming from both the model side (inaccurate model of the stellar content which does not take into account various inhomogeneities, inaccurate extinction estimates, ...) or from the detection side (incompleteness in crowded fields and in detecting close binaries) the following numbers give an idea of the numbers Gaia will face.

Table 1 gives the total number of stars that Gaia should be able to detect, up to magnitude 17 and 20, while Table 2 gives the expected distribution of the stars as a function of spectral type. The majority of stars will be disc stars of type between F5 and M5. But significant numbers of nearly all types are expected, several thousands of O stars and several millions of M5 stars and later. The number of expected 0 stars is only indicative, as it comes from a smooth model while one expects these stars to have a patchy distribution and be present mainly in high-mass star-forming regions.

Table 1. Number of expected stars of each population that Gaia should detect at the limiting magnitudes of 17 and 20.

Population	Nb to G = 17	Nb to G = 20
Disc	1.9×10^8	9.0×10^8
Thick disc	4.4×10^7	4.3×10^8
Spheroid	1.6×10^6	2.1×10^7
Bulge	1.2×10^7	1.7×10^8
Total	2.5×10^8	1.5×10^9

Table 2. Number of expected stars that Gaia should detect at the limiting magnitude of 17 and 20, as a function of their spectral type.

Spectral types	G< 17	G< 20
O	1.0×10^3	5.0×10^3
B0-B4	1.2×10^5	6.6×10^6
B5-B9	1.0×10^6	2.2×10^7
A0-A4	3.8×10^6	8.3×10^6
A5-A9	6.0×10^6	1.4×10^7
F0-F4	1.1×10^7	3.2×10^7
F5-F9	5.4×10^7	1.3×10^8
G0-G4	4.9×10^7	2.0×10^8
G5-G9	3.6×10^7	1.9×10^8
K0-K4	4.6×10^7	2.5×10^8
K5-K9	1.2×10^7	1.0×10^8
M0-M4	7.0×10^6	9.3×10^7
M5-M9	4.2×10^5	6.0×10^6

3.2. White Dwarfs

Among stars which present particular interest for galactic structure studies are the white dwarfs (WD) and the brown dwarfs. The white dwarf luminosity function is a reliable means to determine the age of the population, assuming that the cooling sequence is sufficiently known. Gaia will allow to verify the equation of state of the white dwarfs by checking the cooling sequence as well as determining the luminosity function, allowing to give an accurate estimate of the age of the disc. Table 3 gives the total number of expected white dwarfs up to magnitude G = 17 and G = 20 in the four galactic components. For these estimations, we have assumed for disc WD the luminosity function from Wood (1992) and colours from Bergeron et al. (2005) for hydrogen white dwarfs, DA white dwarfs being the dominant population of stellar remnants.

For the thick disc population, the estimation is based on a luminosity function computed by Garcia-Berro (private communication and Garcia-Berro et al. (1999)) with a Salpeter IMF and an age of 12 Gyr, normalised in the solar neighbourhood such that the number of old white dwarfs having a thick disc kinematics in the Oppenheimer et al. (2001) sample is well reproduced (Reylé et al. 2001b).

The halo population of white dwarfs is nearly unknown. A few old ancient white dwarfs in the Oppenheimer et al. (2001) sample have kinematics similar to the spheroid but the sample is claimed to be incomplete. Estimations from a systematic search of large proper motion stars in the solar neighbourhood (Crézé et al. 2004) show that at most their local density would be 2 – 5% of the density of the dark halo. The numbers given in Table 3 for the halo assume a 2% mass density of the dark halo in white dwarfs (that is 1.33×10^{-2} WD per cubic parsec).

Bulge white dwarfs are estimated from the Bruzual & Charlot evolution model for an age of 10 Gyr and a Salpeter IMF (Bruzual et al. 1997). These objects will be very marginally detected.

Table 3. Number of expected white dwarfs in Gaia instruments at the limiting magnitude of 17 and 20, in the 4 galactic components.

Population	Nb to G = 17	Nb to G = 20
Disc	4000	180 000
Thick disc	140	8000
Halo	0	150
Bulge	0	20

3.3. Brown Dwarfs

Brown dwarfs constitute a major component of the Galaxy in numbers, although not in mass, nor in luminosity. Chabrier (2003) estimates their local density to be 0.13 per cubic parsec and their mass density $0.4 \pm 0.2 \times 10^{-2} M_{\odot}$ pc^{-3}. These estimates suffer from large uncertainties on the slope of the Initial Mass Function at very low masses, extrapolated here to the brown dwarf regime, and on the lower mass cutoff. Present observations lead to many discoveries but due to incompleteness and uncertainties on the internal structure and atmosphere of these objects the selection bias is difficult to estimate. A reasonable estimate would give about 20 000 brown dwarfs older than 0.5 Gyr detected by Gaia. Younger brown dwarfs are more easily detected, because brighter, but their numbers will be smaller. There are many ways to detect brown dwarfs: as companions to stars by their astrometric perturbation, in young clusters, by microlensing effects, and also isolated brown dwarfs in the field may be discovered even if Gaia, being sensitive in the visible, is not the best instrument for brown dwarf detections.

Before Gaia, a number a large surveys will be conducted which will certainly enhance significantly the number of known brown dwarfs. They are already discovered in number in the near-infrared surveys DENIS and 2MASS, in the SDSS, and from systematic searches of high proper motion objects on Schmidt plates (for example, the Super-Cosmos survey from Hambly et al. (2004). The CFHT Legacy Survey (Cuillandre 2004) expects about 40 000 L dwarfs and 4000 T dwarfs. Large infrared surveys are also planned in the near future from UKIDS and WIRCAM large mosaic cameras on Mona Kea and from the VISTA project at Paranal. But there will be very few brown dwarfs with known trigonometric parallaxes. Gaia will strongly improve the knowledge of the physics of brown dwarfs by allowing to measure accurate parallaxes for a large number of them.

4. EXTINCTION AND CROWDING EFFECTS

Expected stellar densities as a function of latitudes for the 4 galactic components are given in Figures 2, 3, and 4.

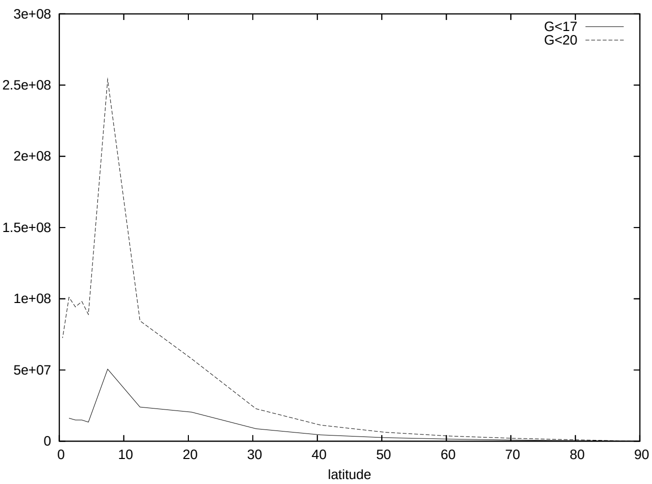

Figure 2. Expected numbers of stars per square degree as a function of latitude for the disc population, up to G magnitude 17 (solid line) and 20 (dashed line).

Most of the observable stars are at low latitudes, where the Gaia telemetry might be very high. However the crowding will be limited at restricted regions in the inner disc and the bulge. Because of interstellar extinction, the low latitude regions are partly obscured. From Figure 2 the most dense regions are not at $b = 0$, but at about $|b| = 10°$. Other high density regions will be the centre of the LMC bar and centres of globular clusters. At the crowding limit of the BBP (estimated at 3 million stars per square degree), about one third of the globular clusters will be free from crowding, and two-thirds will be crowded at a distance from their centre less than 3 core radii. Only a dozen are expected to be crowded at 10 core radii.

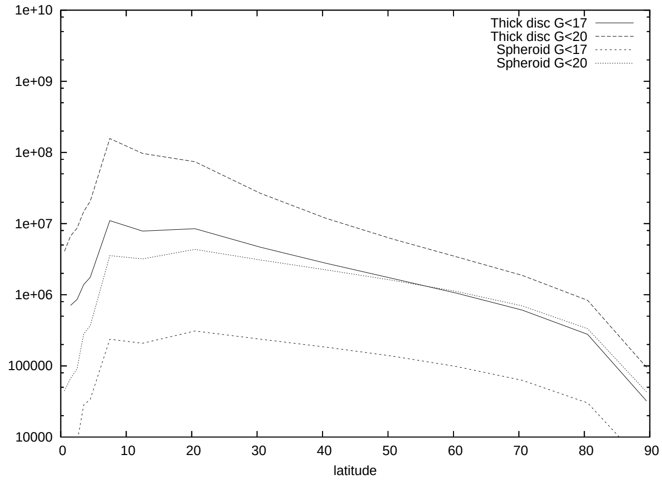

Figure 3. Expected numbers of stars per square degree as a function of latitude for the thick disc and spheroid populations, up to G magnitude 17 (solid and short-dashed lines, resp.) and 20 (long-dashed and dotted lines, resp.).

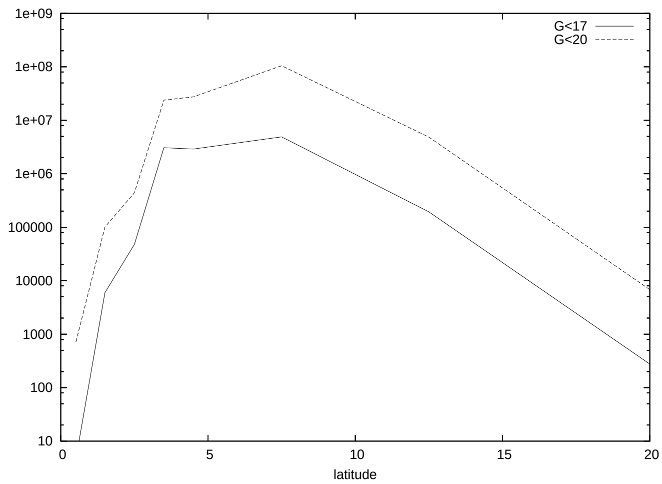

Figure 4. Expected numbers of stars per square degree as a function of latitude for the bulge population, up to G magnitude 17 (solid line) and 20 (dashed line).

In fact, the stellar density strongly depends on the extinction at low latitudes. A detailed knowledge of the distribution of the extinction is needed in order to correctly predict the stellar density at a given apparent magnitude. Several extinction maps have been published in the past years (Schlegel et al. 1998; Schultheis et al. 1999; Drimmel et al. 2003) among others. Schlegel et al. (1998) and Schultheis et al. (1999) are 2D maps with high resolution. The former was deduced from FIR dust emission, covers the whole sky, but may suffer from systematic underestimate of the extinction at low latitudes. The latter was determined from near infrared colour-magnitude diagrams from the DENIS survey (Epchtein et al. 1997). It seems free from systematics but is limited to latitude $|b| < 1.5°$. Drimmel & Spergel (2001) delivered a 3D extinction model assuming a smooth distribution from a disc and spiral arms, and adjusted to reproduce the far infrared dust emission.

We have studied the stellar densities under these different extinction distributions towards the bulge, to investigate whether the bulge population is reachable, in which conditions, and whether the crowding will limit its observation with the Gaia instruments. The results of this investigation can be found in Robin et al. (2004b) and in Reylé et al. (2005). The main conclusions were that while in the BBP most of the bulge will be accessible, in the MBP there will be a small but significant number of regions where bulge stars will be detected and accurately measured in crowded fields. Assuming that the RVS spectra may be extracted in moderately crowded fields, the bulge will be accessible in most regions apart from the strongly absorbed inner plane regions, because of high extinction, and in low extinction windows like Baades's window where the crowding is too severe.

Most recently a new analysis of the distribution of the extinction has been done by Marshall et al. (2005). This 3D map is obtained from adjusting distributions of extinction along lines of sight on 2MASS near-infrared star counts.

These extinction distributions have been used to predict the expected number of stars in the region $-8 < l < 8$, $-3 < b < 3$. Resulting stellar densities, given in Table 4, vary by about 50% depending on the assumed extinction model. Extinction is then critical in order to produce realistic counts. We plan to extend the Marshall et al. (2005) method to deduce a full 3D extinction map which could be used for more accurate density estimations.

Table 4. Number of expected stars of the bulge populations at the limiting magnitudes 17 and 20, in the central region $-8 < l < 8$ and $-3 < b < 3$, considering extinction map from Schultheis et al. (1999), 3D extinction model from Drimmel & Spergel (2001) and from Marshall et al. (2005).

Extinction	G < 17	G < 20
Schultheis et al. (1999)	4.08×10^6	5.57×10^7
Drimmel & Spergel (2001)	5.30×10^6	4.75×10^7
Marshall et al. (2005)	5.44×10^6	3.25×10^7

5. BULGE KINEMATICS

Gaia will provide for the bulge a large amount of accurate measurements, proper motions and parallaxes for most of it, allowing to test its formation scenarii. The relative accuracy of the distance measurement in the bulge (at 8 kpc from the Sun) of a G = 15 magnitude star should be 9% while the accuracy drops to 23% for a star of G = 17. This is to be compared with the fact that at present there are no direct measurements of the distance for bulge stars. The proper motion accuracy for a G = 17 (resp. G = 20) bulge star in Gaia is estimated to be about 20 (resp338) μ as per year leading to a velocity accuracy of 0.8 (resp. 12.8) km s^{-1} at 8 kpc, while presently available proper motions in the bulge have accuracy not smaller than 40 – 50 km s^{-1} (Sumi et al. 2004).

The accuracy on radial velocity from the Gaia Radial Velocity Spectrograph (RVS) will not be very high. At G = 14 one expects 25 km s^{-1}, and 50 km s^{-1} at G = 16. The RAdial Velocity Experiment (RAVE) survey (Steinmetz 2003) is planned to cover the bulge to V = 16 and will be very efficient for measuring the bulge kinematics because it is less sensitive to crowding than the Gaia RVS. However the V = 16 limiting magnitude of RAVE allows to reach the bulge only in regions of limited extinction ($A_V < 3$).

6. DETECTING STREAMS AND SUB-HALO RELICS OF THE GALAXY FORMATION

Following scenarii of halo formation (Klypin et al. 1999; Moore et al. 2001) streams are likely to populate the halo of the Galaxy, as relics of early aggregations of subhalo structures. Bullock & Johnston (2004) show that in the Lambda CDM hierarchical model of galaxy formation the Milky Way should have accreted and tidally disrupted a few hundred low-mass galaxies until now. In which case the halo should be dominated by substructure at galactocentric distances larger than about 50 kpc, but it should be smoother within this radius.

Already several such streams have been found: the Sagittarius dwarf elliptical, still in the process to be accreted by the Milky Way (Ibata et al. 1997); the giant ring at low latitude outside the solar circle (Ibata et al. 2003; Yanny et al. 2003); a structure in Canis Major (Martin et al. 2004a; Momany et al. 2004; Martin et al. 2004b). These structures are identified by a slight or moderate excess of stars in surveys. If the excess is too small, such structures are missed. In the velocity space howevere these structures would be more easily identified. Helmi et al. (1999) claim to have found in Hipparcos data in the solar neighbourhood a subsample of halo stars having peculiar velocities. They emphasize that about 10% of the halo outside of the solar circle comes from a single coherent structure, a relic of a dwarf spheroidal which could have disrupted during or soon after the Galaxy's formation. The existence of this fossil record of a merger in Hipparcos data in the velocity space lets us think that Gaia will be able to detect new, fainter ones. With an expected number of halo stars of 20 millions in the Gaia mission, substructure at the level of less than 0.1% will be easily detected.

Ibata et al. (2002) proposed a new test to determine the clumpyness of the halo. In the velocity space the structure of the tidal tails of globular clusters is very sensitive to heating by repeated close encounters with massive dark sub-haloes. They show that, if the Galactic halo has substantial substructure, globular clusters streams should have a wide dispersion in L_z. These tidal tails will be easily detected by Gaia, thanks to the full six-dimensionnal phase-space information. With a radial velocity uncertainty of about 10 km s^{-1}, Gaia will be able to detect the increase in the z component of the specific angular momentum L_Z, which is expected to be $\sigma_{L_Z} > 200$ kpc km s^{-1} $M_{\odot}^{-1}$ for a halo with substantial dark matter substructure (Ibata et al. 2002).

7. CONCLUSIONS

Estimations of the number of stars at G $<$ 20 detectable by Gaia vary from about 1 billion to 1.5 billion, depending on the method (observations corrected for incompleteness or Galaxy model simulations). These numbers depend mostly on the definition of the Gaia G band, and on the assumed interstellar extinction, while the majority of the stars are in regions where the extinction is patchy and not accurately known. At G $<$ 17 76% of the detected stars will be from the disc population, while up to G $=$ 20, 60% will belong to the disc and 11% to the bulge, the thick disc accounting for about 30% and the spheroid for 1.5%. Gaia will determine distances with an accuracy of 1% for about 20 millions of stars, while Hipparcos did it for only 188 stars.

All spectral types and luminosity classes will be reached by Gaia, including white dwarfs and brown dwarfs. Even if many new brown dwarfs will be discovered before Gaia in visible and near-infrared large scale surveys, the mission will allow to measure accurately their parallaxes, giving unprecedented constraints on their absolute luminosity, internal structure, atmospheres and evolutionary tracks.

The high precision on proper motions, and moderate accuracy on radial velocity, will also allow to detect streams and inhomogeneities in the thick disc and halo, allowing to identify substructures, originating from the Milky Way merging history, and clumpyness of the dark matter halo, an accurate test for cosmological galaxy formation model.

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