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Gaia: a new vision of our Galaxy and our neighbours

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Abstract. A simulation of the universe model developed for the preparation of the mission has been analysed to estimate in more details the statistics of the objects reachable by Gaia. For each object, astrophysical observable parameters, spectra, kinematics and parallaxes are simulated. The simulator also includes the simulation of multiple stellar systems and variability. At the end of the mission we expect to be able to measure 1.1 billion of stars of which about 2% will be variable and 3% have one or two exoplanets (but may be not detectable). At the extragalactic level, observations will be potentially composed of several millions of galaxies, half a million to 1 million quasars and about 50,000 supernovae that will occur during the five years of the mission but may not be all observed.

Key words. Galaxy: structure – Galaxy: evolution – Instruments: survey

1. Introduction

The Gaia mission will be a cornerstone for studies of stars in the Milky Way and beyond and for understanding Galaxy evolution. The satellite has been planned to observe about 1% of the Galactic stars. Parallaxes will reach an unprecedented accuracy better than 10 μas for bright stars (V=10), 10 to 25 μas at V=15 and 300 μas at G=20, to be compared to Hipparcos value of about 1 mas. The Gaia mission will allow to reach an accuracy of about 10% in distances to about 10 kpc for many stars.

Thanks to the RVS spectrometer it will be possible to measure astrophysical parameters, abundances and radial velocity to about 17th magnitude with an accuracy better than 15 km/s. The survey is planned to be complete at magnitude G=20, G being the broad-band magnitude of the Gaia instrument.

In order to prepare the mission, test the softwares, and simulate the intermediate and final data bases, the Data Processing and Analysis consortium (DPAC) has developed a software called GaiaSimu to simulate all the sources that Gaia will observe (the so-called Universe Model) as well as the instruments and satellite properties (the Instrument Model). We describe here the universe model and the expected statistics in the Gaia catalogues and advertise the availability of the simulated catalogue to provide a unique tool for preparing Gaia exploitation.

2. Simulating the Universe for Gaia

In order to estimate the statistics of the sources that Gaia will observe a full sky snapshot (for a given moment in time) has been computed (Robin et al. 2012). It provides the statistics of all the sources which were introduced and simulated in the universe model with their characteristics: magnitudes in the four bands of the instruments, spectra at low resolution for the BP/RP photometer, high resolution spectra in the wavelength range of the RVS spectrometer, positions on the sky and astrometry. These simulations include the following types of objects:

– Solar system objects: planets, satellites, asteroids;
– Stars in the Milky Way: all main types of stars, spectral types from O to L4, luminosity classes from supergiants to white dwarfs, pre-main-sequence stars, Wolf-Rayet;
– Stars in the Magellanic clouds;
– Extragalactic sources: unresolved galaxies, AGN and quasars, with variabilities and supernovae;
– Extinction 3D distribution and maps of microlensing optical depth.

We here presents the statistics of Galactic and extragalactic objects in the Gaia Universe Model Snapshot (GUMS) version 10 as explained in Robin et al. (2012).

2.1. Galactic objects

Galactic objects are generated from a model based on the Besancon Galaxy Model (hereafter BGM) (Robin et al. 2003), which provides the distribution of the stars, their intrinsic parameters, and their motions. The stellar population synthesis combines

– Theoretical considerations such as stellar evolution, galactic evolution, and dynamics.
– Observational facts such as the local luminosity function, the age-velocity dispersion relation, the age-metallicity relation.

The result is a comprehensive description of the stellar components of the Galaxy with their physical characteristics (e.g. temperature, mass, gravity, chemical composition, and motions).

The Galaxy model is formed by four stellar populations constructed with different model parameters. For each population the stellar content is defined by the Hess diagram according to the age and metallicity characteristics. The populations considered here are

– The thin disc: young stars with solar metallicity in the mean. It is additionally divided into seven isothermal components of ages varying from 0–0.15 Gyr for the youngest to 7–10 Gyr for the oldest.
– The thick disc: in terms of metallicity, age and kinematics, stars are intermediate between the thin disc and the stellar halo.
– The stellar halo (or spheroid): old and metal-poor stars.
– The outer bulge: old stars with metallicities similar to those of the thin disc.

In a given volume element with an expected density of N, $\approx$ N stars are generated using a Poisson distribution. After generating the corresponding number of stars, each star is assigned its intrinsic attributes (age, effective temperature, bolometric magnitude, U, V, W velocities, distance) and corresponding observational parameters (apparent magnitudes, colours, proper motions, radial velocities, etc.) and is finally affected by the implemented 3D extinction model from Drimmel et al. (2003).

Characteristics of the density laws for each stellar populations, as well as the Initial Mass Function and Star Formation Histories are given in detail in Robin et al. (2003) and Robin et al. (2012) and not reproduced here. A few characteristics are different from the standard BGM, such as for example the age-metallicity relation, which is taken from Haywood (2008). Alpha element abundances are computed as a function of the population and the metallicity. For the spheroid, the abundance in the alpha elements is drawn from a random around a mean value, while for the thin disc, thick disc, and bulge populations it depends on [Fe/H]. Formulas are given in Robin et al. (2012).

A few rare objects are also included, which were not in the standard BGM, like emission line stars, Oe and Be, Ap/Bp and Am, WR stars.

2.2. Binary systems

While he BGM model produces only single stars, in the Gaia simulation multiple star systems are generated with some probability (Arenou 2011) that increases with the mass of the primary star obtained from the BGM model. The mass of the companion is then obtained through a given statistical relation $q = \frac{M_2}{M_1} = f(M_1)$, which depends on period and mass ranges.

The separation of the components (AU) are chosen with a Gaussian probability with different mean values depending on the stars' masses (a smaller average separation for low-mass stars). Through Kepler's third law, the separation and masses then give the orbital period. A more detailed description can be found in Arenou (2011).

2.3. Variable stars

We simulated different type of variables, assuming for each type a light curve template, a localisation in the HR diagram and a probability of occurence. The simulated variables include: cepheids, δ Scuti, RR Lyrae (type ab and c), RoAp, ZZCeti, Miras, semi-regulars and ACV(α Canes Venaticorum). We also simulate dwarf and classical novae, M dwarfs flares and external variability produced by eclipsing binaries and by microlensing events. More details of the simulation methods are given in Eyer et al. (2005).

2.4. Exoplanets

For a fraction of the stars, one or two extra-solar planets are generated with distributions in true mass M_p and orbital period P which constitutes a reasonable approximation to the observed distributions as of today, and extrapolated down to the masses close to the mass of Earth. A detailed description can be found in Sozzetti et al. (2009). The astrometric displacement, spectroscopic radial velocity amplitude, and photometric dimming (when transiting) induced by a planet on the parent star, and their evolution in time, are presently computed from orbital components similarly to double stellar systems.

2.5. Extragalactic objects

The Magellanic Clouds (MC) are simulated using a ground based observed catalogue. However the catalogues are not complete over the whole galaxy. In the future it is planned to simulate the MCs from a population synthesis model to avoid defects of the observed catalogues which occur when for example crowding effects are important or when data are incomplete for some parameters (like metallicities or kinematics, for example).

Most galaxies observable by Gaia will not be resolved in their individual stars. These unresolved galaxies are simulated using the Stuff (catalogue generation) and Skymaker (shape/image simulation) codes from Bertin (2009), adapted to Gaia by Dollet (2004) and Krone-Martins et al. (2008).

This simulator generates a catalogue of galaxies, each galaxy being shaped by the sum of a bulge and a disc, and a number density distribution in each Hubble type sampled from Schechter's luminosity function (Fioc & Rocca-Volmerange 1999). The adopted library of synthetic spectra at low resolution was created based on the Pegase-2 code (Fioc & Rocca-Volmerange 1997).

Quasars are simulated from the scheme proposed in Slezak & Mignard (2007). To summarise, lists of sources were generated with similar statistical properties as the SDSS, but extrapolated to G = 20.5 and taking into account the flatter slope expected at the faint end of the QSO luminosity distribution. The space density per bin of magnitude and the luminosity function should be very close to the actual sky distribution. Because bright quasars are saturated in the SDSS, the catalogue is complemented by a catalogue of nearby QSOs.

A set of supernovae (SN) are generated associated with galaxies, with a pro-

Table 1. Percentages of each spectral type of generated stars, calculated over the total number of stars for each respective column.

Sp. type	G <20mag	$Grvs$ <17mag	$Grvs$ <12mag
O	<0.01%	<0.01%	<0.01%
B	0.26%	0.50%	0.88%
A	1.85%	3.30%	4.84%
F	23.13%	22.94%	13.83%
G	38.28%	31.58%	15.46%
K	27.68%	32.23%	41.75%
M	7.75%	6.78%	11.38%
L	<0.01%	<0.01%	<0.01%
WR	<0.01%	<0.01%	0.01%
AGB	0.91%	2.50%	11.37%
Other	0.09%	0.07%	0.33%
Total	$1,1x10^9$	$3,9x10^8$	$1,3x10^7$

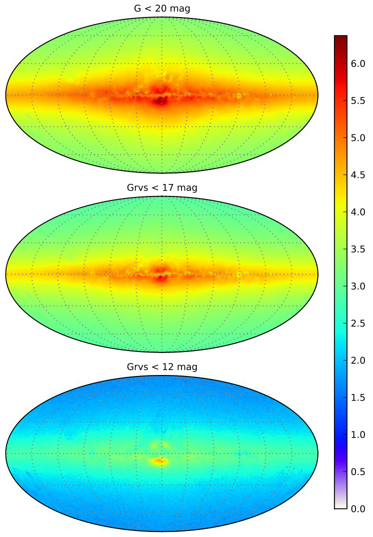

Fig. 1. Total sky distribution of stars for different magnitudes. Top down: $G < 20$, $G_{\rm RVS} < 17$ and $G_{\rm RVS} < 12$. Colour scale indicates the $\log_{10}$ of the number of stars per square degree. Credit: Robin et al. 2012 A&A 543, A100, reproduced with permission © ESO.

portion for each Hubble type. Numbers of SNIIs are computed from the local star formation rate at 13 Gyrs (z=0) and IMF for M*(Bj) galaxy types as predicted by the code PEGASE.2. Theoretical SNIa numbers follow the SNII/SNIa ratios from Greggio & Renzini (1983). The total number of supernovae observable by Gaia during the 5 year mission is estimated to 50,000.

3. Statistics of objects observable by Gaia

From the whole sky simulation we can estimate the occurence of each type of objects as a function of position and the total number of each type theoretically reachable by Gaia. As an example, table 1 presents the statistics of the observable galactic stars as a function of spectral type. Figure 1 shows the star density on the sky at the limiting magnitude of the RVS $G_{RVS} < 12$ (at which detailed abundances can be measured) and $G_{RVS} < 17$ (the limit of usefulness of the spectrometer for metallicities and radial velocities), and at G <20 (photometry and astrometry).

Even in our close solar neighbourhood Gaia will discover many new neighbours thanks to the limiting magnitude of G=20, much fainter than the limiting magnitude of H=9 for Hipparcos. In the 25pc sphere Gaia will detect about 8000 stars where Hipparcos saw only about 3000.

The distribution of the parallaxes have been estimated for each spectral type and presented in table 2.

Table 2. Number of stars for each spectral type at different parallaxes. Percentages were calculated over totals per spectral type, which can be deduced from Table 1.

Sp. type	π >240 μas	π >480 μas	π >960 μas
O	30.25%	1.54%	0.31%
B	38.38%	4.69%	0.99%
A	45.61%	9.87%	2.33%
F	35.06%	8.07%	1.74%
G	44.52%	11.48%	2.46%
K	70.61%	34.28%	7.94%
M	92.75%	90.50%	62.09%
L	0.00%	0.00%	0.00%
WR	27.98%	1.89%	0.23%
AGB	0.05%	0.01%	<0.01%
Other	71.56%	64.73%	57.53%
Total	570,000,000	250,000,000	90,000,000

More tables and figures can be found in Robin et al. (2012). The simulated catalogue is also available at CDS[1].

4. Conclusions

The universe model alone cannot allow to estimate the number of objects really detected and identified by Gaia, but just the statistics of the objects which are brighter than the Gaia limiting magnitude or which have an astrometric effect on another object. The instrument model and the various simulators, GIBIS, GASS and GOG are necessary to make realistic estimates of Gaia capabilities. In particular the GOG simulator (Luri et al. in prep) is able to compute the content of the final database assuming realistic errors estimated from the Gaia data processing softwares. A complete simulation of the mission has been done on Mare Nostrum super computer facility and provides these estimates. Liu et al (2012) have also estimated the errors on astrophysical parameters which should be reachable by Gaia at the end of the mission. Using different algorithm for determining these parameters, they estimate the error as a function of the G magnitude and the spectral type, as well as the correlations between errors, which are large in particular between the effective temperature and the interstellar reddening.

Indeed these estimates are only to our present knowledge and will be revised after Gaia launch and commisionning period. At the end, Gaia will provide an enormous step forward to understand the formation and evolution of our Galaxy and our neighbours in details, from the astrometry, parallaxes and proper motions but also from the astrophysical parameters, that will allow a better understanding of stellar evolution. It will impact our dating methods specially for local galaxies and will give a completely new perspective on the history of the local group.

[1] `http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=VI/137`

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