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GAIA: LUMINOSITY CALIBRATIONS AND DISTANCES IN THE GALAXY AND LOCAL GROUP

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Abstract. The upcoming availability of the Gaia mission data will prompt a significant advancement in many areas of astrophysics and will specially have a huge impact in the determination of luminosity calibration and distances, thanks to the availability of very precise parallaxes.

Already the Hipparcos mission made a huge improvement in these areas with respect to the previous eras, but the advent of Gaia will represent an even larger improvement: the Gaia catalogue will contain about a billion objects, with more than 100 million of them with distances known to better than 10%, all over the Galaxy. All stellar distance indicators will be directly measured in very large number, providing a direct calibration of their luminosity and making possible detailed studies of the impacts of various effects linked to chemical element abundances or cluster membership. Furthermore, Gaia astrometry will be precise enough to reach the Large and Small Magellanic Clouds, allowing for the first time a direct parallax estimation of its distances.

In this paper we will review with the help of simulations the potential contributions of Gaia in these areas.

Keywords: Gaia, astrometry, luminosity calibration, distance scale

1 Introduction

The ESA Gaia astrometric mission has been designed for solving one of the most difficult yet deeply fundamental challenges in modern astronomy: to create an extraordinarily precise 3D map of about a billion stars throughout our Galaxy and beyond (Perryman et al. 2001).

The survey aims for completeness to $V_{lim} \sim 20{-}25mag$ depending on the color of the object, with astrometric accuracies of about $10\mu as$ at $15mag$ (see figure 1). In the process, it will map the stellar motion and provide the detailed physical properties of each star observed: characterizing their luminosity, temperature, gravity and elemental composition.

Additionally, it will perform the detection and orbital classification of tens of thousands of extra-solar planetary systems, and a comprehensive survey of some $10^5 - 10^6$ minor bodies in our solar system; furthermore, it will also include galaxies in the nearby Universe and distant quasars.

This massive stellar census will provide the basic observational data to tackle an enormous range of important problems related to the origin, structure and evolutionary history of our Galaxy and new tests of general relativity and cosmology, and in particular will make a substantial contribution to the determination of luminosity calibrations and the distance scale.

2 The Gaia simulator

Gaia will acquire an enormous quantity of complex and extremely precise data that will be transmitted daily to a ground station. By the end of Gaia's operational life, around 150 terabytes (10^{14} bytes) will have been transmitted to Earth: some 1,000 times the raw volume from the related Hipparcos mission.

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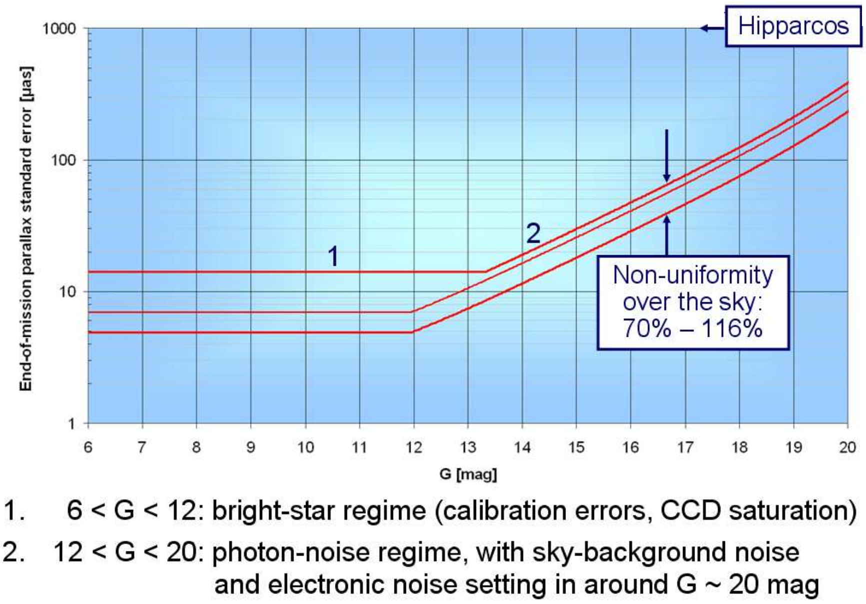

Fig. 1. End of life Gaia parallax errors (courtesy J. de Bruijne, ESA)

An extensive and sophisticated Gaia data processing mechanism is being developed to yield meaningful results from collected data. To allow its development and testing a system has been developed to generate the simulated Gaia data, the Gaia simulator.

The Gaia simulator has been organized around a common tool box (named GaiaSimu library) containing a universe model, an instrument model and other utilities, such as numerical methods and astronomical tools. This common tool box is used by several specialized components and one of its main components is the so-called Universe Model. It allows the simulation of the characteristics of all the different types of objects that Gaia will observe: their spatial distribution, photometry, kinematics and spectra. The universe model is designed to generate lists of astronomical sources whose distributions and the statistics of its observables are as realistic as possible.

The object generation process is divided into three main modules, Solar System, the Milky Way and extragalactic objects. We will not deal here with the first and third modules and we present below a short summary of the second. For more details see (Robin et al. 2011).

2.1 The galaxy model

Galactic objects are generated from a model based on Besançon Galaxy Model (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:

- The thin disc: young stars with high metallicities. It is additionally divided in seven isothermal components of ages varying from 0-0.15 Gyr for the youngest to 7-10 Gyr for the oldest. For computing the scale height at the solar position as a function of age (Bienaymé et al. 1987), the Boltzmann equation (first moment at the first order with the plane parallel approximation) is used assuming an age-velocity dispersion relation deduced from Hipparcos observations (Gómez et al. 1997).

- The thick disc: in terms of metallicity, stars are at half-way between the thin disc and the stellar halo.
- The stellar halo (spheroid): old and metal poor stars.
- The outer bulge: old stars with metallicities similar to the ones in the thick disc.

The distribution in the Hess diagram split into several age bins is obtained from an evolutionary model which starts with a mass of gas, generates stars of different masses assuming an Initial Mass Function and a star formation rate history, and makes these stars evolve along evolutionary tracks. The evolution model is described in Haywood et al. (1997a,b). The evolutionary model produces a file describing the distribution of stars per element volume in the space (M_V, T_{eff}, Age). Similar Hess diagrams are also produced for the bulge, the thick disc and the spheroid populations, assuming a single burst of star formation and ages of 10 Gyr, 11 Gyr and 14 Gyr respectively.

The stellar luminosity function is the one of primary stars (single stars, or primary stars in multiple systems) in the solar neighborhood Reid et al. (2002).

It is worth noting that white dwarf (WD) are taken into account separately but self-consistently. Additionally, some rare objects such as Be stars, peculiar metallicity stars and Wolf Rayet stars have also been added.

In the end, each star from the generated catalogue has assigned intrinsic attributes (age, effective temperature, bolometric magnitude, U,V,W velocities, distance) and observational parameters (apparent magnitudes, colors, proper motions, radial velocities, etc) affected by the implemented 3D extinction model from Drimmel et al. (2003).

3 Simulation overview

The universe model generates a total number of 1,000,000,000 galactic objects at $G < 20$ of which 49% are single stars and 51% stellar systems formed by stars with planets and binary/multiple stars. Individually, the model has created 1,600,000,000 stars where 31.66% of them are single stars with magnitude G inferior to 20 (potentially observable by Gaia) and 68.34% correspond to stars in multiple systems. This last group is formed by stars that have magnitude G inferior to 20 as a system but, in some cases, its isolated components can have magnitude G superior to 20 and will not be individually detectable by Gaia.

3.1 Spatial distribution

Based on these simulations, the Gaia catalogue will sample a large fraction of the galactic volume, thoroughly mapping the solar neighborhood, providing large numbers of objects for a substantial part of the disk and reaching the central parts of the Galaxy although not the centre itself. In figure 2 the sampling of the Galaxy is depicted based on the simulation results.

3.2 The HR diagram

On the other hand, the stars in the catalogue will also fully cover the HR diagram, sampling even the regions with the rarest types of objects. This coverage is depicted in figure 3; the densest regions contain tens of millions of objects and even the rarest types (bottom of the main sequence, brightest giants) are represented with some hundreds of objects.

4 Consequences for the Luminosity calibrations and distance scale

Even though Hipparcos was a major improvement with respect to earlier ground-based astrometric observations, *only* about 30 000 stars (compared to a few hundreds before Hipparcos) obtained a relative precision on the trigonometric parallax better than 10 %, all of them are in the solar neighborhood, and very few standard candles are among them. On the other hand, many different photometric and spectroscopic systems have been used, resulting in the non-uniformity of the color or abundances scales, and have been compared with many different

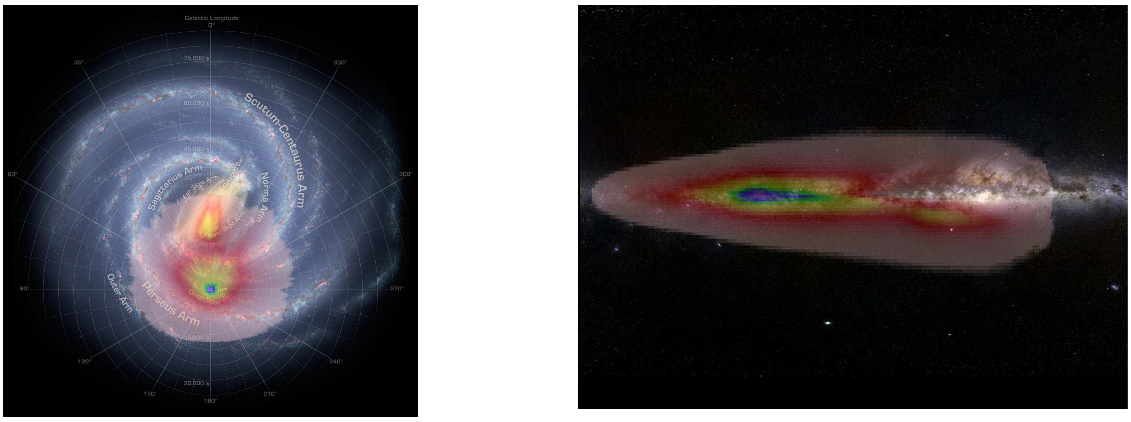

Fig. 2. These images show the expected 3D distribution in the Milky Way of the contents of the Gaia catalogue. They are an overlay of an artistic top view of our galaxy (NASA/JPL-Caltech/R. Hurt) and an illustration of a side view of the Galaxy (right, Gigagalaxy zoom, ESO/S. Brunier/S. Guisard: the Milky Way as seen from ESO, Chile) with the results of a simulation of the contents of the Gaia catalogue. The colors of the overlaid simulation show the expected density of the one-billion stars in the catalogue in different regions of the Milky Way, ranging from purple-blue very high densities around the Sun to pink low densities farther from it. The "spikes" pointing away from the Sun are due to windows in the interstellar extinction, allowing deeper observations. Notice in particular the region in yellow and red, just below the galactic center. It corresponds to the high-density bulge visible through an extinction window around the galactic central region. See `http://www.rssd.esa.int/index.php?project=GAIA&page=picture_of_the_week&pow=141` for the full-resolution images.

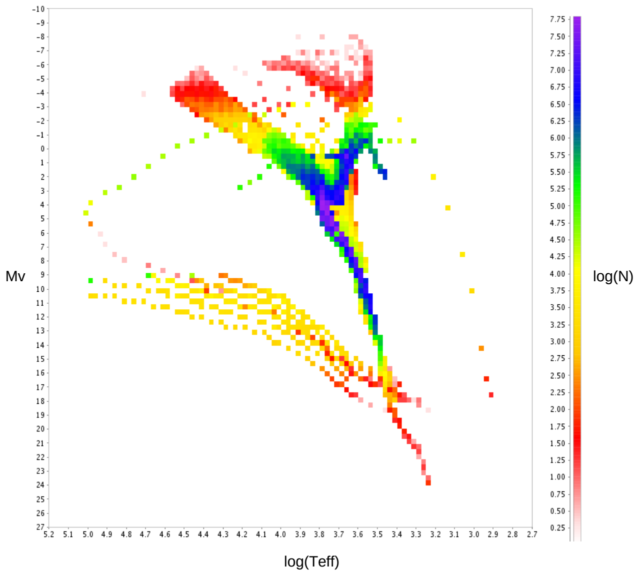

Fig. 3. The Gaia HR diagram. The figure shows the expected density of catalogue objects in the different regions of the HR diagram (single stars and components of systems alike). The color scale gives the decimal logarithm of the number of objects for each [0.025K x 0.37mag] box in the diagram; to properly interpret this figure it is important to take into account that the logarithmic scale strongly enhances the visibility of low-density areas that will be represented in the Gaia catalogue, which makes it somewhat unfamiliar compared with the usual HR diagrams.

models of stellar atmosphere, resulting in various transformations from color to the effective temperature and various estimations of the bolometric correction. Finally, it is difficult to safely compare observations between

Table 1. Luminosity calibrations: from Hipparcos to Gaia (adapted from Turon & Perryman 1999, and updated)

	Hipparcos (a)	Hipparcos re-reduction (b)	GAIA
$\sigma_\pi/\pi < 0.1$ %	-	3	~ 100 000 stars
$\sigma_\pi/\pi < 1$ %	442 stars	719 stars	~ 11×10^6 stars up to 1 – 2 kpc (Mv < 0) up to 0.5 – 1 kpc (Mv < 5)
$\sigma_\pi/\pi < 10$ %	22 396 stars	30 579 stars	~ 150×10^6 stars up to 10 – 15 kpc (Mv < –5) up to 7 – 10 kpc (Mv < 0) up to 2 – 3 kpc (Mv < 5)
Error on Mv (V = 10) due to error on π	0.5 mag at 100 pc		0.002 - 0.007 mag at 100 pc 0.2 - 0.7 mag at 10 kpc
Stellar populations	mainly disk		all populations, even the rarest
HR diagram < 10%	-4 < Mv < 13 -0.2 < $B - V$ < 1.7		all magnitudes all colors

(a)(Perryman et al. 1997; Perryman & ESA 1997)
(b)(van Leeuwen & Fantino 2005; van Leeuwen 2007)

themselves and with theoretical isochrones.

The remaining major sources of uncertainty are the location of the principal sequences of the Hertzsprung-Russell diagram (main sequence, subgiant branch, turn-off stars, red clump stars, blue supergiants) versus metallicity, age or detailed element abundances, the calibration of the period-luminosity(-color) relations of pulsating variable stars with respect to all effects likely to affect their absolute luminosity, the distance (and depth) of the Large Magellanic Cloud, whose Cepheids are often used as reference to derive relative distances to other galaxies.

As we have seen in the previous section the Gaia catalogue will abundantly cover all the above mentioned regions of the HR diagram, and will do it with much more precise astrometry than Hipparcos, as shown in table 1.

Therefore, a huge amount of extremely accurate trigonometric parallaxes will be available for very large samples of all galactic populations, allowing the direct distance determination of large samples of all kinds of stellar candles, and may even provide the first direct test of the universality of the period-luminosity(-color) relations. It will also provide a systematic diagnostic of the duplicity (multiplicity) of all observed targets and reliable abundances and ages for very large samples of field and cluster stars.

Furthermore, Gaia will also observe about 7.5 million stars in the Large Magellanic Cloud and about 1.5 million stars in the Small Magellanic Cloud. Although most of the individual parallaxes will have too large errors to be useful to determine the distance of the individual stars (see figure 4) taking all the millions of individual parallaxes together will allow to determine the mean parallax of the LMC with a relative error of about 0.5%, and that of the SMC with a relative error of about 1.5%. Even more, for the brightest objects in the clouds (including Cepheids) the Gaia parallax error will be still small enough (50% - 100%) to obtain useful distance estimations, allowing for the first time to directly study the 3D distribution of these objects.

5 Conclusions

The precise knowledge of distances is an essential clue to the calibration of the luminosities of stellar candles used to estimate the distances in the Universe, very far beyond the Local Group of galaxies. Hipparcos was a major step forward and the next, spectacular, step will be Gaia, with orders of magnitude improvement in the number of observed targets (from 118 000 for Hipparcos to 1 billion for Gaia) and in the accuracy (from 1 mas for Hipparcos to 10 μas for Gaia), as well as its full coverage of the HR diagram and its direct reaching of the

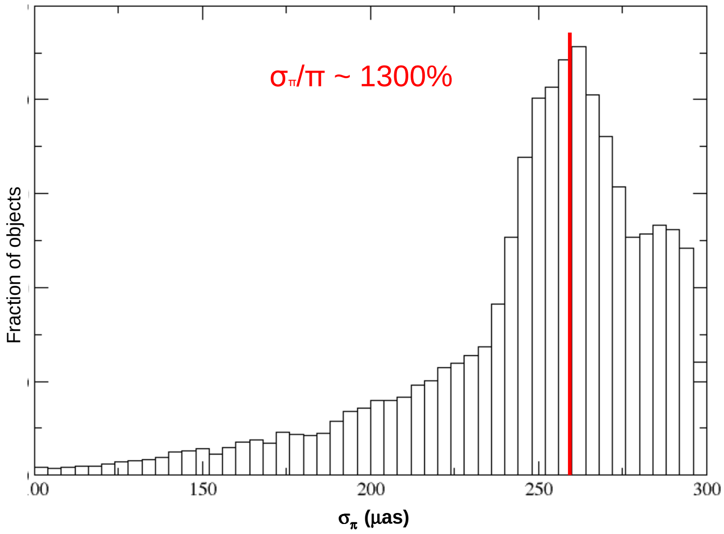

Fig. 4. Distribution of the errors in parallax for the simulated LMC objects. Notice that the maximum is at a relative error of 1300%, but that there is a significant tail of objects reaching low relative errors.

Large and Small Magellanic Clouds.

Finally, the other – also essential – characteristic of Gaia is its capability to obtain photometric and spectroscopic observations quasi-simultaneously with astrometric data. This is a key possibility for a complete study of stellar candles, especially because of the importance of metallicity effects on their luminosity, and holds the promise for a significant advance in the determination of luminosity calibrations and, with them, the distance scale of the universe.

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