SF2A 2008
C. Charbonnel, F. Combes and R. Samadi (eds)

GAIA IN THE EUROPEAN CONTEXT

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Abstract. The ESA Gaia mission is placed in the context of the European and worldwide astronomy: What are its main characteristics? What is its place within the ESA Cosmic Vision? What is its place within the Astronet roadmap context? Which actions should be supported or started for taking full benefit of this ambitious mission?

1 Introduction

In the early '90s, the unprecedented success of Hipparcos (see for example Lindegren *et al.*, 1994; Perryman *et al.*, 1995; Perryman *et al.*, 1997) showed how powerful space was for astrometry and what a powerful tool for astrophysics was high accuracy astrometry, and first ideas on how a future astrometry mission could be enhanced with respect to Hipparcos were already discussed. These were including much higher astrometric accuracy, a much larger number of objects observed systematically down to a fainter magnitude, and the possibility to have the radial velocity and an astrophysical characterisation of the observed objects obtained on-board, in parallel with the astrometric measurements. Within the frame of ESA's *Horizon 2000 Plus* long-term scientific programme, a proposal was made for a new mission, Gaia, able to reach 10 μarcsecond accuracy on positions, trigonometric parallaxes and annual proper motions for some 50 millions stars down to magnitude 15, along with multi-colour multi-epoch photometry of each object (Lindegren & Perryman, 1996). The mission finally included in the ESA Science programme in October 2000 is still much more ambitious (Perryman *et al.*, 2001), with the goal to produce a stereoscopic and kinematic census of about one billion stars, down to magnitude 20, throughout our Galaxy, and into the Local Group.

2 The Gaia mission

Gaia, planned to be launched by the end of 2011, is a unique mission thanks to several of its principles: unprecedented astrometric accuracy; three complementary instruments on board, providing parallel astrometric, photometric and spectroscopic observations, i.e. a complete characterisation of the billion objects which will be observed; a largely uniform scanning of the sky surveying all stellar populations over the whole part of the Galaxy observable at optical wavelengths; an on-board systematic detection of all objects down to magnitude 20 (Solar System objects, stars, galaxies, QSOs); a regular sampling over the five years of mission, leading to about 80 observations per object, which will allow photometric and spectroscopic variability analysis and orbit determination for double and multiple stars, giant planets and Solar System objects; global absolute astrometry with extreme accuracy, providing absolute parallaxes for stars of all spectral types, evolutionary status and populations, and absolute proper motions for stars up to the brightest parts of the nearest galaxies of the Local Group. The only parts of the Galaxy which will be poorly observed by Gaia are zones with very heavy extinction in the bulge or some parts of the disc.

The comparison with the Hipparcos performance (Perryman *et al.*, 1997; van Leeuwen & Fantino, 2005) gives a flavour of the giant step which will be achieved with Gaia (Perryman *et al.*, 2001): number of stars (1 billion versus 118 000), limiting magnitude (20 versus 12.4), astrometric accuracy (best expected accuracy of 8 μarcsecond for stars brighter than 13 versus 0.2 mas for stars brighter than 5; 0.2 mas accuracy at magnitude 20), astrophysical characterisation (multi-colour photometry down to magnitude 20 and spectra

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down to magnitude 16.5 versus 2 colours down to 12.4), observing programme (on-board systematic detection down to magnitude 20 versus preliminary ground-based star selection). In addition, the sixth dimension in the space parameter, the radial velocity, will be measured on-board for stars brighter than 16.5, in parallel with astrometric and photometric observations. Some 10 million stars will have their distances known to 1%, 100 million to 10% (to be compared with 21 000 with Hipparcos); the photometric accuracy of each of the $\sim$ 80 observations of a star brighter than V=15 will be of a few milli-magnitudes in several colours; the radial velocity of stars brighter than 15 will be measured to better than 1 $km.s^{-1}$; for stars brighter than G=16, the effective temperature will be obtained to better than 5%, their gravity ($\log g$) to 0.2-0.3, their metallicity to 0.2-0.4.

Thanks to this variety of observations, Gaia will contribute to many domains in astronomy: complete census of a large proportion of the Galaxy; characterisation of all stellar populations, both in the Galaxy itself and in the brightest parts of the nearest galaxies of the Local Group; dynamical and chemical evolution of the Galaxy; dynamics of the Galaxy and the Local Group, with a much better knowledge of the distribution of the dark matter at small and large scales; distance scale determination, using various distance candles, and impact on H_0; determination of the PPN parameter γ; stellar structure and evolution; stellar variability; complete census, orbital improvement, and taxonomy of Solar System objects; etc. Finally, it will provide a systematic selection of many specific objects (very metal poor stars, stellar groups and streams, variable stars, double stars or stars with planets, etc.etc.); the distinction between foreground Galactic stars and bright stars in dwarf spheroidal neighbours; the systematic detection of relativistic effects; etc.

3 Gaia within the international and European context

International context

Europe has been a pioneer in developing and launching a satellite entirely dedicated to high accuracy astrometric measurements. The dramatic success of Hipparcos (more than 5000 papers are using its data by mid-2008, among which nearly 2000 refereed) stimulated numerous proposals for similar missions in several countries (Russia, USA, Germany, Japan, Europe). At the moment, only a few are still considered or in development:

- JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration, not totally funded) would be the ideal complement to Gaia as it will operate in the 0.9 μm z band. Thereby it will be able to observe deeply in the Galactic centre, the bulge and parts of the disc (not possible with Gaia because of heavy extinction and crowding) with astrometric accuracies similar to Gaia (Gouda *et al*, 2008). A nano-size satellite (5-cm telescope, 14 kg), Nano-JASMINE, is also being developed in Japan (Kobayashi *et al*, 2008).

- SIM PlanetQuest (Space Interferometry Mission, NASA-JPL) is a project for an optical interferometer. The goal is to measure the position, trigonometric parallax and proper motion of stars with an accuracy of 4 μas down to magnitude 20 (Shao, 2008). A SIM-Light mission is under consideration.

- J-MAPS micro-satellite to be launched by 2011 (15-cm telescope), aim at re-observing all Hipparcos stars (as well as virtually all other stars down to around 14th magnitude) with an accuracy of 1 mas down to 12th magnitude and with reduced accuracy down to 15th magnitude (USNO, Dorland & Gaume, 2007).

Gaia in the ESA context

In the last ten years, there has been a festival of Solar System missions launched in the frame of the ESA Science Programme: Soho (Solar observations, with NASA, 1995), Cassini-Huygens (to Saturn and Titan, NASA-ESA, 1997), Cluster (magnetosphere observations, 2000), Mars Express (to Mars, 2003), Smart (to the Moon, 2003), Double-Star (magnetosphere observations, Chinese satellite with ESA collaboration, 2003), Rosetta (to comet Churyumov-Gerasimenko, 2004), Venus Express (to Venus, 2005). The next launches are Chandrayaan-1 (to the Moon, an Indian satellite with ESA collaboration) and Bepi-Colombo (to Mercury, with JAXA, 2013).

The astronomy missions in operation are Hubble (NASA-ESA, 1990), XMM-Newton (observations in X-rays, 1999), and Integral (observations in γ-rays, with Russia, 2002). In addition, ESA is involved in two collaborative missions: AKARI (observations in the IR, JAXA, 2006), and Corot (stellar seismology, exo-planets, CNES, 2006). Herschel (far-IR and sub-mm observations to observe star and galaxy formation) and Planck (map of the Cosmic Microwave Background anisotropies) will be launched in 2009. Gaia is then the only astronomy mission to be launched before JWST (NASA-ESA, 2013).

Four major questions were identified in the **ESA Cosmic Vision 2015-2025** (Bignami *el al.*, 2005): What are the conditions for planet formation and the emergence of life? How does the Solar System work? What are the fundamental physical laws of the Universe? How did the Universe originate and what is it made of? With its unique capability of surveying all stellar populations, over the whole Galaxy, Gaia will be a major contributor to the first steps of the first and last questions:

- From gas and dust to stars and planets. What are exoplanets and which stars have them?
  Gaia will provide unprecedented and complete information on stars of all spectral types, even the rarest, and all evolutionary stages, even the fastest: luminosities, motions, ages, duplicity and chemical characterisation. This will give a detailed picture of which stars form and have been formed where, in each of the component of the Galaxy. Gaia will also make a systematic census of giant planets, delivering insights into the frequency of giant planets as a function of the characteristics of their host stars and their locations in the Galaxy. This will give unique information about the conditions which favour the formation of planets. In addition, since the presence and location of one or several giant planets may severely affect the formation of smaller planets in a system, GAIA will provide important information on the likelihood of finding Earth-like planets orbiting their stars in the habitable zone.
- The Universe taking shape.
  Gaia will bring major inputs to the understanding of the formation and history of our own Galaxy by combining positional, kinematics and chemical information: tests of hierarchical structure formation theories and star formation history; detection of disrupted star clusters and satellite debris; firm establishment of the relations between ages, metallicity and kinematics; determination of the dynamical interactions between the bar and the bulge, the disc and the halo, the disc and the warp; etc. It will also provide insights in the distribution of invisible mass, both in our Galaxy and in the Local Group, with an improved determination of galaxy orbits. Finally, the Galaxy will be described in such exquisite detail that it will be possible to use it as a template for the interpretation of observations of external galaxies.

Gaia and ASTRONET Science Vision
ASTRONET was created to develop a comprehensive strategic plan for European astronomy covering the ambitions of all of astronomy, ground and space, and to establish the most effective approach towards answering the highest priority scientific question. The first step was the development of a *Science Vision* identifying the key astronomical questions which may be answered in the next twenty years by a combination of observations, simulations, laboratory experiments, interpretation and theory (de Zeeuw *et al.*, 2007). Four key questions were identified where significant advances and breakthroughs can be expected in the coming two decades: Do we understand the extremes of the Universe? How do galaxies form and evolve? What is the origin and evolution of stars and planets? How do we (and the Solar System) fit in? The recommendations distinguish essential facilities, without which a certain scientific goal simply cannot be achieved, and complementary ones, which would go a long way towards answering the question, but may have their main scientific driver elsewhere.

In this frame, Gaia was considered as an *essential* facility for two main questions:

- How do galaxies form and evolve? Obtain a complete history of our Galaxy early formation and subsequent evolution.
- What is the origin and evolution of stars and planets? Understand the formation and mass distributions of single, binary or multiple stellar systems and stellar clusters. Unveil the mysteries of stellar structure and evolution, also probing stellar interiors. Explore the diversity of exo-planets, in relation with the characteristics of their host stars.

Gaia was also considered as a *complementary* facility for

- How do we fit in? Dynamical history and the composition of trans-Neptunian objects, asteroids and comets.

4 Gaia in 2012

Gaia will provide a huge quantity of unique data which, in addition to being used for themselves, will help the interpretation of many other data: by making our Galaxy a template for the interpretation of external galaxies observed by JWST, VLT, ELT, XEUS, etc; by providing an unprecedented luminosity calibration for all stellar types from all stellar populations, further observed by the VLT, ELT, JWST, etc; by providing the 3$^{\mathrm{rd}}$

dimension and 3-D kinematics to stellar formation areas observed by Herschel, Planck, and Alma; by providing an extremely accurate determination of the PNN parameter γ to be compared with the future results of LISA.

With a systematic census down to magnitude 20 and a complete characterisation of all observed objects, Gaia will be a fantastic tool to select well defined samples in targeted populations, to be further observed with other instruments. Powerful high spectral resolution spectrographs on JWST, VLT, ELT, etc. could be used to study in detail the chemical abundances of statistically significant samples selected from Gaia data: halo stars in a well defined volume; thin and thick disk samples at different distances from the Galactic plane and at different Galacto-radius; stars in streams; stars of a given metallicity; stars in a very rapid evolutionary phase. Gaia will also be able to make systematic statistics of planetary formation versus stellar type, and identify nearby systems with planets, to be further observed in more detail with JWST, ELT, SIM, Darwin, TPF, etc. Last example, Gaia will systematically observe a huge number of asteroids, further targets for observations over longer periods of time, in order to cover larger parts of their orbits.

It is then essential to get prepared for, and in some cases to start in anticipation, these ground-based observations, which will make the difference in the exploitation of Gaia data: spectroscopic observations of exoplanets detected by their astrometric motion; detailed element abundances for unbiased stellar samples; follow-up observations of variable stars, orbital systems, asteroids; etc. The other aspect is to consider spectroscopic and radial velocity observations in complement to those of Gaia for stars fainter than V=16.5, for example for halo streams, spiral arms, substructures in the disc or bulge, kinematics in the Local Group, etc.

5 Conclusion

Gaia is planned for launch by the end of 2011, the publication of the final catalogue for 2020. However, some intermediate publications may be expected, especially for photometric and spectroscopic data. To take full advantage of the investment made in the preparatory work on Gaia, and take a leading position in the exploitation of these unique data, thoughts and work have to be devoted *from now on* on several aspects: the development of new statistical methods to use such a mass of data, the improvement of theories and modelling of the Galaxy dynamical and chemical behaviour, the choice of the best methods to use Gaia data for the definition of the optical reference system, the definition - and organisation - of the most adapted follow-up and complementary ground-based or space observations. Finally, in addition to the future use of already existing instrument, it would be extremely valuable to define a multi-object wide-field spectrograph, able to observe simultaneously a few thousands stars, well suited for follow-up and complementary observations of Gaia selected samples. This is supported by the recommendations of the ASTRONET Infrastructure Roadmap (Bode *et al.*, 2008) and by ESA-ESO Working Group Report on Galactic science (Turon *et al.*, 2008). The French - and European - community put a major effort in the preparation of the Gaia data processing. Let us be in the best position to use these data in the many domains where it will provide a complete renewal of the observational basis.

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