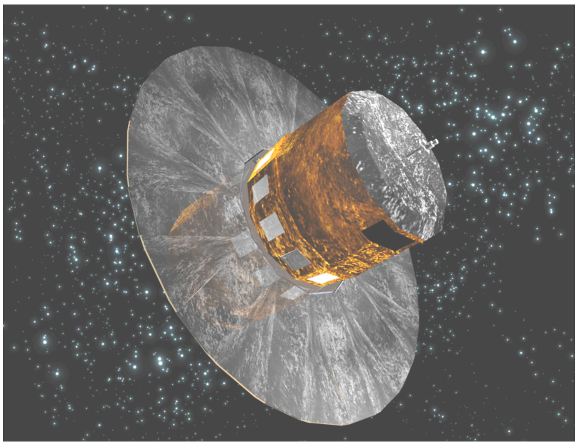

Action Spécifique Gaia

SF2A 2009

29 juin 2009

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Préface

Ce fascicule rassemble l'ensemble des présentations et posters présentés lors de la Journée AS Gaia de la semaine de la SF2A 2009, le lundi 29 juin à Besançon. Les présentations ainsi que les textes individuels sont disponibles à l'adresse suivante : http://wwwhip.obspm.fr/gaia/AS/SF2A-2009.html.

La Journée de l'AS Gaia a permis de rassembler une grande partie des scientifiques travaillant sur Gaia en France, que ce soit pour la préparation de l'analyse des données ou pour celle de l'exploitation scientifique future de la mission. De plus, la SF2A ayant mis à l'honneur cette année la Société Suisse d'Astrophysique et d'Astronomie (http://obswww.unige.ch/ssaa/), nous avons saisi l'occasion pour inviter nos collègues Suisses, nombreux eux aussi à préparer l'arrivée de Gaia.

Cette Journée a été l'occasion de présenter un bilan de deux années de fonctionnement de l'Action Spécifique et, plus particulièrement les comptes-rendus des différents ateliers qui se sont tenus à l'initiative de l'AS Gaia pour préparer l'exploitation scientifique de la mission et commencer à organiser les observations au sol complémentaires aux observations Gaia. Par ailleurs, l'état de développement de la mission ainsi que les projets relatifs à l'archivage et à l'interrogation de l'ensemble des données qui seront obtenues au cours de la mission ont été présentés, ainsi que de nombreux aspects des applications scientifiques futures des données Gaia: les propriétés physiques des astéroïdes ; les masses des binaires spectroscopiques ; la détection systématique de toutes sortes d'étoiles variables ; les complémentarités entre Gaia et les missions spatiales Corot, Kepler et Plato, dédiées à la photométrie d'extrême précision ; les synergies entre les observations spectroscopiques de Gaia et celles des relevés au sol ; les simulations de la Galaxie et des autres objets qui seront observés par Gaia (corps du Système Solaire, QSOs, galaxies) ; la cinématique et la dynamique de notre Galaxie.

Les numéros des pages correspondent à la publication « Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, held 29 June - 4 July 2009 in Besançon, France. Eds.: M. Heydari-Malayeri, C. Reylé and R. Samadi », disponible en ligne sur l'ADS et à l'adresse suivante : http://sf2a.cesr.fr/php/spip/spip.php?article205#6

Catherine Turon et Frédéric Arenou

Présentations invitées et contributions orales Journée AS Gaia

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10:00 - 10:30	Gaia status : *Jos de Buijne*
10:30 - 11:00	Pause
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11:20 - 11:40	Gaia and ground-based observations of Solar System Objects (atelier Nice) : *William Thuillot*
11:40 - 12:00	Asteroid physical properties : *Alberto Cellino*
12:00 - 12:30	Gaia archive plans and status : *William O'Mullane*
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SF2A 2009
M. Heydari-Malayeri, C. Reylé and R. Samadi (eds)

TWO YEARS OF CNRS-INSU 'ACTION SPÉCIFIQUE' GAIA

Turon, C.[1] and Arenou, F.[1]

Résumé. The 'Action Spécifique' Gaia (AS Gaia) has been created by the French National Institute for the Sciences of the Universe with the aim of enhancing the scientific return from the European Space Agency (ESA) Gaia mission, due to be launched during Spring 2012. The various actions taken during the last two years are presented here.

1 Introduction

Space Astrometry is a branch of space science where French scientists, Space Agency (CNES) and space industry have been deeply involved from the very beginning (ESA's Hipparcos was built from an original idea of Pierre Lacroute, the then Director of the Strasbourg Observatory). Building on the success of the Hipparcos mission, Gaia was proposed to ESA in 1993 (Lindegren & Perryman, 1996) within the frame of ESA's *Horizon 2000 Plus* long-term scientific programme. It was included in the ESA's Science Programme in 2000 and is due to be launched in Spring 2012. Many French astronomers contributed, in straight collaboration with other European colleagues, to establish the Gaia science case and to define the specifications of the astrometric, photometric and spectroscopic instruments of Gaia. The DPAC (Gaia Data Processing and Analysis Consortium) is chaired by François Mignard (Observatoire de la Côte d'Azur) and France is the first contributor to the Consortium (about 25 % of the members). Accordingly, the creation of an 'Action Spécifique' was proposed (Turon et al., 2007) to the CNRS National Institute for the Sciences of the Universe (INSU) and created in August 2007, for four years.

The challenge for AS Gaia is to prepare the French astronomers to be in a position to best exploit the Gaia scientific data in their quantity and diversity, and in their various domains of application. Its role is therefore to suggest and support actions in order to fulfil the needs in modelling and theoretical developments and on the complementary and follow-up observations that should be organised before, during and after Gaia operations. AS Gaia has also been requested by INSU to support the ground-based observations required by the Gaia data analysis and not otherwise funded.

Finally, AS Gaia is the voice of the French Gaia community towards our National funding authorities, and as such its chair attends CNES and INSU astronomy working meetings, contributes to the establishment of the INSU roadmap by producing documents and attending the various meetings, and supports the requests for funding or permanent positions.

2 Actions of the last two years

With a global funding of 30 k€ per year (15 k€ in 2007), AS Gaia opened three announcements of opportunity (end 2007, 2008 and 2009). The main broad lines of funding are the following :

- Ground-based observations required by the Gaia data analysis and not otherwise financed ;
- Organisation of topical workshops ;
- Modelling of the various objects which will be observed by Gaia : stars (interiors and atmospheres) ; the Galaxy ; Solar System objects ; galaxies ; compact objects (especially QSOs) ;
- Support to European and, more generally, international collaborations ;
- Support young astronomers attendance to international meetings ;
- Support to public outreach and conferences by the production of Gaia documentation in French.

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2.1 Ground-based observations in support to Gaia data analysis

A number of ground-based observations are required to support the Gaia data analysis and a special group, GBOG, chaired by Caroline Soubiran, has been created within DPAC to co-ordinate these (Soubiran et al. 2008). AS Gaia contributed to the funding of various actions :

- Observation of radial velocity standard stars for the initial calibration of the spectrograph on board Gaia, the Radial Velocity Spectrograph (RVS) : observations performed with the Coralie spectrograph, operated by the Geneva Observatory in La Silla. The observations performed in France with the Sophie (Observatoire de Haute Provence) and Narval (Observatoire du Pic de Midi de Bigorre) spectrographs are funded by other national funding. See Crifo et al. (2009).
- Spectroscopic observations of minor planets to calibrate and test the performance of classification algorithms.
- Astrometric observations of WMAP, a test of the performance of such observations to accurately reconstruct the orbit of the satellite, as is planned to be done for Gaia.
- Support to the realisation of a pipeline for processing the Narval spectra.
- Support to the setting of a network of ground-based observations of Solar System minor bodies, especially near-Earth objects.

2.2 Meetings and workshops

After a kick-off meeting in December 2007, an annual meeting of AS Gaia is now hosted as a parallel session during the 'Journées de la SF2A', which is thanked here. All presentations and papers are available from the AS Gaia web site at wwwhip.obspm.fr/gaia/AS.

In addition to these annual plenary meetings, a number of topical workshops have been or are being organised :

- "**Reference systems and QSOs**", organised at Bordeaux Observatory by P. Charlot and G. Bourda, 24 October 2008. The main topics were : settling of the Gaia reference frame; study of the long-term and short-term variations of the photocentres of AGNs and of potential discrepancies between optical and VLBI positions; link of ICRF to the Gaia frame (Bourda & Charlot, this meeting).
- "**Earth-based support to Gaia Solar System science**", organised in Beaulieu sur Mer by P. Tanga and W. Thuillot, 27-28 October 2008. The main goals were to plan for ground-based observations which would complement Gaia observations (for example to enlarge the period of observation over the orbits of solar system objects, to plan for detailed spectroscopic observations, etc.) ; to identify new techniques which would become possible thanks to the unprecedented accuracy of Gaia positions and proper motions; to organise a network of ground-based observers (Thuillot & Tanga, this meeting).
- "**Multiplex spectroscopy in complement to Gaia**", organised at Nice Observatory by A. Recio-Blanco and V. Hill, 19-20 February 2009, in preparation to the March 2009 ESO workshop 'Spectroscopic Survey Workshop'. The goal was to anticipate the requirements in ground-based spectroscopy in complement to the Gaia data in the domain of Galactic Archeology : radial velocity and chemical abundances for stars not observed by the Gaia RVS or not observed in enough detail (Bienaymé et al., this meeting).
- "**The Milky Way**", organised at the Besançon Observatory by A. Robin, C. Reylé and M. Shulteis, 5-6 November 2009. The meeting will be devoted to the various methods used to test the models of formation and evolution of galaxies, in the context of Gaia.
- "**Gaia et la physique des AGNs**", organised at Nice Observatory by E. Slezak, is planned for early 2010. The AGNs Gaia catalogue will be much larger and much more homogeneous than ever obtained earlier. The aim of the meeting is to initiate the work on the impact of these data over the understanding of the physics of these objects.

These workshops have a high priority in the annual announcements of opportunity and proved to be very efficient to co-ordinate the work of various teams within France and to open the way to new national and international collaborations. We plan to organise other such workshops in the coming years.

2.3 Modelling for Gaia data analysis

Gaia will observe all objects down to magnitude $V = 20$, i.e. a very large variety of stars, Solar System bodies and compact extragalactic objects. To be able to identify, classify and characterise them, it is essential to have good models of these objects as seen by the Gaia instrument. With one billion objects observed, any category of objects will include a huge number of elements and the classification algorithms have to be carefully tested in advance. A number of such actions have been supported by AS Gaia these two last years :

- Improvement of the modelling of massive stars with emission lines. Test and improvement of the classification algorithms.
- Simulation of multiple stellar systems.
- Development of library of synthetic spectra of galaxies to be used for the automatic classification of galaxies unresolved by Gaia observations.
- Simulation of a catalogue of quasars and AGN, and test of its observation with Gaia.
- Simulation of the detection and observation of binary minor planets.
- Simulation of the observation of extended objects.

2.4 Modelling for Gaia data scientific exploitation

Gaia has the discovery potential of a survey which will provide data of unprecedented accuracy, of unprecedented quantity, and for high variety of objects, running from Solar System bodies to unresolved galaxies, through all spectral types and evolutionary stages, even the rarest or the fastest. As a result, the scientific exploitation of such data have to be carefully prepared in advance. In this respect, various works have been supported by AS Gaia :

- Kinematic and dynamical modelling of the galactic bulge ;
- 3D and NLTE modelling of stellar atmospheres, aiming at the improvement of the determination of atmospheric parameters and abundances ;
- Modelling of the various types of emission-line stars and search for criteria to identify each of them from the Gaia spectroscopic and photometric observations ;
- Development of an algorithm and software to predict close encounters between minor planets, with the aim of mass determination ;
- Development of criteria for the taxonomic classification and absolute magnitude determination of minor planets observed with Gaia ;
- Determination of the conditions of observation of comets with Gaia, modelling of the non-gravitational forces perturbing their orbits.

2.5 Communication

A few steps have been taken to help the development of communication in France about the project and produce documentation for conferences and exhibitions : edition of posters and folders, and translation of ESA’s documentation, about the various aspects of the Gaia mission and science, more generally about astrometry and its evolution across centuries ; funding of models of the satellite ; development of a section of the AS Gaia web site dedicated to documentation in French about astrometry, Hipparcos and Gaia.

3 Preparing for the future

AS Gaia, through its Scientific Committee, actively contributed to the preparation of the astronomy roadmap prepared by INSU during 2009 and produced several documents :

- a document about the permanent research positions that would be required to take full benefit of the French involvement in the Gaia data processing and analysis and its major contribution to the DPAC Consortium ;
- a document about ‘observation services’ (which constitute one part of the mandatory activities of scientists with a position of ‘astronomer’ in France).
- a document about ground-based observations, and relevant instrumentation and telescopes that would be needed to complement Gaia observations ;

– a special document dedicated to the complementary spectroscopic observations that would be essential in complement to Gaia measurements in the domain of Galactic astronomy, and to the relevant instrumentation (multiplex spectrograph on a wide field telescope), proposing several possible solutions ;
– a contribution to the document produced for the INSU roadmap by the 'Programme National de Cosmologie et Galaxies" ;
– a contribution to the document produced for the INSU roadmap for 'space-ground-based coordination'
– contributions to the ASTRONET forum about the use of 2-4 m telescopes.

All these actions have to be developed and enhanced in the coming years in straight co-operation both within France with the various 'Programmes Nationaux' and with the European colleagues and networks (ELSA, RTN on European Leadership in Space Astrometry ; GREAT, an ESF network ; and any further network proposal to the European Commission). In particular, the series of topical workshops should be continued, and initiatives related to modelling and ground-based observations will also be strongly supported. A special effort has still to be done about scientific communication and further preparation of documentation and of presentation material.

The Gaia data will give a major input to various fields of astronomy and astrophysics where the French scientists are involved, and it is essential that all steps are taken so that they are fully aware of the characteristics of these data, in accuracy, sky and magnitude coverage, and that they are fully prepared to fully exploit this unique opportunity.

The Scientific Committee of AS Gaia for the years 2007-2010 is composed of Catherine Turon (chair), Frédéric Arenou (substitute to C. Turon in national meetings), Olivier Bienaymé, Daniel Hestroffer, Vanessa Hill (link with Programme National Cosmologie et Galaxies, PNCG), François Mignard (Chair of DPAC), Bertrand Plez (link with Programme National de Physique Stellaire, PNPS), Annie Robin (link with PNCG), Caroline Soubiran (member of the Gaia Science Team), Frédéric Thévenin (link with PNPS). The AS Gaia may be contacted at AS.Gaia@obspm.fr or through its web site wwwhip.obspm.fr/gaia/AS.

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M. Heydari-Malayeri, C. Reylé and R. Samadi (eds)

STATUS OF THE GAIA SPACECRAFT DEVELOPMENT

de Bruijne, J.H.J.[1], Escolar, D.[2] and Erdmann, M.[2]

Abstract.
Gaia, ESA's ambitious astrometric mission due for launch in spring 2012, will provide multi-epoch, micro-arcsecond astrometric and milli-magnitude photometric data for the brightest one billion objects in the sky, down to at least magnitude 20. Spectroscopic data will simultaneously be collected for the subset of the brightest 100 million stars, down to about magnitude 17. This massive data volume will allow astronomers to reconstruct the structure, evolution, and formation history of our galaxy, the Milky Way. It will also revolutionise studies of the solar system and stellar physics and will contribute to diverse research areas, from extra-solar planets to general relativity.

Underlying Gaia's scientific harvest will lie a catalogue, built on the space-based measurements. During the 5-year nominal operational lifetime, Gaia's payload, with at its heart a CCD mosaic containing nearly 1 billion pixels, will autonomously detect all objects of interest and observe them throughout their passage of the focal plane. This contribution addresses the summer-2009 development status of the Gaia spacecraft, with particular emphasis on the torus and the deployable sunshield assembly. These two sub-systems reached important milestones on the day this presentation was orally delivered to the SF2A, namely 29 June 2009. On this day, the qualification model of the sunshield arrived at the ESTEC test facilities for thermal tests inside the Large Space Simulator. On the same day, the torus brazing was successfully concluded.

1 The Deployable Sunshield Assembly

Gaia will perform micro-arcsecond astrometry of over 1 billion objects in our Galaxy and beyond. In order to achieve the required measurement precision, the spacecraft and payload must be shielded from direct sunlight and maintained at a stable, low temperature: any thermal instability at the level of a few tens of micro-Kelvins or more can affect the final accuracy of the measurements that will be made.

The thermal stability of the Gaia spacecraft will be largely determined by a sunshield, with a diameter of 10.2 m when fully deployed and covering a surface of $\sim$75 m^2, the sun-facing area of which has to remain flat within a few millimeters deviation over the entire spacecraft lifetime. The sunshield assembly is composed of 12 rigid, rectangular panels and 12 foldable, triangular sections. In order to fit inside the launcher fairing, the assembly must be folded against the sides of the Gaia spacecraft during launch. After launch, the sunshield will deploy to form a flat structure at the base of the spacecraft, supporting two parallel blankets of multi-layer insulation (MLI) which will act as thermal shields so that the solar flux is damped by a factor of $\sim$280. In addition, the sunshield has to provide structural support for 8 deployable solar panels. All this has to be achieved with a mass of 125 kg. The large size and foldable MLI sections make this a unique sunshield design.

The qualification model (QM) of Gaia's deployable sunshield assembly (DSA) is functionally representative of the flight model and comprises three rigid panels plus the two sections of foldable MLI between them. Thermal vacuum and thermal balance (TV/TB) testing of this model is part of a comprehensive qualification test campaign designed to verify the compliance of the sunshield with design and operational specifications. The qualification test campaign includes functional testing (deployment), vibrational testing (launch conditions), environmental testing (including the TV/TB test), and life-cycle testing (ensuring its endurance with multiple deployment tests).

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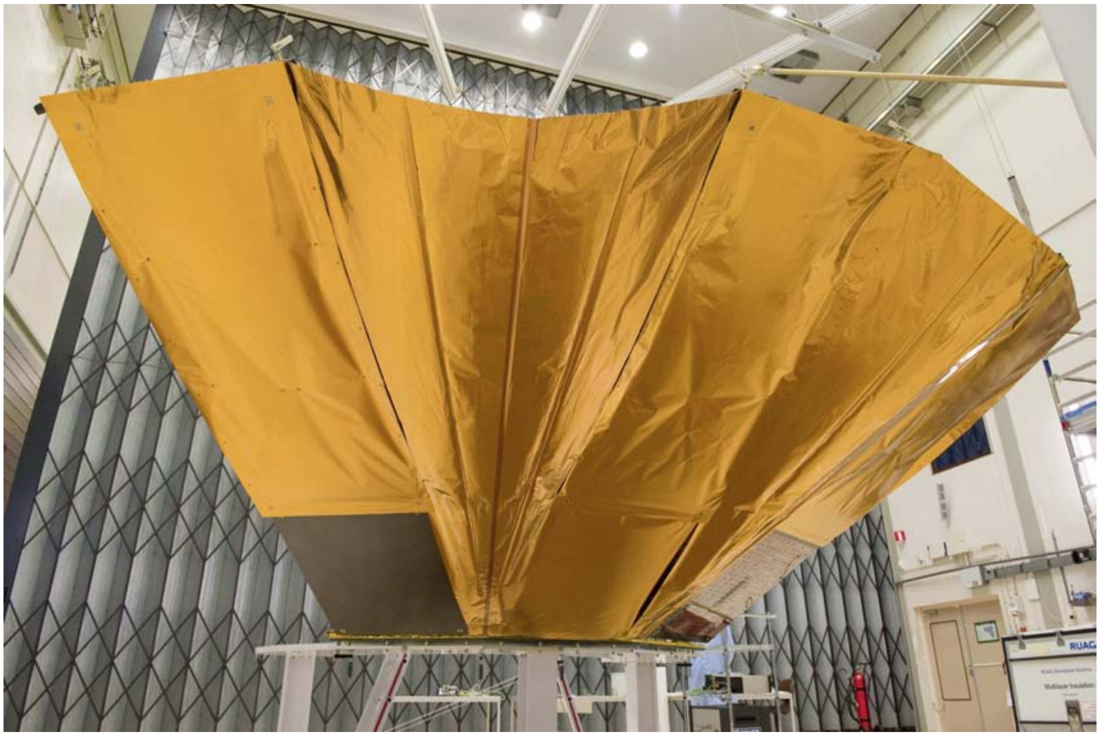

Fig. 1. This picture shows the Gaia deployable sunshield assembly (DSA) qualification model (QM) during deployment tests in the cleanroom at ESTEC, Noordwijk, The Netherlands. This model arrived at the ESTEC test facilities on 29 June 2009 for thermal tests inside the Large Space Simulator (LSS). Before the tests inside the LSS, several deployment tests of the sunshield were performed in the cleanroom at ambient conditions. This view shows the qualification-model sunshield during this deployment. The gold-coloured blanket of multi-layer insulation (MLI) is the sun-side blanket of the sunshield. Like the parallel-installed, shadow-side blanket behind it, it is made up of fixed sections attached to the three rectangular frames, and two foldable sections between the frames which are rolled in stowed configuration and unroll during deployment. The dark-coloured squares at the left and right bottom of the sunshield are solar panels. Copyright: ESA.

On 29 June 2009, the qualification-model sunshield arrived at ESA's ESTEC space centre in Noordwijk, the Netherlands, after transport from the SENER[1] premises in Spain. After arrival, the sunshield was unpacked and prepared for a deployment test at ambient conditions inside the ESTEC cleanroom. The MLI blankets were attached to the sunshield, and a zero-gravity kit – three masts with pulleys and counterweights used to simulate weightlessness – was installed. The deployment test involved the sunshield opening from its stowed configuration to its fully deployed configuration and was successfully completed on 3 July 2009 (Figure 1).

On 11 July 2009, the sunshield was transfered to the Large Space Simulator (LSS) for the TV/TB test. The LSS, with its 9.5-metre-diameter main chamber, is the only facility in Europe where tests of the Gaia sunshield can be performed in deployed configuration under simulated space conditions. The rectangular panels of the sunshield each measure about 0.8 m $\times$ 3.2 m and, once deployed, the qualification-model sunshield measures roughly 6.0 m $\times$ 4.0 m.

The main objective of the TV/TB test is to verify the deployment performance in simulated orbit conditions, the alignment and planarity (flatness) of the sunshield once it is deployed and exposed to the Sun, and the thermal performance of the sunshield. Inside the LSS chamber, the environmental conditions are regulated to simulate conditions encountered during operations in space. Shrouds with liquid nitrogen flowing through them cool the chamber to below 100 K. The chamber is vacuum pumped to a pressure of less than 10^{-8} bar.

During the tests, the planarity of the deployed sunshield was tested with videogrammetry measurements.

[1]SENER is developing the Gaia sunshield. The company is subcontractor to EADS Astrium, responsible for the overall design and development of the spacecraft. The frames and the blankets of the sunshield are supplied to SENER by RUAG, Austria.

Fig. 2. This picture shows the Gaia flight-model torus at the BOOSTEC premises at Bazet, near Tarbes, France. Pictured are members of the BOOSTEC and EADS Astrium SAS team just after the torus removal from the brazing furnace. The 3-metre-diameter, quasi-octagonal torus, which will support the two Gaia telescopes and the focal-plane assembly (FPA), is composed of 17 individual, custom-built, Silicon-Carbide (SiC) segments, all of which were constructed by BOOSTEC under contract to the Gaia prime contractor, EADS Astrium SAS. Starting on 28 April 2009, the 17 elements were assembled and aligned into the form of the torus. The torus brazing took place from 24–29 June 2009. Following the successful completion of the brazing, the torus has been delivered to EADS Astrium SAS in Toulouse for assembly of the bipod and release mechanisms (BRMs). Copyright: ESA.

This technique uses video observations of reflectors placed at specific points on the sunshield to accurately determine the relative positions of these points during the test. Deviations from the desired flat shape of the sunshield in its deployed configuration can be identified this way.

The thermal performance was monitored by 150+ temperature sensors attached to the sunshield and by temperature-map measurements of the sun-exposed surface of the deployed sunshield using an infrared camera. During the TB/TV test, the solar illumination was simulated at different intensity levels with special lamps generating up to 1400 W m^{-2} (just over 1 solar constant). The collimated light beam from these lamps was horizontal so the sunshield was deployed from horizontal to vertical position while inside the LSS. A mask in the form of a large foil shield, with a window exactly matching the shape of the deployed sunshield, stood in front of the opening where the collimated beam entered the main chamber. This mask allowed light to impinge directly only onto the sun-exposed side of the sunshield and blocked light that would otherwise pass the sunshield and reflect inside the vacuum chamber back onto the shadow side of the sunshield. Weightlessness conditions were simulated using the zero-gravity kit.

On 11 July 2009, the sunshield was lowered into the LSS chamber using an overhead crane. In the following days leading up to the TV/TB test, the set-up and the sunshield were prepared inside the LSS chamber. A dry run of the deployment inside the LSS was performed on 17 July 2009 under normal cleanroom conditions with the chamber still open. After bringing the sunshield back to its stowed configuration, the chamber door was closed on 20 July 2009, signalling the start of the TV/TB test in simulated space conditions. This test lasted 7 days. After completion of the TV/TB test, the sunshield was removed from the LSS and moved back to the cleanroom, where the life cycle deployment testing in ambient conditions was completed.

At the time of writing, the sunshield is waiting for a second slot of LSS tests to be performed in October

2009. After these tests, the qualification model will be delivered to the Gaia prime contractor, EADS Astrium SAS. Upon successful completion of this test campaign, the manufacturing of Gaia's flight-model sunshield will commence, incorporating all results from the qualification-model test campaign in the definitive design and assembly of the flight-model sunshield.

2 The torus

On 29 June 2009, the Gaia spacecraft development passed an important milestone when the 17 individual segments of the torus, a key structural element of the payload, were brazed into one coherent structure at the BOOSTEC premises at Bazet near Tarbes, France. The results of this process were successfully concluded after a mandatory inspection point (MIP) of the torus on Monday 20 July 2009.

The 3-metre-diameter, quasi-octagonal torus, which will support the two Gaia telescopes as well as the focal-plane assembly (FPA), is composed of 17 individual, custom-built segments. The scientific requirements of the mission translate to a requirement for a payload that is mechanically and thermally ultra stable, reaching micro-Kelvin and pico-meter levels. For these reasons, all elements of the torus are constructed from Silicon Carbide (SiC), a ceramic material with very special physical characteristics: it is very light-weight and the low thermal expansion coefficient and high thermal conductivity of SiC mean that it is a very stable material which can quickly dissipate thermal gradients. In addition, SiC is twice as stiff as steel.

Construction of the individual torus segments began more than one year ago at BOOSTEC. The process started with a 'green body' SiC powder and an organic binder material that was compressed with hydrostatic forces in a high-pressure facility. The resulting chalk-like material is easy to mill, although very abrasive in nature. Each of the 17 segments of the torus was milled from a green body. The segments were then sintered in a furnace to produce a solid, hard body. The segment interface surfaces were subsequently lapped to create an extremely flat surface so that there was a tight interface between segments during the brazing process. After lapping, the individual segments were subject to static-proof tests in which forces exceeding the range and magnitude of those experienced during launch were applied. Silicon Carbide, like most ceramics, is a hard material which is subject to fracturing due to microscopic flaws in the structure. The likelihood of fracturing is statistical in nature. The best way to ensure that the segments that are used in the construction of the flight model of the torus will not crack when in space is to verify their integrity by means of static-proof tests. Segments which passed these tests were validated for launch conditions and have been used to construct the torus.

Starting on 28 April 2009, the torus began to take shape as the individual elements were assembled together and precision-aligned using laser trackers and reference points on the torus segments. A special braze paste was applied to the interface points between each of the segments. When heated above 1000 degrees, this paste melts and seals the joints by capillary action: the torus then becomes one complete unit.

The completed torus was placed in the brazing furnace[2] at BOOSTEC on Wednesday 24 June 2009 and remained there until the morning of Monday 29 June 2009. After a cooling-down period, the torus was removed from the furnace and moved to the laboratories for post-brazing quality control (Figure 2). This included a thorough visual inspection of external and internal surfaces – the latter by means of borescopes – and ultrasonic inspection to confirm the integrity of the structure. On 20 July 2009, the torus was formally declared flight ready, marking a major milestone of the spacecraft development.

In August 2009, the torus was delivered to EADS Astrium SAS, the Gaia prime contractor, in Toulouse, France. At the time of writing, the assembly of the payload module, including the torus and mirrors, is being prepared. The first elements in line to be integrated are the folding optics structure (FOS) – supporting the M4/M'4 mirrors and the RVS optics module – and the bipod and release mechanisms (BRMs).

The oral presentation associated to this contribution was delivered on 29 June 2009, the day that the torus brazing cycle ended and the qualification model of the sunshield arrived at the ESTEC test centre. This proceedings contribution is heavily based on web articles which appeared on ESA's Science and Technology Gaia webpages. We gratefully acknowledge the contribution of Karen O'Flaherty and Guido Kosters of the Programme Management Support Office of the European Space Agency in the preparation of these web articles. High-quality versions of Figures 1 and 2, as well as other images, can be downloaded from http://sci.esa.int/gaia.

[2]The furnace at BOOSTEC was built for brazing the Herschel 3.5-metre-diameter primary mirror, and has also been used for the optical bench of the JWST NIRSPEC instrument.

CELESTIAL REFERENCE FRAMES IN THE GAIA ERA

Bourda, G.[2,1] and Charlot, P.[2]

Abstract. A working meeting about Gaia and celestial reference frames, funded by the French AS-Gaia, took place in Bordeaux in October 2008. Researchers from Paris, Nice and Bordeaux observatories met in order to lay the foundations of future studies and collaborations in this field. The fundamental celestial reference system is materialized by the International Celestial Reference Frame (ICRF), based on the VLBI (Very Long Baseline Interferometry) position of extragalactic radio sources with sub-milliarcsecond accuracy. On the basis of at least 10 000 Quasi Stellar Objects (QSOs), Gaia will permit to create its own celestial reference frame by 2015–2020, with an unprecedented positional accuracy (ranging from a few tens of microarcseconds (μas) at magnitude 15–18 to about 200 μas at magnitude 20). For consistency between optical and radio positions, it will be important in the future to align these two frames (the Gaia reference frame and the ICRF) with the highest accuracy. This alignment will be important not only for guaranteeing the proper transition if moving from the radio domain to the optical domain, but also for registering the radio and optical images of any celestial target with the highest accuracy. In this paper, we present the context and the goals of this meeting, review the work carried out in each of the three observatories, and present the outcome of the meeting as well as prospects for the future.

1 Introduction

The French "Action Spécifique Gaia" (AS-Gaia) allocated in 2008 a financial support for organizing a working meeting about the International Celestial Reference Frame (ICRF) and the future extragalactic celestial reference frame from Gaia, as proposed by Patrick Charlot. This workshop took place in Bordeaux Observatory, on 24 October 2008, with 13 participants from three different institutes in France: Laboratoire d'Astrophysique de Bordeaux (LAB – Bordeaux), Observatoire de la Côte d'Azur (OCA – Nice), and SYstèmes de Référence Temps-Espace (SYRTE – Paris). The goal of this meeting was to present the work carried out in each laboratory in the framework of the celestial reference frame for Gaia, in order to coordinate the activities at the national level and generate potential collaborations. Accordingly, several relevant scientific topics were examined in the light of the most recent studies (e.g. the celestial reference frame in the optical and radio domains, the astrometric observations of quasars, or the determination and simulation of catalogs of QSOs). In this paper, we report about this meeting and introduce briefly the research activities presented and discussions that took place during this workshop (for more details see http://www.obs.u-bordeaux1.fr/m2a/meeting/meeting_gaiasrqso).

2 Context

The ICRF is the realization at radio wavelengths of the International Celestial Reference System (ICRS; Arias et al. 1995), through Very Long Baseline Interferometry (VLBI) measurements of extragalactic radio source positions (Ma et al. 1998; Fey et al. 2004). During the International Astronomical Union (IAU) 27$^{\mathrm{th}}$ General Assembly at Rio de Janeiro (Brazil), in August 2009, the ICRF2 was adopted as the new fundamental celestial reference frame (see http://www.iers.org/documents/publications/tn/tn35/tn35.pdf). The ICRF2 currently consists of a catalog with the VLBI coordinates of 3414 extragalactic radio sources (from which 295 are defining sources), including the VLBA Calibrator Survey (VCS; see Petrov et al. 2008 and references therein), with sub-milliarcsecond accuracy. It has a noise floor of only 40 μas and an axis stability of 10 μas.

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The ESA space astrometric mission Gaia, to be launched beginning 2012, will survey all stars and QSOs brighter than the apparent optical magnitude 20 (Perryman et al. 2001). Optical positions with Gaia will be determined with an unprecedented accuracy, ranging from a few tens of μas at magnitude 15–18 to several hundreds of μas at magnitude 20 (Lindegren et al. 2008). Based on current estimates from local surveys, it is anticipated that 500 000 such QSOs should be detected. Of these, only the objects with the most accurate positions (e.g. with magnitude brighter than 18) will be used to define the frame. Simulations show that the residual spin of the Gaia frame could be determined to 0.5 μas/yr with a "clean sample" of about 10 000 sources (Mignard 2002). A preliminary Gaia catalog is expected to be available by 2015 with the final version released by 2020.

In the future, aligning the ICRF and the Gaia frame will be crucial for ensuring consistency between the measured radio and optical positions. This alignment, to be determined with the highest accuracy, requires several hundreds of common sources, with a uniform sky coverage and very accurate radio and optical positions. Obtaining such accurate positions implies that the link sources must have an apparent optical magnitude brighter than 18 (for the highest Gaia astrometric accuracy), and no extended VLBI structures (for the highest VLBI astrometric accuracy). This work is identified as the Gaia work package GWP-S-335-15000 "Alignment to ICRF source list" within the Gaia Data Processing and Analysis Consortium (DPAC).

3 Scientific domains involved

3.1 The celestial reference frame with Gaia

François Mignard (OCA) reviewed the process for determining the Gaia celestial reference frame, which eventually may be based on the optical positions of about 20 000 QSOs (if the criterion "magnitude brighter than 18" is kept). This frame will be at first entirely independent from the ICRF (i.e. with an arbitrary origin and rotating with respect to ICRF), and various steps will have to be completed in order to obtain a frame with no global rotation. The CU8 (Coordination Unit 8: "Catalogue Access") procedure to recognize quasar emission based on photometric information was presented. This will lead to the separation of QSOs from stars or galaxies within the Gaia data. Additional activities relevant to the determination of the Gaia frame will be necessary in the future and have already begun (e.g. simulation of catalogs of QSOs, construction of initial catalog of QSOs for Gaia, alignment with the ICRF). Furthermore, the various possible transverse motions the QSOs may suffer from have been identified (e.g. microlensing, matter ejection, superluminous motion, variable galactic aberration, macrolensing, accelerated motion in the local group), hence leading to an estimate of the accuracy that the Gaia frame should achieve of the order of 0.5–0.3 μas/yr for the residual spin, based on a sample of 50 000–20 000 QSOs.

Jean-Christophe Mauduit (OCA) presented the simulations carried out to create a realistic photometric and spectroscopic catalog of QSOs (i.e. good position distribution, fully representative of photometric and redshift distributions, and synthetic spectra) in the framework of CU2 (Coordination Unit 2: "Data Simulations"), on the basis of a complete Universe model and previous photometric investigations (Slezak & Mignard 2007). A primary spectro-photometric catalog considering the AGN variability has been completed, but discriminating between the various types of quasars (i.e. AGN, QSOs, Seyfert, BL Lac) from spectro-photometric information seems highly challenging for the future.

Jean Souchay (SYRTE) presented the Large Quasar Astrometric Catalog (LQAC; Souchay et al. 2008), which is a compiled catalog of QSOs based on the most reliable optical and radio information available in the literature (e.g. optimized positions, u b v g r i z photometry, redshift, flux densities in several radio bands, and absolute magnitude). This catalog is meant to improve over the catalog of Véron & Véron (2006), where several heterogeneities remain. It is also the basis for constructing the Initial Catalog of QSOs for Gaia (the Large Quasar Reference Frame, LQRF), which is a specific task Alexandre Andrei (Brazil – SYRTE) is responsible for within the DPAC of Gaia (CU3; Coordination Unit 3: "Core Processing"). This catalog should help classifying the Gaia data (Andrei et al. 2009).

3.2 Ground-based optical observations of QSOs, prior to the launch of Gaia

Sébastien Bouquillon (SYRTE–Paris Observatory) presented the current optical astrometric projects, relevant to the Gaia mission, for which observations are planned in the near future. Their purpose is to study: (1) the link between the variations of the magnitude and the photocentre of a quasar, (2) the relation between radio and optical positions of quasars, and (3) the influence of the host galaxy on the photocentre of a quasar. Apart from observing the WMAP satellite (which has similar characteristics as the future Gaia satellite) in preparation of the Gaia mission, thinking of supplementing the observations of Gaia, they plan to observe QSOs down to magnitude 25.

Patrick Charlot presented the optical observations carried out with the meridian instrument at Bordeaux Observatory, which contribute to studying the AGN short and long-term variability. About 50 objects are regularly monitored and for some of them the data base is more than 10 years long.

3.3 Aligning Gaia and VLBI celestial reference frames

François Mignard presented the theoretical basis to establish an accurate alignment within the next 10 years between the two extragalactic celestial reference frames, Gaia (optical) and ICRF (VLBI), in order to ensure continuity between these frames. To establish this alignment, one must define the pole and the origin of the Gaia frame, and then on the basis of a sample of common sources, the best fit between the two frames has to be determined by estimating three rotations. Typically, the accuracy of $\sim$80 μas could be achieved with $\sim$100 sources brighter than magnitude 20. A problem still remains unresolved with the optical-radio core shift (i.e. physically different optical and radio positions), which should induce an additional random noise. On one hand, one can think of solving this issue by averaging and finally removing this effect with the use of several link sources, but on the other hand, this information can be of high interest for astrophysical purposes. As mentioned by Patrick Charlot, a recent study by Kovalev et al. (2008) showed that on average the optical-radio core shift between VLBI and Gaia positions might be of the order of 100 μas (on the basis of a sample of 29 sources, from which they extracted the core-shift between S and X radio bands), which is not negligible at all regarding the anticipated accuracy of the Gaia and VLBI frames by 2015-2020.

Finally, it was shown that only 10% of the current ICRF sources (70 sources) are suitable for the alignment with the future Gaia frame (Bourda et al. 2008), which highlights the need to identify further link sources. We are now extending this study to the ICRF2, which also comprises the VCS surveys (as mentioned above). From the 2197 VCS sources within ICRF2, we found that 2108 have an identified optical counterpart, but only 208 sources are brighter than magnitude 18. We expect to identify another 50–100 sources suitable for the Gaia link. From these studies, it is already clear, however, that one will have to go to weaker flux level to come up ultimately with several hundreds of appropriate Gaia-ICRF link sources. This is the reason why we initiated a multi-step VLBI observational project to observe a sample of 447 sources selected from the NVSS catalog (NRAO VLA Sky Survey; Condon et al. 1998). This project, aimed at finding new VLBI sources suitable for the alignment with the future Gaia frame, will be carried out in three steps, in collaboration with the Max Planck Institute for Radio Astronomy (Bonn, Germany) and the Jodrell Bank Observatory (Manchester, UK). About 90% of the sources (398 sources) were detected in the initial step, conducted during two 48-hours experiments with the EVN (European VLBI Network) in June and October 2007, showing promising results for the future stages of this project (i.e. the mapping of the sources detected and the determination of the astrometric positions for the most point-like of these). The second stage of this project began in March 2008, with global VLBI observations (EVN+VLBA; Very Long Baseline Array) of 105 sources from those detected in step 1. About half of these were found to be point-like (Figure 1), hence indicating that they are suitable for the Gaia alignment. A proposal for observing the rest of the sources detected (293 sources) was submitted to complete the imaging of all the sample. Subsequent astrometric observations are expected to be completed within the next two years.

4 Conclusion

Several actions are conducted within the Gaia community in France in order to prepare for the determination of the Gaia frame as well as to align it with the ICRF or its successor by 2015–2020. The working meeting reported in this paper, financed by the French “Action Spécifique Gaia”, was found to be very fruitful, generating many discussions. It was suggested that another such meeting be organized again (in 2010 ?). The idea of an international meeting in the framework of the Gaia DPAC astrometric community (CU3/CU8) was also mentioned as a possibility.

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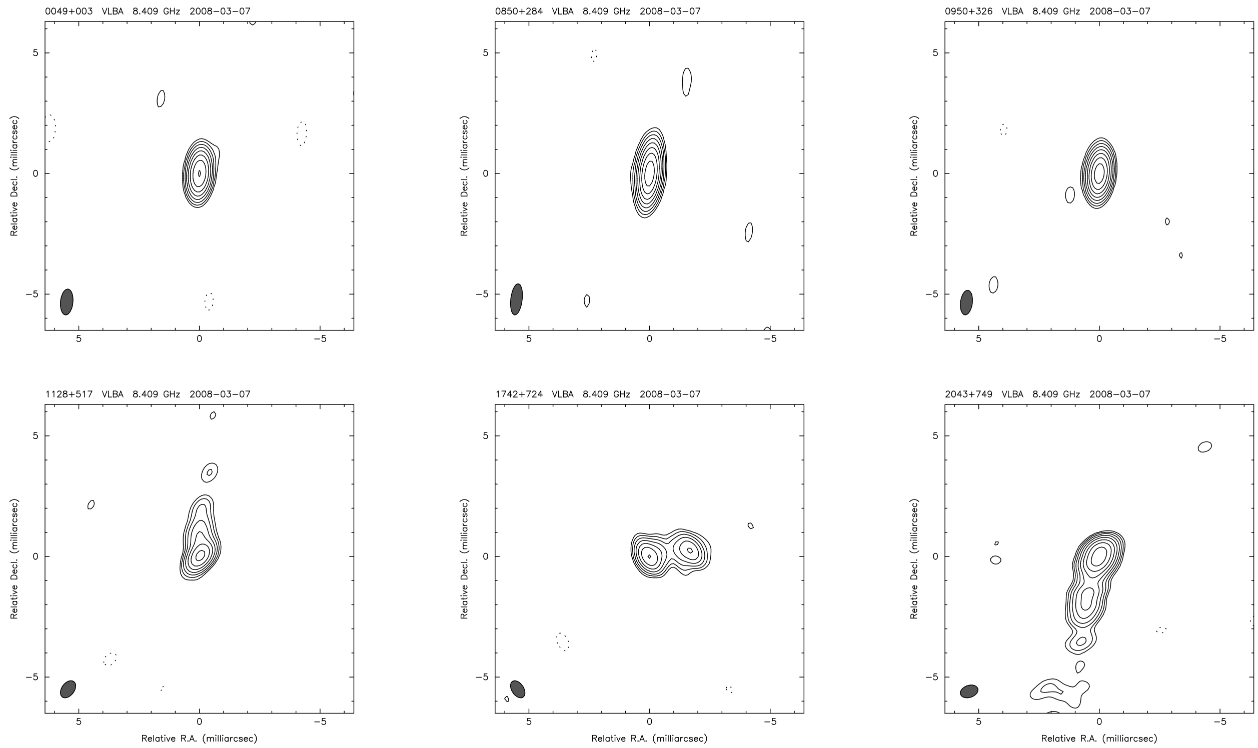

Fig. 1. Examples of VLBI maps (at X band), produced at Bordeaux Observatory, for sources observed during the first global experiment mentioned above (in March 2008). Upper panel: Sources suitable for the ICRF-Gaia alignment (i.e. point-like sources). Lower panel: Sources that are not suitable for the ICRF-Gaia alignment (i.e. sources with extended VLBI structures).

allowed us to organize this working meeting.

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GAIA AND THE GROUND-BASED OBSERVATIONS OF THE SOLAR SYSTEM OBJECTS

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Abstract. An important part of the Gaia mission is devoted to the study of Solar System Objects. In this domain, ground-based observations can be favorably combined with the space observations and in some cases they appear as a unique support for completing the Gaia data. We have organized a workshop in Beaulieu/mer near Nice in October 2008 with the goal to discuss this topic. 26 participants attended this workshop, coming from several observatories in different countries. They have underlined different aspects of the ground-based observations related to the expected Gaia Solar System science. These aspects includes the determination of asteroid mass, shape and density, the measurement of Yarkorvsky effect, the astrometric follow-up of new objects, the improvement of astrometric measurements of ancient observations of natural satellites and those of the stellar occultation predictions.

1 Introduction

Among a huge amount of astrophysical objects, the Solar System bodies will be observed by the Gaia space probe during its five years mission. In the DPAC structure (Data Processing and Analysis Consortium) which deals with the data processing of this mission, the Coordination Unit 4 (CU4)is partly dedicated to prepare the data processing related to these objects. Beyond this data processing, several teams are thinking about the scientific impact of the mission which will certainly lead to an important update of our knowledge of the Solar System itself. Mignard et al. (2007), for example, describes the expected applications of the Gaia mission to the asteroid science. Therefore Gaia has the potential of changing our view of the asteroid population in particular. Furthermore, due to the peculiar characteristics of those bodies, and to their physical description, ground-based observations will be a fundamental mean to reinforce the scientific progress by complementing the Gaia data (Hestroffer et al. 2008). This situation is very different from that found, for example, in stellar physics where ground-based observations will essentially be used for calibration. In the Solar System domain, in fact, we deal with a possible concrete increase in the Gaia scientific impact. This is essentially due to the following:

- the mission duration (5 years) that could prevent extracting from Gaia data alone all the subtle dynamical effects;
- the geometry of observation, that could prevent obtaining precise orbits for dynamically peculiar objects discovered by Gaia itself (Inner-Earth and Earth-Crosser Asteroids);
- the possibility of opening new paths for future techniques, thanks to the availability of Gaia ultra-precise measurements;
- the contribution of other available techniques, namely adaptive optics and photometry.

In particular, it has been shown that an extension of the observation period to more than five years through ground-based instruments could improve the sample of masses measured by mutual perturbations; similar predictions can be formulated for non-gravitational forces such as the Yarkovsky effect. Also, the unprecedented precision of orbits and star positions could vastly improve predictions of star occultations by asteroids. Adaptive

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Optics and photometry could also contribute with shape and size measurements, especially valuable for determining the density of some key targets. Furthermore, a ground-based network is being structured for follow-up observations of possible discoveries.

The preparation and the optimization of ground-based complementary observations requires a good understanding of the expected Gaia results, and an international coordination effort. Dedicated and/or automated instruments could also be conceived and used for the future.

These are the reasons why we convened the interested people to discuss this subject at the workshop "Earth-based support to Gaia Solar System Science" which has been held in Beaulieu-sur-mer (near Nice, South of France) on 2008, October 27 and 28. 26 participants attended this workshop, coming from several observatories in different countries and addressed several questions involving mainly the small Solar System bodies.

2 Asteroids

Gaia will observe more than 250 000 asteroids down to magnitude 20 with an incomparable precision (0.1 to 1 mas for each single measurement). Near-Earth Asteroids (NEAs), Trojans and Centaurs will be concerned by these observations. Several contributions to the workshop have stressed the interest to organize ground-based campaign for some selected asteroids in order to improve the scientific return of these observations.

For example, the determination of around 100 asteroid masses by Gaia will be possible by measuring the gravitational deflection during close encounters (Mouret et al. 2007). But at the edge of the mission period, arcs of trajectories will be incomplete. In these cases, ground-based observations will allow to extend our knowledge of the orbital arcs and to add around 25 masses. This requires to organize campaigns of astrometric observations of these specific asteroids before the launch and after the end of the mission. This will be a valuable improvement of our knowledge, since at the present time only a small number of masses are known (only 40 masses are known with uncertainties better than 60 percent).

But other questions have also been addressed. High angular observations from the ground will allow to get a better understanding of the photocenter-barycenter offset and will give a mean to improve the determination of several orbits. It will allow to calibrate the sizes (Carry 2009) and in some case to reach the bulk density of several objects. On the other hand, such observations and also radar astrometry measurements, could lead to an important improvement of our knowledge of the Yarkovsky effect (Delbó et al. 2008)which is a main factor of uncertainties for NEAs in particular. Thus, the determination of size, shape, orientation and thermal properties could allow us to add more than 60 Yarkovsky effect detections to the 30-50 which will be detected by Gaia (detections for asteroids (6489) Golevka and 1992 BF are the only two direct detections known at this date).

The photometric measurements of asteroids by Gaia will give sparse measurements due to the scanning law, they will lead nevertheless to data very useful for the inversion problem. In some ambiguous cases, ground-based photometric observations of selected asteroids will allow us to get complementary data and to reach better results to model their shape.

The combination of Gaia astrometric observations with ground-based ones have been studied. The case of the orbits of newly detected NEAs appears to be drastically improved in some cases, when a too small number of Gaia measurements can be combined with ground-based astrometric measures. Nevertheless, due to the location of the probe at the Lagrange point L2, a strong parallax effect will affect the celestial coordinates of objects close to the Earth. This will require an accurate process for their detection from the ground after the discovery by Gaia and for the combination of the data. These problems have been discussed.

The figure 1 shows a global view of the asteroid science based on the Gaia data. It gives the number of asteroids involved in each of the six main fields of research: orbit improvement, shape and orientation, taxonomy, detection of binaries, estimate of the size, estimate of the mass. For three groups among these fields it gives the number of asteroids for which the following goals can be reached: estimate of the dynamical properties and composition and rotation parameters, estimate of the rotation parameters, composition, mass and albedo, estimate of all these parameters and of the non gravitational effects. For the two last groups, ground-based additional observations will bring an improvement for almost 2000 asteroids.

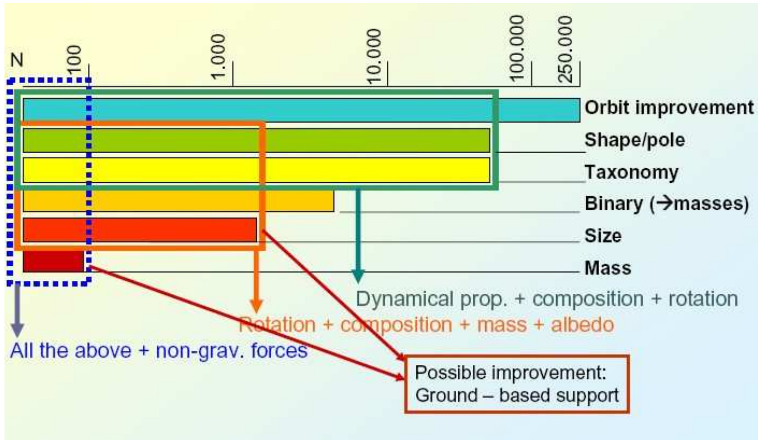

Fig. 1. A new global picture of the asteroids (courtesy P. Tanga)

3 Natural satellites

The Gaia astrometric measurements will be useful but not so efficient to improve the orbital models of the natural satellites. One main reason is that the duration of the mission is not long enough with respect to the periodic effects which have to be analyzed and which are generally much more long. The propagation of errors of the ephemerides of the main satellites of Saturn, in particular Mimas and Titan, has been studied (Desmars et al. 2009) by using the bootstrap method. One result is that in order to get a good accuracy of the models outside the period of observation, accurate observations on a short period is not necessarily better than average observations on a long timespan. The simulation of Gaia observations included in this analysis does not change significantly the global behavior.

In addition, ground-based observations remain necessary for the large satellites which will not be observed by Gaia. One major point is that a new reduction of many ancient astrometrical observations (photographic plates but also CCD frames) on the basis of the stellar astrometry using the Gaia catalogue will have an important impact on the dynamical models of the natural satellites, but also of the models of the planets (observed positions of its satellites lead to observed position of the planet itself). Therefore, the re-reduction using the Gaia catalog will be an important level to get accurate ephemerides useful for planetology, and for example for the detection of small secular effects induced by the tidal forces.

4 Comets

Gaia is not well suited for cometary science because of its limiting magnitude, of the lack of large field, of the slitless spectroscopy. Nevertheless around 50 cometary observations are awaited with the capacity to give access to astrometric measurements of the nucleus and to estimate the non gravitational forces. The modeling and simulation of the Gaia cometary observations are still in progress. Complementary observations from the ground could be interesting for a follow-up of possible cometary and unexpected activity of some Solar System bodies.

5 Stellar occultations

The observation of stellar occultations is a powerful method probing the Solar System Bodies and to estimate the size, the shape and the possible duplicity of the planetary objects. It allows also the probe of the atmosphere if any is present (see for example Widemann et al. 2009 or Sicardy 2006). Applying this method to investigate the transneptunian objects (TNO) is nowadays a big challenge, since the apparent diameters of the biggest ones (30 to 100 mas) is equivalent to the accuracy of the stellar catalogs (around 40 mas). Thus predictions are generally not accurate enough to ensure the success of these observations.

The Gaia stellar catalogue will then lead to a huge improvement of this kind of observations : predictions of the events will be more accurate, events by small objects will be more predictable (Tanga and Delbó 2007). One can foresee that in a few years of observations through a network, we could reach completeness of diameters measurements for asteroids down to 20 km .

6 Ground-based facilities

In some cases, complementary ground-based observations will required specific facilities. For example, transient events such as the detection of new fast moving objects by Gaia can be not reobserved by the probe due to the scanning law. The concerned objects (NEA, in particular Inner Earth Asteroid) may even be lost. A ground-based network of observing sites is then necessary and the setup of such a network is a task of the CU4 as well for observations on alert as for follow-up observations of specific objects.

In this context the robotic telescopes appear well adapted. A presentation of this facility, especially the TAROT system (Klotz 2008), has been presented at the workshop. The possibility to operate through a worldwide network of such telescopes (setted up with Tarot1 in France, Tarot2 in Chile, Zadko in Australia, Satino & Rosace in France) has been emphasized.

7 Conclusion

The Beaulieu workshop (Tanga 2008) was a nice opportunity to gather different teams interested by using the space data from Gaia and completing them with data from ground-based activities. Several physical and dynamical parameters of the Small solar System Bodies will be drastically improved. Asteroid astrometry will extend the number of the determined masses, will avoid the loss of some possible new objects, and help to get a better knowledge of some dynamical effects. Photometry will give help to determine the pole orientation. High Angular Resolution observations such as the adaptive optics, will give access to the bulk density of several asteroids, the mass of which will be estimated by Gaia. It will also permit the estimate of the Yarkovsky effect on several asteroids.

The observers that are running programs concerning physical properties of Minor Bodies have stressed the importance of having intermediate releases of Gaia astrometry. In particular, our knowledge of TNO possible atmospheres and asteroid sizes is strictly related to the capacity of providing predictions accurate enough for ensuring stellar occultation observations. The community has thus expressed a strong interest in the possibility of accessing intermediate releases (even degraded in quality or magnitude) of the Gaia star astrometry catalogue.

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THE DETERMINATION OF ASTEROID PHYSICAL PROPERTIES FROM GAIA OBSERVATIONS. GENERAL STRATEGY AND A FEW PROBLEMS

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Abstract. Gaia observations are expected to produce a real revolution in asteroid science. Apart from major improvements in the determination of orbital elements, Gaia data will make it possible to derive for large numbers of objects a determination of the most important physical properties, including mass, size, average density, rotational period, spin axis direction, overall shape, and geometric albedo. Here, we focus mainly on the determination of sizes, rotational properties and shapes, and show some of the main problems that are encountered in the data analysis procedures.

1 Introduction

In spite of the tremendous progress that has been made in recent years in the field of the determination of physical properties of the minor bodies of our Solar System, our knowledge of these bodies is still not satisfactory due to the difficulty in getting detailed physical information about them, due to their intrinsic faintness, and also due to the fact that both asteroids and comets are extremely heterogeneous, and include bodies characterized by great diversity in many respects. Fundamental physical parameters including masses and sizes are mostly unknown for the vast majority of the objects, since they are extremely difficult or impossible to obtain by means of remote observations. For instance, only for a handful of objects which are either among the biggest members of the asteroid population, or have been visited *in situ* by space probes, we have reasonable measurements of the mass. As a consequence, also the average density is largely unknown for the vast majority of the population. What is done usually is only some tentative estimate based on extrapolations of the values found for a handful of objects observed *in situ* by space probes. Since the asteroid population exhibits a heterogeneity of spectral reflectance properties, likely related to differences in overall composition and thermal histories, such extrapolations are mostly tentative and quite uncertain in most cases. Needless to say, it is very frustrating to carry out astrophysical studies of objects for which even the average density is essentially not known. Unfortunately, even in this new era of development of increasingly large telescopes and increasingly sensitive detectors at different wavelengths, it is very difficult to expect that ground-based remote observations can produce in the near future a big wealth of new accurate measurements of the fundamental physical parameters of a large sample of asteroids and comets. In this respect, this branch of Planetary Sciences is still waiting for a revolution.

In this paper, we show that the forthcoming Gaia mission can be this much expected revolution, especially for what concerns the studies of the physical properties of the asteroids. This is a consequence of the fact that Gaia will be in many respects a major step forward in the history of the tools available for remote observations of bodies as the asteroids. Due to its unprecedented performances in terms of astrometric accuracy, Gaia will produce a huge improvement in the determination of the orbits of the minor bodies, eventually leading to the measurement of the mass for a significant number of large asteroids, and to the direct measurement of non-gravitational effects affecting the orbital motion of several small near-Earth objects. Moreover, the direct measurement of the size for a big sample of main-belt objects is also expected to be possible. Combined estimates of mass and size will lead to reliable estimates of the average density for a sizeable sample of objects belonging to different taxonomic classes. In addition, the excellent photometric and spectroscopic performances of Gaia

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are expected to produce a wealth of data including the determination of the rotational properties, the overall shapes (useful to improve the reliability of density estimates), the reflectance spectra at visible wavelengths and a taxonomic classification for a significant sample of the asteroid population.

In the following sections we present more in detail some of the results we expect to obtain from Gaia observations of asteroids, and we point out some technical problems that are relevant for a thorough exploitation of the future Gaia data.

2 Asteroid signals in the GAIA astrometric field

In this Section, we assume that the reader is familiar with the overall design of the Gaia scientific payload, in particular the optical design, the scanning law of the satellite, the design of the CCD matrix in the focal plane, and the TDI (transfer delay integration) mode of data acquisition. This general information is given in several papers, including Mignard et al. 2007.

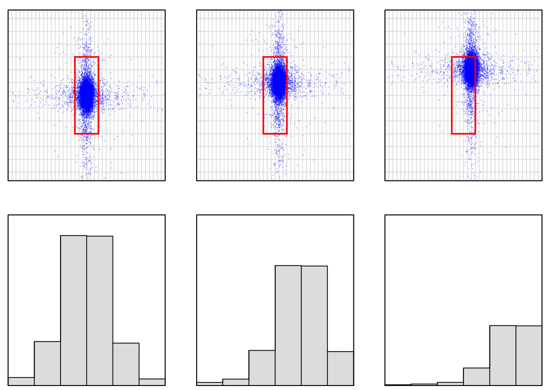

Fig. 1. Signal collected in the observing window of three consecutive CCDs in the astrometric field of view, for an asteroid moving 15 mas/sec in the along-scan direction, and 45 mas/sec in the across-scan direction. The corresponding recorded signals are shown at the bottom.

Figure 1 shows the simulated signal of an asteroid moving across the field of view of Gaia, as it transits in the observing window in different CCDs. The Figure summarizes some important problems related to the observation of moving objects. In particular, the collected photons tend to shift outside the observing window during a single transit in the Gaia field of view, and the corresponding signal recorded by different CCDs progressively changes as the object tends to exit the window. Since the position and size of the observing window in each different CCD in the focal plane is fixed at the beginning of the object's transit, a moving object tends to move progressively off-center in the observing windows of adjacent CCDs, and may in principle even exit the window if the apparent motion is sufficiently fast. Note that the recorded signal is the sum of all the photoelectrons integrated over each column of the observing window. In Figure 1 an observing window consisting of 6 columns is shown as an example. This corresponds to the most general case, wider windows being automatically selected on the basis of increasing apparent brightness of the source when it is first detected at the beginning of its transit across the Gaia field of view. The analysis of the signal is carried out by the routines of CCD processing, which are based on a standard signal model, solving simultaneously for the apparent angular size of the asteroid, and for its apparent motion, generally only in the along-scan direction.

The signal of an asteroid is fit by a model which takes into account the object's motion and apparent angular size. In particular, at a preliminary stage, the signal is fit to a very simple and not very realistic model of a spherical object seen at zero phase angle, i.e., at perfect sun opposition. In a second step, when the result of the inversion of disk-integrated photometry is available (see below), a more realistic model of a triaxial ellipsoid object with semi-axes $a > b > c$, seen at the correct phase angle is applied. If the number of collected photo-electrons is sufficiently large, i.e., when the object is sufficiently bright, and at the same time the angular size of the object is not negligible, it is possible to solve for the largest semi-axis of the triaxial ellipsoid shape (the b/a and c/a axial ratios being already known from photometric inversion). The measurement of the size gives reliable results whenever favorable conditions are met in terms of the apparent angular size of the object, and its apparent brightness. For a given object, these conditions can be met or not in different transits, depending on its absolute size and on the observing circumstances. In cases in which it turns out that the signal analysis can produce an estimate of the size with an uncertainty better than 10%, we speak of an actual size measurement. Based on an extensive simulations of five years of Gaia observations, Figure 2 shows, as a function of the diameter in km, how many times the size of different asteroids will be measured with an accuracy better than 10%. As it can be seen, the results are very encouraging, and show that direct measurements of the sizes of asteroids will be possible for all objects down to sizes a little above 20 km. This corresponds to a number of objects of the order of $1,000$ for which Gaia is expected to provide direct size measurements, a very impressive result.

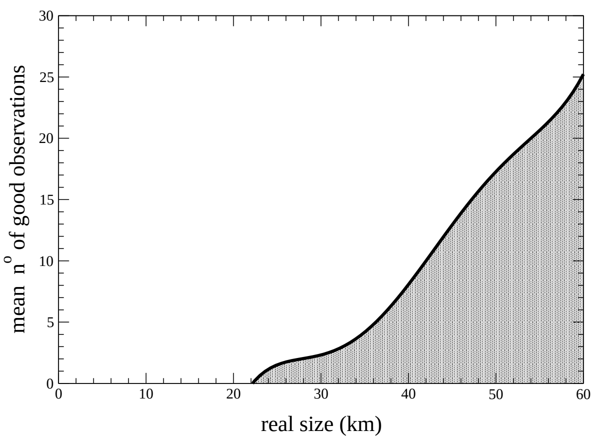

Fig. 2. Number of "good observations", namely transits for which the size can be measured with an accuracy better than 10%, for objects of different sizes. Based on an overall simulation of the Gaia detections of known main belt asteroids.

When the apparent angular size of an object will be measurable, the signal being different with respect to that of a point-like source, another very important parameter will be derived, mainly the amount of the difference between the apparent position of the photocenter of the signal, and that of the sky-projected barycenter of the object, taking into account its apparent projected shape and defect of illumination. The amount of this so-called "photocenter shift" will be important, since it will be used to correct the astrometric measurement of the object resulting from the photocenter position. When applicable, this correction will be used to improve the accuracy of the astrometric measurement, and will lead to a more accurate computation of the object's orbit.

3 Masses, densities and Yarkovsky effect

Every main-belt asteroid will be observed on the average about 70 times during the five-years operational lifetime of Gaia. While the usual astrometric accuracy of ground-based asteroid observations ranges between 0.05 and 1.0 arcsec, the astrometric accuracy of Gaia measurements for each single transit will range between 0.1 and 1.0 milli-arcsec (mas). As a consequence, the uncertainties in the orbital elements of the asteroids observed by Gaia will decrease by a factor of about 100. This will make it possible to measure tiny dynamical effects that are usually beyond the limit of ground-based observations. In particular, the deflections experienced by small asteroids when having close encounters with the largest objects in the main belt will be measurable, leading to the derivation of the masses of the perturbers. According to simulations, in this way the masses of about 100 among the largest asteroids will be measured. The accuracy of each single mass measurement is expected to be of the order of 10^{-12} solar masses, but combining different mass measurements for a single asteroid, corresponding to close approaches with different smaller objects, the accuracy should sensibly improve, possibly reaching values of the order of 10^{-14} solar masses. In the case of (1) Ceres, this would correspond to an accuracy of 0.01% in the mass determination, a very impressive result.

Having at disposal masses, sizes and overall shapes for about 100 asteroids, the average densities of these objects will be also determined with good accuracy. This will be another tremendous improvement in our knowledge of the physical properties of asteroids, taking also into account that among these 100 objects there will be asteroids belonging to a wide variety of taxonomic classes. For the first time, we will have the possibility to assess whether different taxonomic classes correspond also on the average to different densities, determined by differences in overall composition and/or internal macro-porosity.

Another consequence of the excellent astrometric accuracy of Gaia measurements will be the direct measurement of the effect of non-gravitational mechanisms on the orbital motion of small asteroids. In particular, the Yarkovsky effect is known to produce a small, steady drift in semi-major axis of small asteroids. This will produce a measurable effect on the recorded positions in some cases. According to simulations by Delbò et al. 2008, a measurement of the Yarkovsky drift should be possible for a number of about 35 near-Earth asteroids that will be observed by Gaia. Since the Yarkovsky effect depends on many physical parameters of an object, including size, spin axis orientation, rotation period and thermal inertia, the direct measurement of the effect for these objects will be a very important achievement for the physical studies of the asteroid population.

4 Spin, shape, taxonomy

Gaia will have remarkable photometric and spectrophotometric capabilities. For thousands of asteroids, disk-integrated photometric data, corresponding to different transits in the Gaia field of view, will be recorded. For each object, this will be a series of photometric snapshots taken over a five-years time span. As explained by Cellino et al. (2007, 2009) these data will be used to obtain information on the rotational properties of the objects (spin period, spin axis direction) and on their overall shapes. As explained in the above papers, the procedure developed to perform the photometric inversion of Gaia data is based on a genetic algorithm, and will use a simple triaxial ellipsoid model to fit asteroid shapes. According to the tests carried out so far, the spin properties are expected to be derived with good accuracy, of the order of fractions of a second for the rotation period, and a few degrees in the coordinates of the spin pole. As for the shapes, the results should be more qualitative, due to the simple shape model adopted to minimize CPU time. The number of objects for which we can expect to derive an accurate photometric inversion should be of the order of $10,000$. This will be another major result of Gaia, and will make it possible to carry out studies of the distributions of spin properties among dynamical family members, with important consequences on our overall understanding of asteroid collisional evolution. The determination of overall shapes will also be very useful to improve the accuracy of volume computations, needed to compute average estimates of density for the largest asteroid in the main belt (see previous Section).

Spectrophotometric data will range between 0.33 and about 1 μm, and will be used to derive a new taxonomic classification based on Gaia data. The sample should include several tens of thousands objects. Interestingly, the blue region of the visible spectrum, that has been largely lost in recent taxonomic classifications, will be included in Gaia data. This will be very important to identify distinct sub-classes of objects having a generally primitive composition, including the very interesting F class. Objects of this class have been found to be interesting in many respects, and might share asteroidal and cometary properties (Cellino et al., 2001). In addition to being *per se* an important resource, the taxonomy obtained by Gaia will be also an excellent tool to discriminate among membership of asteroids to mutually overlapping dynamical families.

A.C. gave a presentation on this subject at the SF2A 2009 conference in Besançon, while being Invited Researcher at the IMCCE in Paris (June - July 2009). This article summarizes the results obtained by an international team of scientists working in the Coordination Unit 4 of the Data Processing and Analysis Consortium (DPAC) of Gaia. We thank in particular F. Mignard, K. Muinonen, T. Pauwels, J. Berthier, W. Thuillot, J.-M. Petit, M. Delbò, S. Mouret, Ph. Bendjoya.

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GAIA CATALOGUE AND ARCHIVE, PLANS AND STATUS

O'Mullane, W.[1]

Abstract. The Gaia Data Processing and Analysis Consortium (DPAC) has been, and continues to, work on the software for processing the Gaia data. The result will be an unprecedented celestial catalogue of about one thousand million objects with astrometric accuracies far exceeding anything currently available. But little has been heard about the catalogue itself, its availability, content etc. Some work has been done in this area and the status is explained in this short article.

1 Introduction

The Gaia Satellite and its capabilities are covered by de Bruijne (2009). ESA will build, under contract to EADS Astrium, the satellite and launch it from French Guiana aboard a Soyuz in 2012. The Data processing is a community task and the DPAC was officially put in place in 2006 to perform this task. Currently over 300 DPAC members (a DPAC member must work a minimum of 10% on Gaia) are working on the data processing systems. There is also some ESA involvement in DPAC with ESAC contributing to many tasks an leading some. In particular CU1 concerning the overall architecture of the system is led and heavily supported by ESAC. There will also be ESAC involvement in the archive.

When DPAC was made official via an Announcement of Opportunity from ESA in 2006 the catalogue/archive was explicitly excluded. DPAC as agreed in 2006 consists of nine coordination units, the ninth of which was to deal with the archive and to be activated at a later stage. This may entail a further announcement of opportunity but it is a matter for the DPAC Executive and Gaia Science Teams to agree with the Project Scientist.

Hence what we are really discussing here is Coordination Unit 9 (CU9). A first set of requirements (O'Mullane 2009) regarding the Archive has been agreed with DPACE and GST and are discussed below. Some tentative agreements on data releases are included in the document and will be outlined below.

2 Architecture of the archive

Within the DPAC architecture the Gaia Main Database (MDB) will contain all processed data from the satellite. This will be versioned at regular intervals and is the logical starting point for creating the Gaia catalogue as depicted in Figure 1. The catalogue is not however a simple copy of the MDB, it must be more refined and must present a single coherent dataset to the community (no longer divided by coordination unit). Furthermore the MDB is not designed for the type of arbitrary querying or data mining which will be required of the archive.

Figure 1 also shows multiple archives, ESA must have a copy of the archive as ESAC has been designated repository of all space science data for the agency. This does not preclude other copies for institutes who seriously want a copy. The system should be fairly portable.

In general CU9 will be an integral part of DPAC - it could function in no other way. Indeed, as for CU1, some CU9 members will have to come from the existing CUs, of course in many cases this will mean finding additional effort within the CU. For the purposes of discussion the archive is seen as comprising several components as depicted in Figure 2. Some of these are discussed further below. The components are :

- **Ingestor (ING)** to populate the archive.

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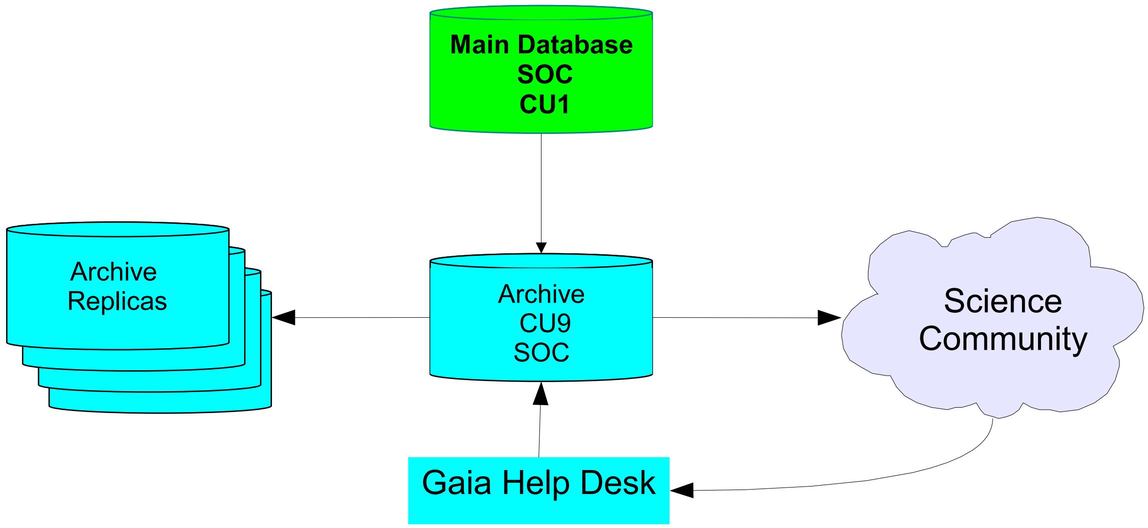

Fig. 1. Context of the Gaia archive. Derived from the Main Database the archive provides an interface to the general community. The possibility for multiple archive copies is also considered.

- **Storage System** Physical disk, machines and DBMS.
- **Interrogation System (ITG)** to effectively query the archive.
- **Advanced Applications (ADV)** for value added access.
- **Documentation (DOC)** to allow users understand the archive.
- **Science Alerts (SAA)** Anomaly based Science Alerting.
- **Public Outreach (PBO)** to engage general public.
- **Help desk (HLP)** to answer users' questions.
- **Community Interface (CIF)** to provide a consolidated portal.

2.1 Community Interface

The general idea is that the archive should have a public oriented feel - no special "professional" site should exist. Rather all come to the same starting point but the professional obviously will dig deeper to a more extensive set of tools and information. Some form of no-login access should be provided with advanced features available with fairly easy self-registration. Many tools should be included in the archive for example; some sort of sky browser - perhaps a customisation of the SDSS Sky Browser (Szalay 2002) or Google Sky. Availability, of at least higher level information, in multiple language of course goes without saying.

2.2 Documentation

Documenting the catalogue will be CU9's most important task. Again much information exists in the document repository of DPAC and the MDB Dictionary Tool but it will need to be made presentable to a general audience and brought up to date. Knowledge of the algorithms will need to be extracted from the various CUs. There should be extensive pre-calculated statistics e.g. source and observation maps, histograms of sources per magnitude bin, spectral type, etc . Additionally some informational plots should be provided e.g. Hertzsprung-Russell diagrams, Hess diagrams, galactic-kinematics diagrams etc. A project history should be provided.

Although undoubtedly too large to print in its entirety some printed volume or volumes would be interesting. Perhaps the source catalogue, without transits and spectra, could be provided on some form of media.

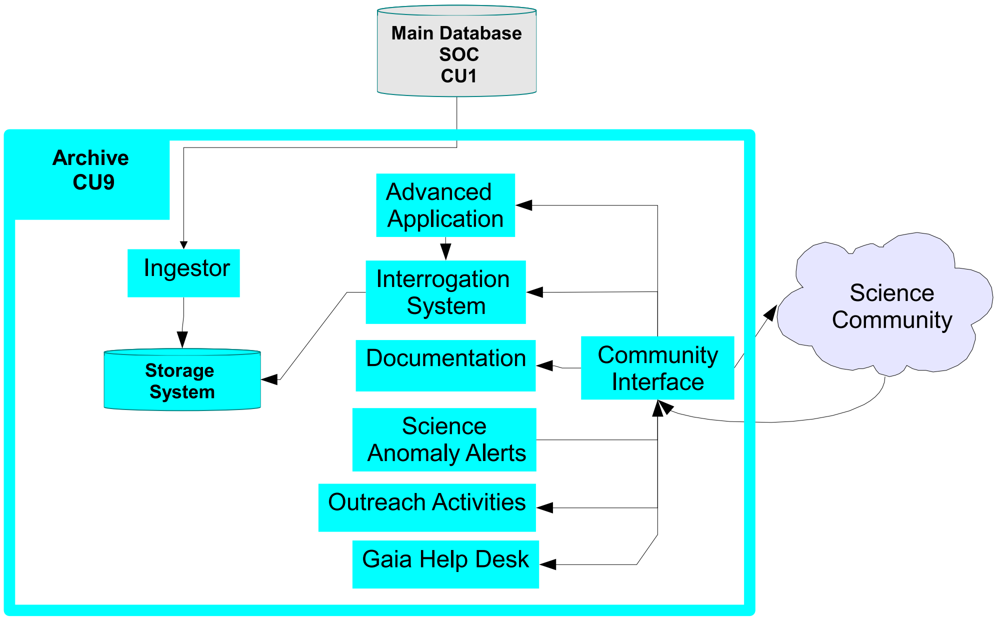

Fig. 2. Gaia archive components. This decomposition was done only to facilitate thinking about the archive, it does not mean CU9 will end up with this exact set of components.

2.3 *Interrogator*

There will be both graphical and programmatic interfaces to the archive. Virtual observatory protocols such as TAP and SIAP shall be implemented. Users will have access to a SQL equivalent and/or ADQL. All of these interfaces require a fast engine to answer queries. Simply putting the data in a Database will not work - it will need to be tuned and will need to make use of spatial indexing techniques such as HTM and HEALPix (O'Mullane 2001). Whatever it is, it needs to be fast !

2.4 *Science Alerts*

From early in the mission, flux based alerts will come from CU5 - these should be VOEvent based. Additionally CU4 are in direct contact with IMCCE to provide NEO orbits as they become available. The archive should contain at least a record of the alerts and possibly a publishing mechanism for alerts coming from other CUs. Currently DPAC is concentrating on data processing - possibly other alerts will arise later. In any case first results coming from Gaia should be available not too long after the nominal mission starts.

3 Schedule

A definitive release schedule has not yet been finalised between GST, DPACE and ESA and depends very much on the data quality from the satellite and the processing systems. The intention is certainly not to wait until 2020 and the *final* catalogue before getting data to the community. It should be possible to provide some form of astrometry and possibly photometry about two years in to the mission. This could be followed in the fifth year by an update, with the final release after eight years as planned. Only the final date is definitive of course but there is agreement to do several other intermediate releases, the Science Management Plan (Gaia Project Scientist 2006) calls for at least one intermediate catalogue release.

Mignard also considers a special release after possibly six months of nominal mission. With the first full sky from Gaia it would be possible to pick out the hundred thousand Hipparcos stars and provide new proper motions for them spanning 21 years and with accuracies of 50 to 100 $\mu as/year$. This is generally seen as desirable.

Technically it is not feasible to have a data release until about eighteen months of nominal mission data have been collected. Allowing for processing time it would be about two years of nominal mission before a reasonable release could be made. One must remember that most of Gaia's calibration involves the data taken by Gaia itself during the mission. Hence CU9 could start after launch which would reduce risk for CU9 of launch delays. It is acknowledged that some work does need to start before that time. GST and DPACE are considering how best to achieve this, (O'Mullane 2009) is a start.

4 Open Areas

There are several open areas which require far more investigation in CU9. The final archive is so far in the future that we should not be bound by our current thinking as to what constitutes an archive.

Brown suggests an attempt at a *living archive* in which new ground based observations could be coupled with Gaia data to improve the source catalogue. This, for example, would allow improved solutions for binaries. The question of allowing additions to the released catalogue is quite tricky, there are issues of quality, security and maintenance. But since a complete printed catalogue is impossible why not a completely new type of archive?

Modelling is also very popular and sophisticated these days. Binney asks how we will be able to compare a model to the Gaia catalogue. Should such a facility be provided ? How would it work? Hogg (Hogg 2008) goes further and suggests archives should be encoded in a model to answer other questions, not just to compare models.

Although virtual observatory protocols will be implemented and the VO provides dynamic cross matching it is felt that perhaps a few major catalogues should be matched. The VO can do no more than give the lowest common denominator - a focused match could provide better results. It may merit including some match tables in the archive.

Szalay has said for many years that with the new surveys we need to bring the processing to the data not the data to the processing. Virtualisation could be an excellent way to do this - one could make a range of virtual machines available *in the archive* for users to install and run their programs on. Then just let them download the result. The local storage provided by CasJobs and VO Space partially does this but the complexity of code which can be sent is limited i.e. for CasJobs one can only send SQL programs. Virtualisation with appropriate access libraries would allow almost any code to be run. This may be the only way to bring fully general models to the data. This obviously has very serious security implications.

5 Conclusion

Coordination Unit 9 (CU9) will be tasked with setting up the Gaia archive. Since most data will not be suitable for public consumption before about two years into the mission, CU9 could start in earnest after launch. Initial ground work would need to be laid in the coming years however. The Gaia archive will be an excellent resource challenging us to rethink our concept of an archive. With Science alerts indeed the first Gaia data will be available before any catalogue is released.

The Gaia Data Processing Consortium Executive and the Science Team Members have provided valuable insights in the production of (O'Mullane 2009) upon which this short article is based.

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A SELECTION OF SB WHICH COULD GET ACCURATE MASSES FROM GAIA ASTROMETRY

Halbwachs, J.-L.[1] and Arenou, F.[2]

Abstract. Gaia will provide astrometric measurements accurate enough for deriving the masses of spectroscopic binary (SB) components with uncertainties around 1 %. A list of a bit less than 100 SB is set up for that purpose. However, the spectroscopic elements of these systems need to be derived again from accurate radial velocity measurements in order to achieve a 1 % accuracy on the masses.

1 Introduction

Several progresses in our knowledge of double stars are expected from the forthcoming Gaia mission. The statistical properties of binaries, which are clues for the understanding of their formation process, will be derived from samples larger from the present ones by several orders of magnitude (Halbwachs et al. 2003a). Ten years ago, Halbwachs & Arenou (1999) pointed out that the astrometric Gaia measurements could lead to the masses of a lot of components of double-lined spectroscopic binaries (SB2). The elements of the SB2 orbit lead to the products $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$, where $\mathcal{M}$ refers to component masses and i to the inclination of the orbital plane. Up to the present time, accurate stellar masses have been obtained from SB2 which are also eclipsing binaries. The inclinations of these systems are then derived from the analysis of the light curve. This method is quite reliable, but it may be applied only to few SB2, since it requires inclinations very close to $\pi/2$. Moreover, eclipsing binaries have usually short periods and close components, and are therefore not representative of single stars since they often suffer from mass exchange between the components. At the opposite, an astrometric orbit is easier to derive when the period is close to the time span of the observations (5 years with Gaia) than when the components are close. For these reasons, masses derived from SB orbits and inclinations coming from the astrometric observations of the forthcoming Gaia satellite would be quite relevant, if their uncertainties would be sufficiently small. In practice, it is considered that errors around 1 % or less are required for improving the models of stellar physics.

2 A method for selecting SB that could provide accurate masses

Let us consider a binary for which we have a list of radial velocity (RV) measurements and a list of astrometric measurements. In practice, the most efficient method for deriving the orbital elements of such system consists in using together the measurements of all kinds in a sole computation. However, our purpose hereafter is to select known SB for which Gaia could provide an important missing information, that is the sinus of the inclination. The SB elements of these binaries were usually obtained from RV measurements with moderate uncertainties, i.e. a few hundreds of m/s, or even around 1 km/s. Therefore, we have estimations of $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ which are not very accurate, but may be greatly improved by measuring again the RV of these stars with a CCD-spectrovelocimeter. The RV errors are then around 1 m/s for stars with small RV amplitudes, and it should be a few tens of m/s for a typical SB. For selecting the SB which could receive accurate masses, it is assumed hereafter that the spectroscopic elements of the binaries may be derived with negligible errors. Then, the elements period P, eccentricity e, periastron epoch T_0, periastron argument ω, and projected semi-major axis of the photocenter $a_0 \sin i$ are fixed in the derivation of the astrometric orbit, and the errors of the

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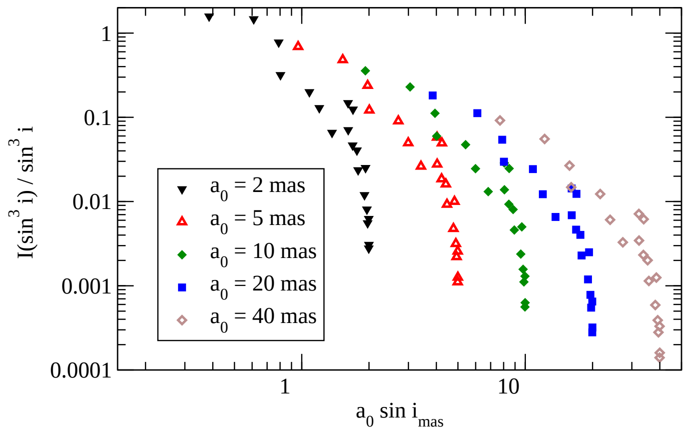

Fig. 1. Uncertainties of $sin^3 i$ derived from Gaia astrometric observations for simulated SB with various semi-major axes.

masses will come only from the errors of the astrometric measurements. The selection problem consists then in evaluating the uncertainty of $\sin^3 i$ (i.e., of i) that may be expected on the basis of the SB elements. It is not difficult to calculate $a_0 \sin i$ from the elements of the SB orbit and from the distance of the system, assuming a mass-luminosity relation: For the wavelengths used by Gaia astrometry, the difference of magnitudes between main sequence components is simply $\Delta G = -7.3 \log q$, where q is the mass ratio.

It comes from simulations that, for periods shorter than 5 years, Gaia could provide inclinations with uncertainties $I(i)$ which roughly obey the equation:

$$I(i) = \frac{3}{a_0 \sin i} \tag{2.1}$$

where $a_0 \sin i$ is in mas and $I(i)$ is in degrees. This relation is only approximate (by a factor of about 2), since the actual error will depend on parameters like the eccentricity of the orbit and the position angle of the periastron, and on the observation epochs. A consequence of Eq. 2.1 is that the relative error of $\sin^3 i$ is then related to both $a_0 \sin i$ and $\sin^3 i$, since it is:

$$\frac{I(\sin^3 i)}{\sin^3 i} = 3\, \frac{I(i)}{\tan i} \times \frac{\pi}{180} \tag{2.2}$$

Therefore, it is impossible to predict the uncertainties of the masses which may be obtained from Gaia astrometric measurements for a given SB2. This is illustrated by Fig. 1, where the relative errors of $\sin^3 i$ are plotted as a function of $a_0 \sin i$ for a few simulated SB2 with different a_0. It appears that the relative error of $\sin^3 i$ is dramatically rising when the inclination decreases.

In a rough approximation, it comes from Eq. 2.1 and 2.2 that we will get masses with errors smaller than 1 % when the actual inclinations are larger than the limit:

$$i_{min} = \arctan \frac{5\pi}{a_0 \sin i} \tag{2.3}$$

where $a_0 \sin i$ is again in mas. As a consequence, it is only possible to derive a probability to obtain masses with an error better than 1 %, assuming a statistical distribution for the inclinations. Since it is reasonable to assume that the orientations of the orbits with respect to the plane of the sky are isotropic, we assume hereafter that the distribution of i is $f(i) = \sin i$. This relation applies to all binaries in space, and we assume it hereafter for any known SB, except for those for which the inclinations are already known thanks to Hipparcos astrometry.

It is worth noticing that a priori estimations of the inclinations could be obtained from $\mathcal{M}_1 sin^3 i$ by evaluating the masses of the primary components from their spectral types. However, this method would be hazardous, since it would introduce a bias in favour of the systems with primaries less massive than expected from the mass – spectral type relation. It is safer to discard it for that reason.

3 A list of stars which could get masses with a 1 %–accuracy

Our purpose is to search masses better than 1 %. Since it is not possible to compute a priori the expected accuracy of a component mass, we select the SB for which the probability to get such accurate masses is larger than 50 %. We consider SB2, but also SB1 when the minimum mass ratio is larger than 0.3. The secondary spectra could then be visible on high-resolution CCD observations.

In order to obtain accurate RV measurements, only the stars brighter than 12.5 mag and with declinations above -5 degrees are considered hereafter; moreover, the stars brighter than 6 mag are discarded from the selection, since they will not receive accurate astrometric measurements from Gaia. Three lists of known SB were thus prepared:

1. The nearby G-K dwarf binaries with astrometric orbits derived from Hipparcos (Halbwachs et al. 2003b). This list contains 25 SB with inclination errors less than 15 degrees. The mass ratios of these systems are coming from SB2 orbits or from the astrometric solution.

2. The SB9 catalogue (Pourbaix et al. 2009). This up-to date catalogue contains 776 SB with F to M spectral types and periods between 30 days and 10 years.

3. A list of SB members of common proper motion (CPM) systems (Halbwachs, Mayor & Udry, 2007). This list contains 34 SB with unpublished orbits and periods longer than 30 days.

The distances of the stars were derived from various methods. The trigonometric parallaxes were used when their uncertainties are better than 20 %. Otherwise, a spectroscopic parallax was derived. When the luminosity class of the star was not known, it was inferred from the reduced proper motion, $H = V + 5 \log \mu + 5$, where μ is the proper motion in arcsec. When $H > 0$, the star was assumed to be a dwarf, otherwise it is a giant. For the stars of the SB9 list, the spectroscopic parallaxes were corrected for extinction, using the coordinates of the stars and a galactic extinction model (Arenou et al., 1992).

For each SB, thousands of simulated binaries were generated, assuming known the actual elements and generating the unknown parameters like i and Ω, the position angle of the periastron. For each virtual binary, Gaia astrometric measurements were produced with a simple model (Halbwachs 2009), and the inclination of the orbit was derived from these observations, assuming the elements of the SB orbit. The proportion of virtual systems with inclination errors better than 1 % was thus obtained. The SB was selected when this rate was larger than 50 %. At the end, 96 SB were retained: 10 nearby G-K dwarfs with Hipparcos astrometric orbits, 78 SB9 stars, and 8 CPM stars. The faintest is a 10.17 mag star. Seven stars are earlier than F5 and 2 are of M-type, but the vast majority are G-K stars.

4 On the accuracy of $\mathcal{M} \sin^3 i$

We have selected SB for which $\sin^3 i$ may be found at the 1 % level of accuracy, assuming that the SB orbital elements are perfectly known. In this section, we want to be sure that $\mathcal{M} \sin^3 i$ may be accurately derived with a few high-precision RV measurements. For that purpose, RV measurements were generated with the following hypotheses: (a) The observation epochs obey a Poisson distribution, with an average number of 14 RV measurements within 7 years, starting from 2011; (b) the standard error of the epoch measurements is 50 m/s. Again, thousands of virtual SB were generated for each of the 96 SB of the list, and the standard deviation of the errors of $\mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ are computed. Figure 2 shows the selected SB plotted in a eccentricity vs relative error of $\mathcal{M}_1 sin^3 i$ diagram. About 50 SB in our selection should get $\mathcal{M}_1 \sin^3 i$ with errors less than 1 %. This is rather encouraging, since, for simplicity, the measurements already available were not taken into account in the computations above. In reality, they will be considered and the periods of the binaries – and therefore the $\mathcal{M} \sin^3 i$ terms – will be much more accurate than in the simulations. This concerns especially the periods larger than 7 years, and which were not covered with the simulated RV. Moreover, it is visible on Fig. 2 that the accuracy of $\mathcal{M}_1 sin^3 i$ is falling when the eccentricity increases, especially when it is larger than 0.6. Again, the accuracy should be much better in reality, if the observation epochs are not taken at random but chosen in order to observe near the periastron, each time this would be feasible.

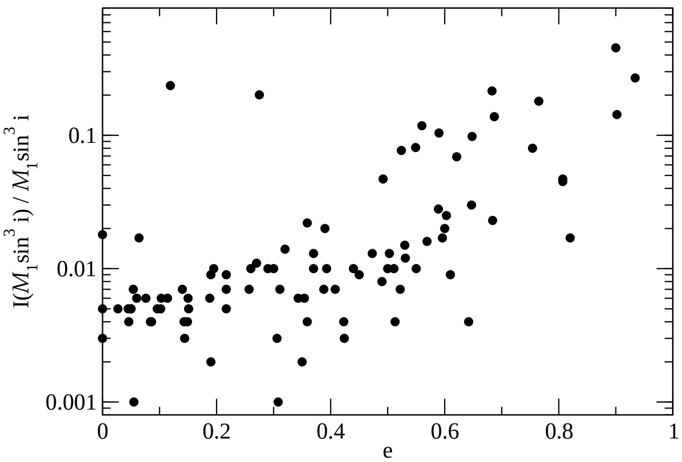

Fig. 2. Uncertainties of $\mathcal{M}_1 sin^3 i$ derived from high-precision RV measurements as a function of eccentricity.

5 Conclusion

We have prepared a list of 96 SB which could get masses with a 1 % accuracy if the elements of their spectroscopic orbits are derived again from high precision RV measurements. An accuracy of 50 m/s, which is quite feasible now, should be sufficient for that purpose. Would the RV observations begin in 2011, more than one hundred stars (2 per SB) could get accurate masses as soon as the Gaia astrometric measurements will be delivered.

This research has made use of the VizieR catalogue access tool and of the SIMBAD database, operated at CDS, Strasbourg, France

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THE GAIA MISSION AND VARIABLE STARS

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Abstract. The Gaia satellite, to be launched in 2012, will offer an unprecedented survey of the whole sky down to magnitude 20. The multi-epoch nature of the mission provides a unique opportunity to study variable sources with their astrometric, photometric, spectro-photometric and radial velocity measurements. Many tens of millions of classical variable objects are expected to be detected, mostly stars but also QSOs and asteroids. The high number of objects observed by Gaia will enable statistical studies of populations of variable sources and of their properties. But Gaia will also allow the study of individual objects to some depth depending on their variability types, and the identification of potentially interesting candidates that would benefit from further ground based observations by the scientific community. Within the Gaia Data Processing and Analysis Consortium (DPAC), which is subdivided into 9 Coordination Units (CU), one (CU7) is dedicated to the variability analysis. Its goal is to provide information on variable sources for the Gaia intermediate and final catalogue releases.

1 Introduction

Each object will be observed by Gaia a mean of 70 times during the 5 year mission. For each transit, Gaia will have quasi-simultaneous broad-band (G) photometry, blue (BP) and red (RP) spectro-photometry, and radial velocity spectrometer (RVS) measurements (in half of the cases for this latter instrument). As the shortest integration time is 4.4 seconds, variable sources can be detected on time scales from tens of seconds to years. The photometric precision should reach the milli-magnitude level at the bright end, and about 20 mmag at a magnitude of 20. In addition, the highly accurate astrometry will provide parallaxes and proper motions that will complement the photometric and RVS data. Most of the known variability types will benefit from the Gaia mission, thanks to its multi-epoch observations. In order to give to the scientific community the opportunity to perform follow-up ground based observations, the Gaia consortium puts in place a system of alerts and intermediate releases. For some events that occur uniquely and on a short time scale, a flux-based alert will be issued by the DAPC Coordination Unit 5 dedicated to the Photometric reduction. Variability announcements that are less time critical, for example those providing a list of candidates of interesting variable sources such as RR Lyrae stars, will be prepared by the Coordination Unit 7 (CU7) responsible of the analysis of all types of variables outside the solar system.

2 The Gaia scanning law

Gaia is a survey mission and is scanning the whole sky according to a prescribed law, designed to optimise the astrometric results. The Gaia sampling has been previously described in Eyer & Mignard (2005). Since that study, some modifications have been brought to the satellite design and to the scanning law. However, the general conclusions for the sampling properties do not change for the astrometric field.

The general behaviour of the time sampling pattern results from the design and operating mode of the satellite: Gaia has two fields of view separated by 106.5 degrees, and rotates around itself with a period of 6 hours. As a result, a sequence of measurements consists of several transits separated successively by 1h46m

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and 4h14m, which correspond to the times elapsed from one field to the other. The next sequence of transits appears about 1 month later, due to the rotation axis precession and the satellite orbital motion. Between 40 and 250 per transit measurements will thus be collected for each star during the five year mission, depending on its ecliptic latitude, with a predicted mean number of 80 measurements. If we take into account "dead times", a recent study shows that the expected mean number of measurements lowers to 70 (de Bruijne 2009).

The Gaia time sampling is very similar to the time sampling of Hipparcos since their scanning laws were built on the same principle, but it significantly differs from the time sampling of ground based photometric surveys. In Fig. 1, we present the sampling properties of different missions and projects for a randomly chosen star. The spectral window of Gaia varies quite a lot from one region of the sky to another. We also remark that the high amplitude peaks in the spectral window, which are causing aliases in the Fourier space, are located at high frequencies for Gaia, as it is for Hipparcos.

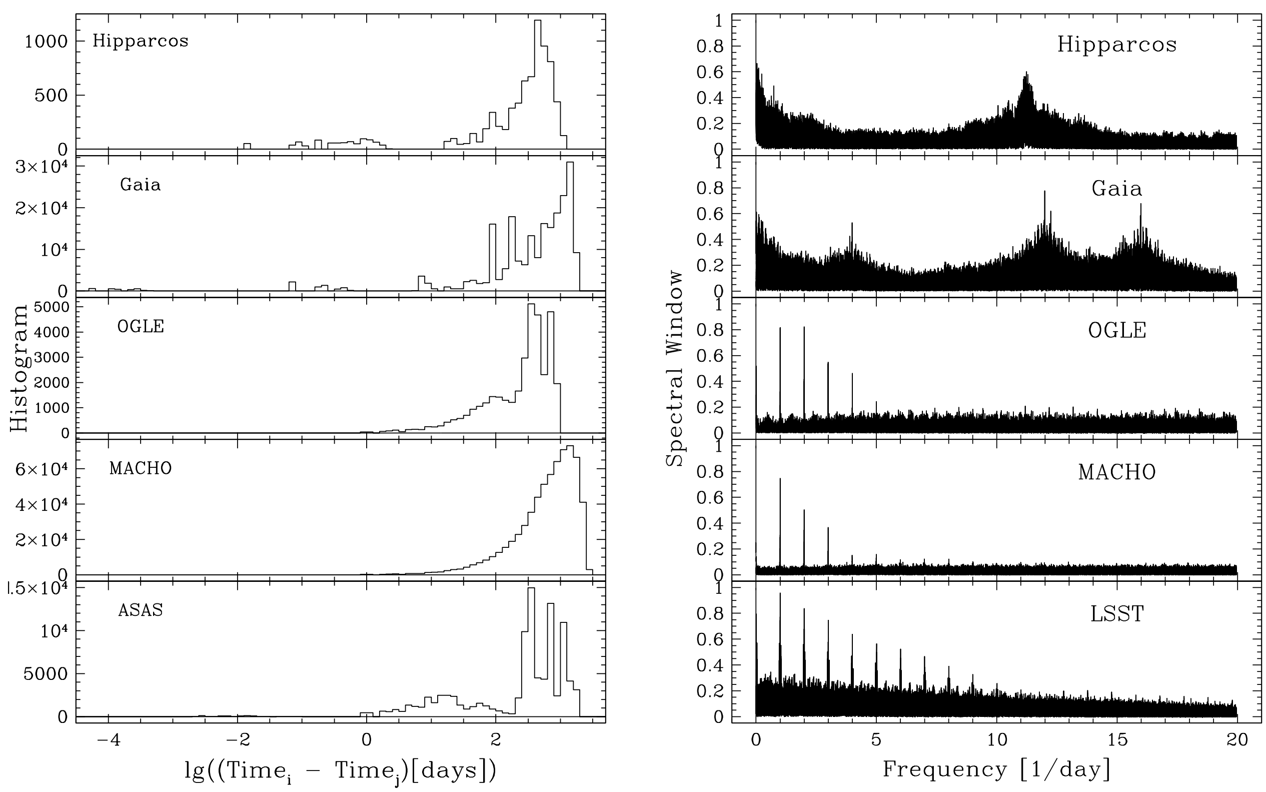

Fig. 1. Sampling properties of different missions and projects. Left: Histograms of the time differences between two successive measurements for a randomly chosen star, per mission or project. Right: Spectral windows of different surveys. The predicted time lags for Gaia are given based on per CCD photometry.

3 Periodic and short periods variable stars

The detection rate of mono-periodic signals observed by Gaia is expected to be quite good for a wide range of periods. Eyer & Mignard (2005) showed that this period recovery for regular variable stars depends on the ecliptic latitude, reaching more than 95% over more than 40 degrees of ecliptic latitudes and for S/N ratios as low as 1.3.

The Gaia time sampling and the CCD data acquisition scheme allow in principle to probe stellar variability also on time scales as short as several tens of seconds, thereby giving potential access to the study of short-period (less than a few hours) variable stars in a large and homogenous sample of stars. In order to explore that time scale regime, Varadi et al. (2009), in a first step, extended the work of Eyer & Mignard (2005) to periods shorter than two hours, and showed that the period recovery of a sinusoidal signal with a Gaia time sampling is above 90% for S/N ratios as low as 1.0, provided that per-CCD photometry is used. A second step has been initiated by Mary et al. (2006) to introduce multi-periodic sinusoidal signal, simulating the case of the roAp star HR 3831. Simulating 16 frequencies for that star, they were able to recover three frequencies from a noiseless curve. The third step consists in testing the recovery capability of non-linear multi-periodic light curves. The study is performed on simulated light curves of ZZ Ceti stars (Varadi et al. 2009) and takes into account the flux transfer of a sinusoidal signal from the base of the convective envelope of those stars to their surface. The results of those simulations show that the non-linear effect introduced by the flux transfer through the envelope degrades by only a few percents the performance of the recovery rate of the main period for multi-periodic ZZ Ceti stars. The next step should consider the case of non-stationarity of variability that characterises several classes of short pulsators. In these cases, the stellar pulsation periods and amplitudes can change on time scales from weeks to years. Further studies are under way to analyse the impact of those effects on the Gaia detection capability of those stars.

4 Pseudo-periodic and irregular variable objects

Due to the nature of the Gaia sampling, the behaviour of irregular and pseudo-periodic variable objects poses many challenges. First, their irregular nature makes their characterisation particularly difficult. Some methods such as the structure function/variogram (Eyer & Genton 1999) can help characterising the variability time-scales present in the source. This technique was applied for example by Eyer (2002) to search QSOs in OGLE-II database. Second, they may "contaminate" the sample of periodic variable stars. The analysis of the pseudo-periodic stars can indeed identify spurious frequencies from their Fourier spectrum and wrongly classify them as periodic variables. This lowers the quality of the catalogue of periodic variable objects.

The analysis of irregular or pseudo-periodic variable objects is however interesting, as it can lead to the detection of rare cases of variable objects. An example is given by the secular variable stars such as post-Asymptotic Giant Branch stars.These stars are evolving so fast that the photometric variations due to their stellar evolution can become detectable on human time scales. Few such stars have been seen to cross the entire colour-magnitude diagram in some decades. In Gaia, a work package is dedicated to the detection and characterisation of such stars based on the search of global changes in their magnitude or colour. Preliminary studies are carried out in existing surveys such as OGLE (Spano et al. 2009) and EROS.

5 Transients

The detection of transient events is also challenging. About 6,000 supernovae, for example, are expected to be detected by Gaia down to magnitude 19 (Gilmore 2009), with one third of them being detected before maximum light. While they are not likely to be a source of contamination for the catalogue of periodic stars, their possible confusion with other types of non-periodic stars remains to be addressed, and an adequate procedure should be put in place for their detection.

Microlensing events are other transient phenomena that are of potential interest for Gaia. Over the 1988 microlensing events detected in OGLE-III, 66% (1324 events) have at least one measurement within the lensing event (Wyrzykowski 2009). For events with time-scales longer than 30 days the statistics improves to 93%. The automatic detection and fast identification of microlensing events are not obvious though, despite the fact that they have clear signatures with a smooth and achromatic rise and fall. An algorithm is being set up to detect such events (Eyer et al. 2009). A preliminary comparison of our microlensing event candidates with those of Wozniak (2001) indicates a high recovery rate on OGLE-II data. The application of our algorithm to the Hipparcos catalogue resulted in only few false detections, showing that the robustness of the identification procedure.

6 Variable stars simulations

In order to test the algorithms that are set up in CU7 to detect and characterise the variable objects observed by Gaia, simulated light curves are produced for an increasing number of types of variable stars (Mowlavi 2009).

Currently, Cepheids, RR Lyrae of types ab and c, delta Scuti stars, ACVn stars, Miras, roAp stars, semi-regular variables, ZZ Ceti stars, dwarf novae, active galactic nuclei and microlensing events are simulated.

The simulated light curves, together with the properties of each type of variable stars (their location in the HR diagram and the probability of their occurrence), are provided to Coordination Unit 2 (CU2) in order to feed their Gaia simulation code. Simulated Gaia time series of variable stars, as realistic as possible, are thus aimed to test the CU7 software.

7 Ground based Observations

The Gaia DPAC may need some ground based data to help the preparation of its data processing. A Working Group, Ground-Based Observations for Gaia (GBOG), has been formed and is establishing the need of such observations and is also coordinating the proposals to ESO. For the variability analysis, it has been felt that there is a wealth of data which are already available, e.g. Hipparcos, MACHO, EROS, OGLE, CoRoT, HAT, SDSS data and therefore there is no need to gather additional data for the moment.

A network of 12 telescopes of 1-2 m size is currently in place within CU7. It is worth mentioning that the use of such 1-2 m class telescopes is particularly adequate also for the photometric follow-up studies of variable stars. Within DPAC, such follow-up should be only done for validation purpose. However these telescopes could be used for the scientific exploitation, once the data is public. Spectroscopic studies of bright variables such as Cepheids, Long Period variables or RR Lyrae stars will also benefit from those small size telescopes.

We would like to thank the whole Gaia team in Geneva: M. Beck, P. Dubath, L. Guy, A. Jan, K.Nienartowicz, L. Rimoldini, as well as the CU7 members who are contributing to the work on the CU7 Variability Processing and Analysis. We also want to thank J. de Bruijne for discussions on the scanning law.

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GAIA AND ULTRA HIGH PRECISION SPACE PHOTOMETRY

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Abstract. The era of ultra high precision stellar photometry from space on long and continuous duration has started with the launch of CoRoT. It is followed by Kepler (NASA) and will continue hopefully in the next decade by PLATO (ESA). All these missions need precise determinations of the fundamental parameters of their targets through other means. GAIA will be the mission to provide these data and then to increase significantly their scientific return.

1 Introduction

With the launch of CoRoT, starts a very rich period for high precision relative stellar photometry.

The major scientific objectives to be accessed by this technique are of essentially two kinds:

- detection of candidate exoplanets through their transit in front of their parent star
- stellar flux variability as an indicator of the physics of the stellar body, through asteroseismology but also through direct time indicators like modulation due to rotation.

Both fields need a good knowledge of the stellar fundamental parameters (temperature, mass, luminosity, chemical composition......) as illustrated with some CoRoT results. GAIA, with the determination of distance, temperature, chemical composition and in some cases mass, will be the best complementary mission to fulfill this need.

Table 1. The 3 major ultra high stellar photometry missions

Mission	CoRoT	Kepler	PLATO(n)
Period of operation	2007-2012	2009-2014+	2017- 2023
Duration: 1 obs	150 d	5 y	3y + 2y +nx(3-5 months)
Sampling	32s	15 to 1min	50s
Continuity	97%	?	$\geq$ 95%
Diameter (cm)	27	90	76
Targets Nb	150 000	100 000	250 000 (500000)
Magnitude range	10-16	9-14	4-13
Distance range	500-1000	400-800	10-500

2 Preparation and Interpretation

The need for stellar fundamental parameters is important for both the preparatory phase, and the interpretation of the data, but is treated in a different way.

During the preparatory phase, one has to optimise the selection of the targets among the different candidates in a given field. The interpretation needs the best knowledge of the properties of the observed stars, obtained by all possible means.

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As CoRoT and Kepler have been launched before GAIA, the complementarity will concern only the intepretation phase. Their preparations have used specific ground based observations to determine luminosity class and spectral types. For PLATO, the situation is more favorable, as GAIA will be able to contribute to both phases.

3 Stellar variability as seen from CoRoT

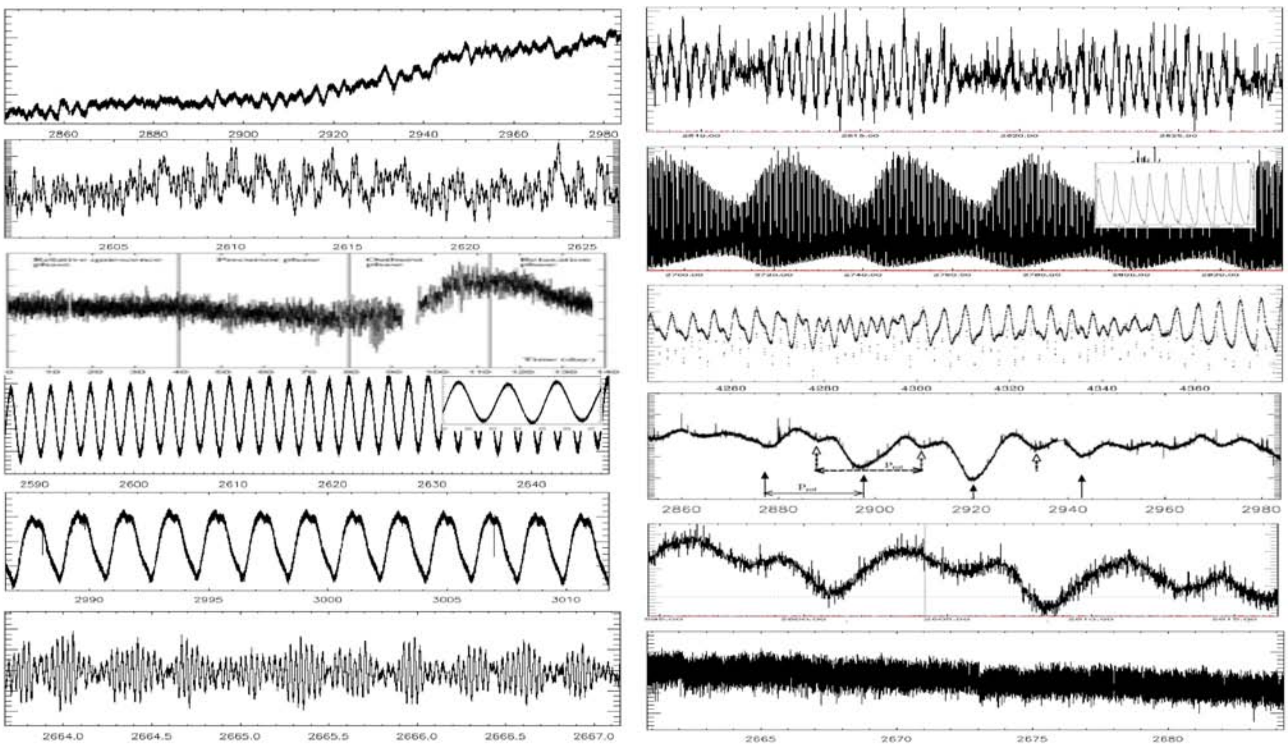

Fig. 1. Lights curves of several CoRoT targets on different durations. The left part correponds to the seismology channel, and the right one to the exoplanet channel. The accuracy on each measurement is approximately 10^{-4}

At the level of CoRoT photometric accuracy, more than 45 % of stars have detectable periodic variations. Many more vary but with no detected periodicity, and more work is needed to interpret all these data. What does this infomation tell us about stellar physics? Let's cite just a few early examples.

3.1 Rotation

The generally spotted nature of the surface of stars is seen in very accurate photometry as modulations at the rotation frequency. So true surface rotation is a direct product of CoRoT. Combined to other fundamental parameters it becomes possible to trace its variations during the evolution of stars using a large sample of targets if their parameters (T_{eff}, M, L) are well known (Fig. 2,a).

3.2 Seismology

Results are numerous in seismology as already 100 stars have been observed with a sufficient quality for such studies. Interpretation take more time than expected because Nature is always more complex than we foresee! The discovery of solar like oscillations in solar like stars, which was the major goal fo CoRoT has been achieved (fig 2b). But, in the already observed targets, which are slightly hotter than the Sun, the data analysis and mode identification is difficult due to small life times of the modes, the larger rotation, and a quite strong surface activity. The first interpretation leads to a determination of the convective core larger than expected. In B stars, the low frequency modes discovered by CoRoT can be interpreted only with an analogous structure.

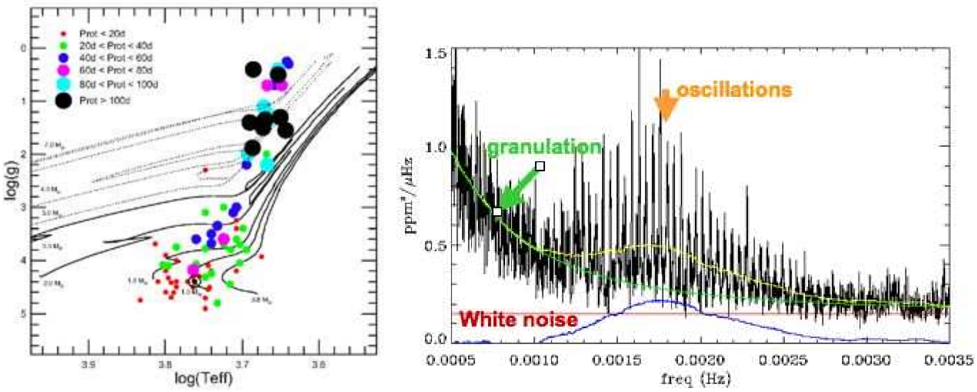

Fig. 2. *a, left*: Evolution of the rotation along the evolutionnary track of the Sun derived from CoRoT observations. *b, right* : Power spectrum of a 6th magnitude solar-like star, observed during 60 days, showing the different components : white instrumental noise, granulation and oscillations, in the frequency domain (0.5, 3.5) mHz.

3.3 Seismology and galactic structure

CoRoT has discovered solar like oscillations in a large sample of red giants, as a additional programme of the exoplanet field. They are identified as red-clump stars. The distribution of the maximum amplitude and of an average large separation give access to the distribution of the stellar radius and mass, and thus represent a most promising probe of the age and star formation rate of the disk, and of the mass-loss rate during the red-giant branch.

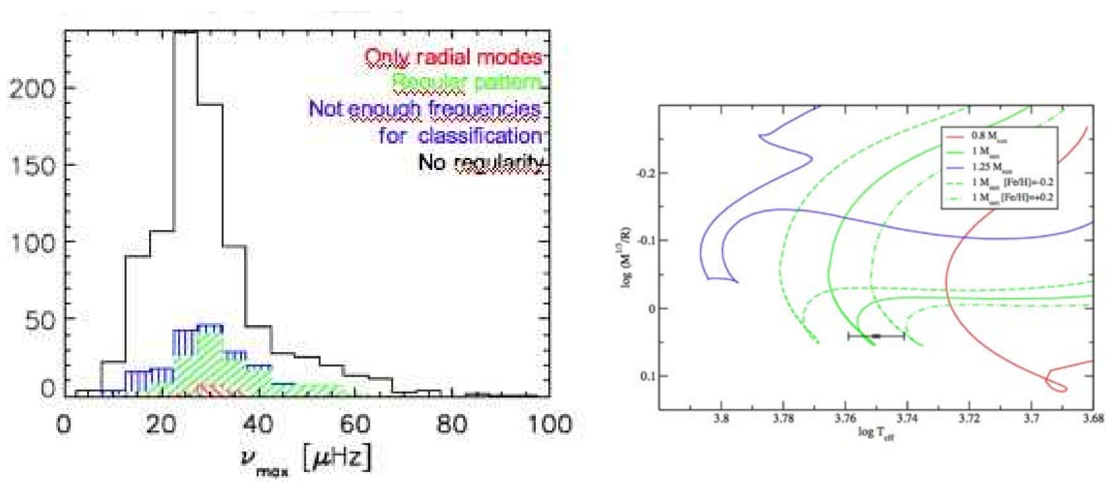

Fig. 3. *a, left:* Histogram of the frequency of the maximum amplitude of the solar like osclations in red giants. *b, right*: Evolutionnary tracks in the $logT_{eff}$, $\frac{M_{star}^{1/3}}{R_{star}}$ plane illustrating the uncertainties in the mass determination.

3.4 Granulation

Superimposed on the oscillations in the domain of frequencies around one mHz, a continuum component, already known in the Sun is easily measured in most solar type stars with CoRoT (Fig. 2,b). These stars (slightly hotter than the Sun) have higher energy in the granulation. More targets will confirm this result (or not!).

4 Planets ans stellar parameters

Transits give access to $\frac{R_{pl}}{R_{star}}$ and $\frac{M_{star}^{1/3}}{R_{star}}$ with a very high precision (10^{-3}). Radial velocities measure the amplitude of the orbital variations and determine $\frac{M}{M_{star}}$ $\sin i$. If the planet transits, i is known from the light curve, so the mass ratio is determined with a high precision. But, as illustrated by Figure 3b, uncertainties on the stellar parameters remain quite large. For instance, an uncertainty of 50K on the effective temperature (which is preently not reachable) leads to an uncertainty on the mass of 0.06 solar mass. Even more important is the determination of the chemical composition. An uncertainty of 20% translates into an uncertainty on the mass of 10% (assuming that the surface composition is the initial composition of all the material).

The very poor knowledge of the mixing proceses in the stellar interiors lead to estimate the corresponding uncertainties to at least 13% in Mass, 5% in Radius. But the situation will certainly be improved by the seismology results. Only the knowledge of the size of the convective cores of intermediate stars will help improving the ages determintations close to the main sequence.

5 The PLATO(n) mission

Selecting targets for the PLATO input catalogue:
The observation strategy is to have two long (2 to 3 year) sequences of monitoring of two distinct fields, followed by a one-year step-and-stare phase during which several additional fields will be observed for a few months each.

A first major task in preparation of the mission will be to identify the cool dwarfs/subgiants in the very wide field of view of the instrument. A most efficient way of achieving this target selection will be to rely on stellar radii determined from early GAIA results. With stellar luminosities known to better than 30-40% and effective temperatures determined to within about 10% (500 K accuracy), which is well achievable using astrometry and multiband photometry in the first two years of GAIA exploitation, stellar radii will be known to within 15-20%, which is amply sufficient to distinguish dwarfs and subgiants from giants and supergiants.

This information is needed at least 18 months before launch, i.e. in mid-2016 for a launch at the end of 2017, in order to allow enough time to set up completely the PLATO input catalogue, and prepare all parameters of the data treatment software. This is more than four years after GAIA launch, and more than two years after the expected first partial release of GAIA results. Access to the needed data should therefore present no difficulty, even in the hypothesis of a GAIA delay, either of the launch, or of the first data release.

Characterizing the neighbourhood of PLATO selected targets:
PLATO photometry will be sensitive to the presence of nearby polluting sources, which can either be intrinsically variable, or simply create spurious signal in the photometric algorithm due to satellite jitter. Methods have been developed to correct for these perturbations, but a precise knowledge of the vicinity of each PLATO target is needed for these corrections to be applied.

What is needed is a full catalogue of faint neighbouring sources, including their positions, magnitudes and colours, down to approximately 19th magnitude, in sub-fields of at least 1 arcmin around each PLATO target. This information will be used to optimize the photometric algorithm for each target, and therefore will impact on the fine tuning of the onboard data treatment software. It is therefore also needed by mid-2016. The information that could be contained in GAIA first release (positions, G band magnitudes, and colours from the red and blue spectrophotometry) will be sufficient for this purpose.

Interpretation of the PLATO(n) data:
A more precise measurement of the radii of all stars observed by PLATO, and more particularly of the host stars of the detected exoplanets, will be necessary at the time the first results from PLATO will become available. This will happen about 2 to 3 years after the launch, i.e. not earlier than 2019. The final release of GAIA may be available by then (in the case that the observational phase is five years and the final catalogue is produced two years after that). In that case the access to the needed data should be straightforward. However, if GAIA is extended to six years, it is probable that the intermediate GAIA data releases will suffice.

More precisely, stellar radii to within 2-3% will be necessary, both to measure the planet radii to the same kind of accuracy, and second to place tight constraints of stellar interior structure models of the exoplanet host stars, coming in addition to the seismic observations of PLATO. This implies a knowledge of the stellar luminosities to within 5%, which will be easily achieved by GAIA for cool dwarfs as bright as 11th or 13th magnitude, and therefore closer than 200 (resp 500) pc. Effective temperatures will also need to be determined to within 1% (50 K). This will be achieved with the help of dedicated high resolution, high signal-to-noise spectroscopic observations obtained as part of the groundbased follow-up programme.

Hopefully, new generations of ultra high recision velocimeters as EXPRESSO will be available at that time beng able to measure the masses of planets as small as 1 earth mass and even smaller.

6 Conclusions

The ESA cosmic vision programme, if it selects PLATO will provide a unique combination of stellar parameters measurements which will improve considerably our physical knowledge of the stars, of their role in the galactic evolution, and of their planetary systems.

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GAIA SPECTROSCOPY: OVERVIEW AND SYNERGIES WITH GROUND-BASED SURVEYS

Katz, D.[1]

Abstract. This talk reviews the current status of the Gaia-RVS design and performance. It examines the synergies between Gaia and ground-based spectroscopic surveys. It concludes on the possible additional spectroscopic surveys that could complement Gaia in the quest for understanding the Milky-way.

1 Introduction

The first science driver of Gaia is the understanding of the structure, formation and history of our Galaxy. To fulfil this objective, Gaia will continuously scan the celestial sphere during 5 years with its 3 instruments: the astrometric instrument (providing the positions, parallaxes and proper motions), a low resolution spectro-photometer made of 2 "arms", i.e. blue and red (providing the atmospheric parameters, interstellar reddening and mean alpha elements to iron ratio) and a middle resolution spectrograph, the Radial Velocity Spectrometer - RVS (for the derivation of the radial velocities, but also for the "brightest" stars: rotational velocities, atmospheric parameters, some individual abundances and interstellar reddening). This talk reviews the current status of the RVS design (Sect. 2) and performance (Sect. 3). It examines the synergies with the current ground-based spectroscopic surveys (Sect. 4). It concludes on the possible additional spectroscopic surveys that could complement Gaia in the quest for understanding the Milky-way (Sect. 5).

2 RVS design

The Radial Velocity Spectrometer (RVS) is an integral field spectrograph, i.e. it disperses all the light that enters its 0.22×0.39 square degree field of view. It is a medium resolving power spectrograph, $R = \lambda/\Delta\lambda = 11\ 500$, with a 27 nm wavelength range in the near-infrared: [847,874] nm. The RVS focal plane is located on the edge of the Gaia focal plane (all the instruments share the same focal plane) and, as the other instruments, it is illuminated by the 2 Gaia telescopes. The RVS focal plane is paved with 12 red-enhanced CCDs (3 in the direction of the scan times four in the perpendicular direction). Over the 5 years of the mission, the RVS will observe on average 40 times each source (times 3 CCDs along the scan direction, for an average number of 120 spectra over the mission). The exposure time per CCD is 4.42 s, leading to an average total exposure time of $\sim$530 s.

In late type stars, the strongest features in the RVS wavelength range is the ionised Calcium triplet. Several weak lines of e.g. Iron, Titanium or Magnesium are also present. In early type stars, the dominant lines are Hydrogen lines from the end of the Paschen series. The domain also contains weak lines, e.g. the Calcium triplet that has strongly decreased in intensity, ionised Iron, Nitrogen or Neon. The RVS domain also contains a Diffuse Interstellar Band, DIB, located at 862 nm, which unlike many DIBs seems to correlate reliably with the $B - V$ excess (Munari et al. 2008) and therefore can be used to map the interstellar reddening. Figure 1 presents 2 examples of synthetic spectra, convolved to the RVS resolving power, for a G5 (left) and a B5 (right) main sequence stars.

The full Gaia focal plane is made of 102 "science-CCDs" (of 8.847 mega-pixels each) for a total of about 902 mega-pixels. The CCDs are operated in Time Delay Integration (TDI) mode, i.e. the charges are continuously

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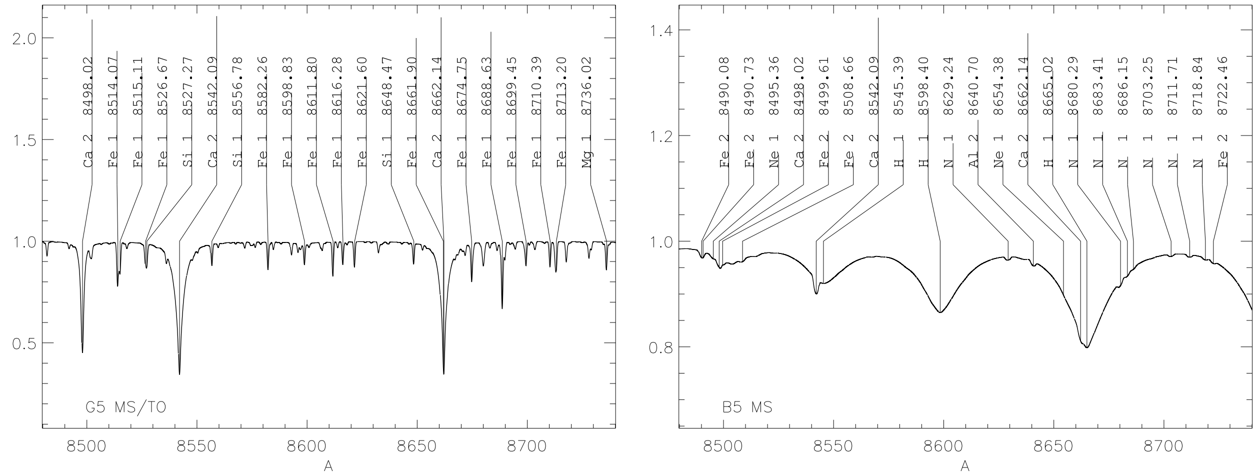

Fig. 1. Synthetic spectra of a G5 (left) and B5 (right) main sequence stars in the RVS wavelength range. The two spectra have been convolved to the RVS resolving power. The main lines are identified.

transferred through CCD columns in order to follow the sources as they cross the field of view. The antenna bandwidth is too restricted to allow for continuously transmitting the full focal plane (almost 1 billion pixels) from the second Lagrange point (at 1.5 millions kilo-meters from the Earth), where the satellite will be located. Instead, astrophysical sources are detected by the on-board software in real-time and "windows" are allocated around the objects that should be transmitted to the ground. The RVS windows are 1260 pixels long (in the spectral dispersion direction, which is also the scan direction) and 10 pixels high (in the direction perpendicular to the dispersion). Inside a window, different samplings are used depending on the magnitude of the target: the brightest sources $6 \leq V \leq 8$ are transmitted in 2D full resolution, the intermediate brightness sources $8 \leq V \leq 11$ are collapsed to 1D (i.e. summed over the spatial dimension) before reading and the faintest sources $11 \leq V \leq$ 17-18 are both collapsed in the spatial dimension and binned by group of 3 pixels in the spectral direction, in order to limit both the telemetry load and the readout noise.

There is a maximum number of windows that can be allocated at any given time. As a consequence, in dense areas, the RVS will be limited to observe the 36 000 brightest sources per square degrees. In the case of, e.g. the Baade's window, this surface density translates into a limiting magnitude for the RVS of V$\sim$13-14.

3 RVS performances

Table 1 summarises the RVS performance. The left part presents the signal to noise ratio expected for a G2V star as a function of V magnitude for (i) a single transit and (ii) at the end of the mission when all the observations will be combined. At the faint end, even the total signal collected is small and it will be possible to extract the radial velocities only from the combined information and not from a single spectrum.
The central part shows the limiting magnitude of the RVS for the different parameters that will be extracted from its spectra. The cumulative numbers of stars down to the respective limiting magnitudes are provided in the next column. It should be noted that for the atmospheric parameters and interstellar reddening, the limiting magnitudes provided in the table correspond to the limits where spectro-photometry and RVS data can be jointly used to constrain these parameters. At fainter magnitude, the spectro-photometer will still provide estimates of the atmospheric parameters and mean metallicity (with a precision of 0.2 to 0.4 dex for stars brighter than V=16 and 0.5 to 0.7 dex around V=18).
The right part recalls the specifications for the radial velocity precisions as defined in the "Gaia Mission Requirement Document - MRD" (ESA, 2006), which contains all the scientific specifications for the Gaia mission. The acronym MP stands for metal-poor and corresponds here to $[Fe/H] = -1.5$ dex.

Table 1. Summary of the RVS performance. Left: Signal to noise ratio for a G2V star as a function of magnitude, for 1 transit and for the total mission. Centre: Limiting magnitudes (and the corresponding cumulative numbers of sources) for the different parameters that will be derived from RVS spectra. Right: Radial velocity performance specifications (MP stands for metal-poor, i.e. here $[Fe/H] = -1.5$ dex).

V	S/N (per transit)	S/N (full mission)
6	150	1000
10	20	150
12	8	50
14	2	10
16		2

Parameters	V_{lim}	N stars
Vr	17-18	150-300 10^6
v sin i	13	5 10^6
Teff logg	13	5 10^6
$[Fe/H]$	13	5 10^6
$[X/Fe]$	12	2 10^6
E(B-V)	13	5 10^6

Spectral type	V	Vr (km/s)
B1V	7	1
B1V	12	15
G2V	13	1
G2V	16.5	15
K1IIIMP	13.5	1
K1IIIMP	17	15

4 Synergies with ground-based spectroscopic surveys

4.1 Gaia and RVS boundaries

The modern multiplex spectrograph technology allows ground-based surveys to complement Gaia and the RVS in the areas were they show limitations:

- In dense areas (such as the Galactic disk and bulge), the RVS will be limited to the 36 000 brightest stars per square degrees.
- The radial velocity precision in the magnitude range [15,17] is modest, e.g. ≥ 5 km.s^{-1} for a G5V star.
- In the faint Gaia magnitude range, i.e. about [17,20], the RVS will provide no radial velocities.
- For stars fainter than about 12-13, the mean metallicities provided by Gaia will have a relatively modest precision, i.e. 0.2 to 0.4 dex down to V=16 and about 0.5 to 0.7 dex at V=18.
- Individual abundances will be available only for the 2 millions brightest stars down to V=12.

4.2 Kinematical synergies

The ground based spectroscopic surveys will complement Gaia kinematics in several ways:

- The LAMOST-LEGUE (Cui, 2009) survey (2.5 millions stars over the magnitude range $17 < g < 20$ in the northern hemisphere) and SEGUE (Yanny et al. 2009) survey (240 000 stars in the magnitude range $14 < g < 20$) will provide radial velocities for stars that are too faint to be observed by the RVS and down to the Gaia limiting magnitude.
- RAVE (Zwitter et al. 2008 - several fields in the Galactic plane), APOGEE (Allende-Prieto et al. 2008 - 100 000 stars in the disk and bulge) or WINERED (Tsujimoto et al. 2008 - 1 million stars) will observe in dense areas of the sky, where the RVS observations will be affected by the overlapping with neighbouring sources and by the limitation to the 36 000 brightest stars per square degrees.

4.3 Chemical synergies

Ground-based spectroscopic surveys will also complement Gaia in the study of the chemistry of the Galaxy:

- With higher resolving powers, WINERED ($R = \lambda/\Delta\lambda = 100\ 000$), HERMES (R=30 000) and APOGEE (R=20 000) will provide finer spectroscopic information.
- With larger and/or complementary wavelength range, ground based surveys will allow to both refine the precisions on the measured abundances and to measure additional species. This is the case for WINERED ([0.9,1.35] μm), APOGEE ([1.52,1.69] μm) or HERMES ([370,950] nm).

- HERMES (1.2 millions stars in the southern hemisphere down to $V < 14 - 15$) and APOGEE ($H < 13.5$) will provide abundances 2 to 3 magnitudes fainter than the RVS.
- WINERED (bulge) and APOGEE (disk/bulge) will provide abundances in dense areas (where the RVS will be affected by the crowding and restricted to the 36 000 brightest stars per square degrees).

5 A need for additional complementary surveys

With several surveys showing clear synergies with Gaia (in particular LAMOST and SEGUE for the kinematic and HERMES for the chemistry), one can wonder whether additional complementary surveys are needed to support Gaia? A lot of activity, meetings, thinking, studies have taken place over the last two years, to answer this question: e.g. ESO-ESA working group on Galactic populations, chemistry and dynamics (Turon et al. 2008), the Nice (http://www.oca.eu/rousset/GaiaSpectro) and ESO (http://www.eso.org/sci/meetings/ssw2009/index.html) meetings.

From these reflexions, it appears that (at least) two additional instruments would be extremely valuable in support to Gaia:

- For the radial velocities, a LAMOST-like instrument, but located in the southern hemisphere: a low resolving power (R∼5 000), a large field of view (1 or several square degrees) a high multiplexing (1000 or more fibbers). A wavelength range in the infra-red would help observing in absorbded areas. This instrument would aim to observe stars in the magnitude range $16 < V < 20$ with a precision of 1 to a few (i.e. better than 5) km.s^{-1}.
- For the chemistry, an HERMES-like instrument, but located in the northern hemisphere: a high resolving power ($20\,000 < R < 40\,000$), a field of view of the order of 1 square degree, a high multiplexing (about 500 fibbers). The wavelength range should allow for the full characterisation of the targets (i.e. derivation of effective temperature, surface gravity, micro-turbulence and mean metallicity) and for the derivation of the abundances of the key chemical species for the study of the Milk-Way chemical history. The aim of this instrument would be to observe about 1 million stars down to magnitude V∼ 16.

Over the last 2 years, a lot of people have worked on defining the best ground-based strategy to support Gaia's science case. This presentation incorporates many of their ideas presented in documents, meetings or e-mail discussions. I would like to thanks the actors of these discussions, in particular F. Arenou, C. Babusiaux, O. Bienaymé, P. Bonifacio, A. Gómez, M. Haywood, V. Hill, A. Recio-Blanco, A. Robin, F. Royer, A. Siebert, C. Soubiran, F. Thévenin and C. Turon.

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MULTIOBJECT SPECTROSCOPY AS COMPLEMENT FOR GAIA

Recio-Blanco, A., Hill, V.[1] and Bienaymé, O.[2]

Abstract. The Gaia mission will have an unprecedent impact on our knowledge of the Milky Way by unveiling populations through the study of chemistry and dynamics. It will open new horizons that, nevertheless, will need to be completed with specific surveys of Galactic Archaeology. An analysis of those needs for the different Galactic stellar populations has recently been carried out during a workshop gathering the French community involved in Galactic Archeology and stellar physics. The outcome of this meeting regarding the needs for ground-based spectroscopic surveys as a complement to Gaia, placed in the context of present and future surveys, is presented here.

1 Introduction

Gaia is a pioneering ESA astronomy mission set to revolutionise our view of the Galaxy with a precise and detailed stereoscopic survey of the billion brightest celestial objects. High-accuracy astrometry will allow Gaia to exactly pinpoint the position of a star and to measure its movement across the sky, whilst spectroscopic measurements will allow the radial velocity to be determined. Gaia will also gather photometric data, measuring the brightness of a star in a few dozen colours. This array of data will reveal a moving, three-dimensional Milky Way map of unprecedented scope and precision, as well as providing profiles of the physical properties of each star, including luminosity, surface gravity, temperature and elemental composition. The Gaia satellite will be launched Spring 2012.

Gaia will provide accurate estimates of a range of key parameters, however, the Gaia Radial Velocity Spectrometer (RVS) indeed has a higher limiting magnitude than the astrometric instrument (g$\sim$ 14 to 16.5 vs. 20) and a very limited spectral coverage hampering the chemical analysis of the stars. During the Nice workshop, supported by the AS Gaia, (19-20 February 2009; http://www.oca.eu/rousset/GaiaSpectro/), the needs of complementary spectroscopic observations were examined at the light of the Gaia inpact on our knowledge of the different Galactic populations. The workshop gathered 23 participants, and was specifically timed to trigger thoughts about such complements in the french community, in time to participate the ESO Spectroscopic Survey Workshop (http://www.eso.org/sci/meetings/ssw2009), where we presented the conclusions[1] of our meeting. The context of other present and future surveys has also been taken into account.

2 The context of future surveys

On the observational front, the international scene is evolving fast. Very wide (or all-sky) multi-band photometric (SDSS, 2MASS), have flourished, allowing to probe the Milky-Way populations (especially the halo) to a depth (and homogeneity) that had never been reached before. One striking example concerns the recent tomography of the Milky Way halo from SDSS down to magnitudes of g$\sim$22 by Juric et al. (2008) or Ivezic et al. (2008), providing strong constraints on stellar densities associated with the discs and halo, as well as rough but very large scale metallicity maps that are challenging our views of the thick disc formation. Large spectroscopic surveys (SDSS including SEGUE; RAVE) are also on the way, promising to unravel the chemo-dynamics of Galactic stellar populations. Both these surveys are based on low-resolution spectra (R$\sim$2000 for

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[1] http://www.eso.org/sci/meetings/ssw2009/presentations/RecioBlanco.pdf

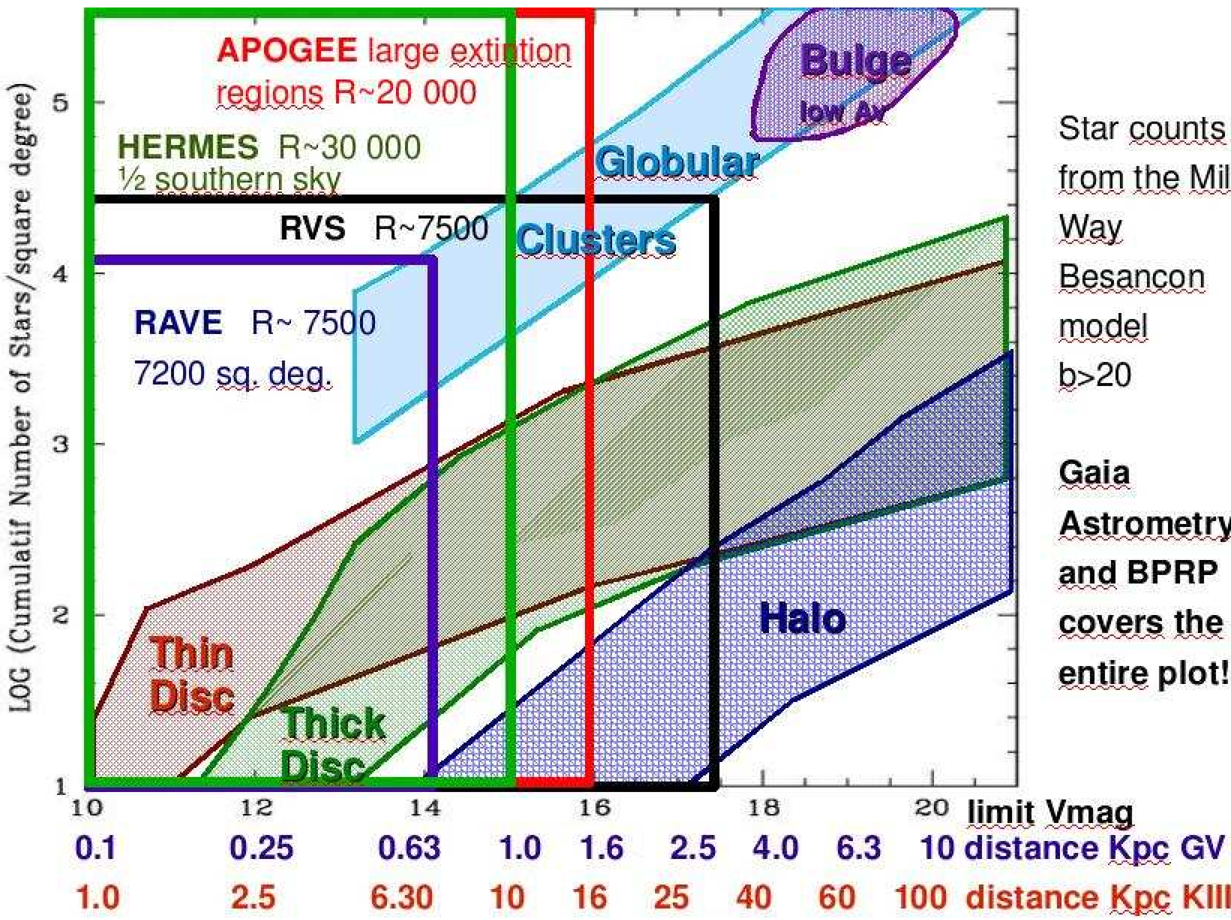

Fig. 1. Plot of the number density and locus of different components of the Milky Way v. V magnitude and equivalent distance for two spectral types as relevant to the follow-up of stars from Gaia. Stellar densities were computed using the Besancon model (Robin et al. 2003) for lattitudes of b>20. The magnitude limits of some other spectroscopic surveys are indicated for comparison, and their resolution and total area coverage are are noted. [note: the various y-axis location of these surveys are meerly for lisibility and do not correspond to any real stellar density.]

SDSS and 7500 for RAVE), and will provide radial velocities (to ∼5-10 km/s and 2km/s accuracy resp.) as well as stellar parameters and a global metallicity indicator for gigantic numbers of stars (around 240000 and ∼80000 respectively). These two major surveys are complementary in that the SDSS is much deeper (g∼20) and probes mostly the galactic halo and thick disc, while RAVE is restricted to a much smaller volume (limited to I=13) and therefore probes best the thin and thick discs. Future stellar surveys at the 2014 horizon include low-resolution surveys such as SEGUE II (part of SDSSIII), LAMOST, but also a new generation of surveys based on higher resolution spectra (R∼20000 or more) such as APOGEE (part of SDSSIII, dedicated to the Galactic plane in IR), WFMOS (GEMINI-Subaru project), or HERMES (R∼30000, V<14, covering one half of the southern sky).

Figure 1 is a plot of the stellar number density and locus of different components of the Milky Way vs. V magnitude and equivalent distance. Two spectral types as relevant to the follow-up of stars from Gaia are considered. The star counts have been taken from the Besancon model for a Galactic latitude b>20. The locus of most of the previously mentioned spectroscopic surveys is shown. The Gaia astrometry and spectrophotometric data will cover the entire plot. It can be seen that there is lack of a high resolution survey *in the north* for stars with V<16, that is, stars that will have good geometric distances and kinematics from the Gaia observations. On the other hand, no high or low resolution surveys are planed for the fainter stars, for which Gaia will furnish neither the radial velocity nor the precise chemical information. This opens two different pathways for the Gaia complementary observations.

3 Science cases

During the workshop, the science cases concerning the different Milky Way and dwarf galaxies populations were examined. The impact of the Gaia mission, but also the information that will not be provided by Gaia were taken into account.

Concerning the Milky Way Thin disc, Gaia will provide, for the first time, disc evolution constraints as a funtion of stellar absolute ages. In particular, the star formation rate over several kiloparsecs will test the inside-out formation scenario. In addition, the infall evolution will be constrained by the chemical abundances evolution with age. For all those purposes, an improvement of the Gaia atmospheric parameters for stars fainter than V=16 (with no RVS measurements) will be necessary to get good age estimations. Moreover, a spectroscopic survey allowing to refine the chemical abundance information for those faint stars (the Gaia spectrophotometry will only give an estimation of the star's global metallicity) would allow the identification of kinematic groups, the study of the Thin Disc structure and constrain the existence of a radial mixing.

Regarding the Thick Disc, Gaia will allow its characterization far from the solar neighbourhood and the detection of accretion events and inhomogeneities. Nevertheless, a complement of the Gaia radial velocity and chemical abundance measurements for faint stars will be necessary. This will permit, in particular, to constrain the radial and vertical chemical and velocity gradients, the scale-heigh variation with Galacticentric distance and che chemical evolution.

The view that Gaia will provide of the Galactic Bulge has been recently been analysed by Reylé et al. (2009), and turns out to be quite partial, owing to the combination of extinction on the line of sight and crowding. Complementary measurements of radial velocity and chemical abundances for faint stars and a larger (l,b) coverage are mandatory for a better constraint of the the Bulge formation scenario, the star formation history and the impact on disc chemical evolution and dynamics as well as for the search for matter accretion traces. Because the Bulge is heavily redened in most regions, spectroscopic measurements will be best suited in the infrared.

The external regions of Galactic globular clusters will be observed by Gaia, that will provide the parallaxes of several thousands to several tens of stars (depending on the distance and the cluster concentration). On the contrary, the RVS, due to its lowest density limit will only observe for a subsample of the clusters, several hundreds to some tens of stars. A complement of the Gaia radial velocity measurements is necessary to improve the impact of Gaia on the study of the Globular cluster's internal dynamics. On the other hand, possible new clusters will be identified by the Gaia survey, and follow up observations constraining radial velocitys and chemical abundances will be needed. Similar complementary data will be necessary to improve the scientific exploitation of Gaia measurements in the Halo, including the nearby satellites of the Milky-Way. In particular, the refinement of the Halo substructure, with an estimate of the fraction of accreted stars, and a comparison of the field Halo population and the Milky Way dwarf galaxies will require additional radial velocity and chemical abundance measurements for faint stars. In this case, a wide field of view (>1-2 square degrees) is necessary for dedicated Halo observations, due to the low stellar density.

4 Conclusions - Recommandations

Based on these science cases, two basic recommandations can be made for large public surveys to complement the Gaia database for studies of the Galactic structure, kinematics and stellar populations.

• **A high-resolution follow-up of the relatively bright objects in Gaia (V<16-17)** This survey would aim at characterizing in detail the chemical composition of the stars for which Gaia will provide exquisite 3D kinematics. This will in turn provide direct information to complement kinematics in identify stellar populations, to identify their origins and formation mode(s). The resolution needed to obtain detailed chemical information is of a minimum of R=20000-40000. The scientific cases that will mostly benefit from such a survey are the understanding of the thin and thick disk outside of the solar neighborhood (including their radial, azimuthal and vertical structures, aswell as origin), aswell as the identification of stellar streams in these components. This survey would overlap partly with the current HERMES project, although aiming at deeper observations (typically 1-2 magnitudes deeper). It would therefore be best suited for the northern hemisphere where it would then be complementary to HERMES.

The Galactic halo at these magnitudes is still rather scare (probed mostly by giants), and would benefit most from a deeper survey (down to V of 19), in selected sky regions (requiring a 10m-class telescope).

The Galactic Bulge is heavily reddened and therefore calls for a specific survey in the infrared. The currently planned APOGEE survey (part of the SDSS-III surveys) will partly cover this area (having ideal resolutions and wavelength coverage), but being located in the Northern hemisphere, its visibility of the Bulge will be rather poor, leaving space for a similar survey from a southern 4m-class telescope.

• **A medium-resolution survey of faint stars in Gaia (17<V<20):** This survey would aim at aquiring the third velocity vector (radial velocities), in the magnitude range where it is unreachable with the onboard Radial Velocity Spectrograph (RVS), thereby complementing the transverse motions of Gaia to obtain 3D kinematics for a large fraction of the Gaia catalogue in this magnitude range. Aiming at a minimum resolution of R=5000 insure simultaneously that the radial velocity accuracy is of the order of 2-3km/s, sufficient to resolve cool kinematical streams (including dissolving globular clusters), and a robust estimate of the stellar metallicity. This survey, one magnitude deeper than the SDSS & SEGUE and twice its resolution, is mainly aimed at unravelling the structure and assembly history of the galactic halo, in particular detecting streams and substructures in the halo (out to 100kpc).

• **Need for single-object high-resolution spectrographs:** In addition to these large surveys, Gaia will also call for high-spectral resolution (or even extremely high resolution R>80000-100000) follow up of a limited number of object (hence with extremely low densities on the sky). For example, among others, exquisite chemical abundances and rotationnal velocities, are needed for a whealth of fundamental stellar physics issues that Gaia will adress, ranging from non-standard mixing and diffusion in stars, angular momentum evolution, nucleosynthesis, etc... For these follow-up, the Gaia stellar community will need access to high-resolution echelle spectrographs on 2-30m telescopes.

Resolution	FOV deg^2	Multiplex fibers/deg^2	λ Coverage Å	$\Delta\lambda$ Å(in one shot)	V mag	Total area
20000−40000	0.25 (1 for Halo)	250-1000	3700-12000	> 500	<16-17	Wide
20000−40000	0.25 (1 for Halo)	250-1000	3700-12000	> 500	17-20	Selected regions
> 20000	0.25	1000	J-H bands	one full band		Bulge
5000−10000	>1	250-1000	3700-12000	> 500	17-20	Very wide

We thank the AS-Gaia for supporting the workshop that was held in Nice in February 2009. Thank-you also to Olivier Bienaymé who presented the conclusions of the workshop at the SF2A meeting on very short notice.

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SIMULATING GAIA OBSERVATIONS USING A "UNIVERSE MODEL"

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Abstract.
Preparing the Gaia mission requires large efforts dedicated to simulations of the observations. Several simulators have been constructed, generating telemetry, images, or the final database. All these tools use a "Universe Model" containing essentially the astronomical objects seen by Gaia and their characteristics, as well as a Relativity model and a radiation model for estimating the potential dammage to the CCDs. The construction of the Universe Model will be described, together with the computation of the astronomical sources characteristics, and the applications and limitations of such a model.

1 Introduction

The Gaia DPAC (Data Processing and Analysis Consortium) has decided to put a big effort on the simulation of the mission in order that all softwares prepared for the mission be sufficiently and extensively tested prior to launch. The simulation effort consists in doing several simulators. The GIBIS simulates the images at the output of the CCDs, GASS simulates the telemetry sent to the ground from the satellite after selecting objects and windows around the objects on board. GOG is dedicated to generating intermediate and final data in the data base, including estimations of measuring errors. These 3 simulators make use of two models : the Instrument Model, and the Universe Model (hereafter UM).

This UM is a set of algorithms for computing the positions at any time, and observational properties of any objects expected to be observed by the Gaia instruments. The distributions of these objects and the statistics of observables have to be as realistic as possible for simulations to be usable for estimating telemetry, testing software, simulating images, etc. The algorithms have also to be optimised in order that the simulations can be performed in reasonable time and can be redone when necessary. The complexity of the model is expected to increase during the preparation of Gaia.

Objects which will be, in fine, simulated are: solar system objects (planets, satellites, asteroids, comets), galactic objects (stars, nebulae, stellar clusters, diffuse light), extragalactic objects (galaxies resolved in stars, unresolved but extended galaxies, quasars and active galactic nuclei, supernovae). On top of these objects, a relativity model has to be implemented. The interstellar extinction has to be taken into account. Backgrounds have to be simulated, like the zodiacal light, or extended nebulae. The radiation environment of the satellite and its variation with time is also an element of the UM. For each of these simulated objects one needs to have their full 3D spatial distribution together with their spectral characteristics (to be able to compute photometry and spectroscopy, stable or variable in time), and their motions (for astrometric computations and for spectral corrections). Gravitational lensing for stars and galaxies are also to be simulated.

We here describe the main UM assumptions, the characteristics of the simulated objects, the spectral libraries, and we present the global statistics of the objects as computed from the UM.

2 Astrosources

For each "astrosource", the UM defines its characteristics in order to compute the observables. This includes: the photometry and variability with time, the astrometry (position at a given time, 3D velocities to compute radial velocity and proper motion, distance to the observer to compute the trigonometric parallax) and the

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physical parameters which define the spectrum (effective temperature, gravity and metallicity for stars, Hubble type for galaxies, equivalent width and slope of the spectrum for quasars, taxonomical type for asteroids, etc.). The spectra are taken from spectral libraries, interpolated for the astrophysical parameters of the astrosource, and corrected for interstellar extinction, rotation and radial velocity.

Exoplanets are simulated orbiting single stars and creating transits. Multiple stars are generated and eclipses simulated when necessary. The proportion of multiple stars and the distribution in mass ratio and semi-major axis and statistically generated according to Arenou and Soderhjelm (2005). Multiple star simulations are of course not static. Beyond the Galactic properties of multiple stars, the astrometric, spectroscopic (radial velocity) and photometric (eclipses) effects of these objects have to be taken into account: in the course of the simulations of Gaia transits, the orbits are thus computed, the positions of both components are modified, though crudely in the case of eclipse. For extended objects (comets, asteroids, nebulae, etc.) shapes have to be modelled to allow the computation of the image. Figure 1 shows the main classes which allow to describe an astrosource.

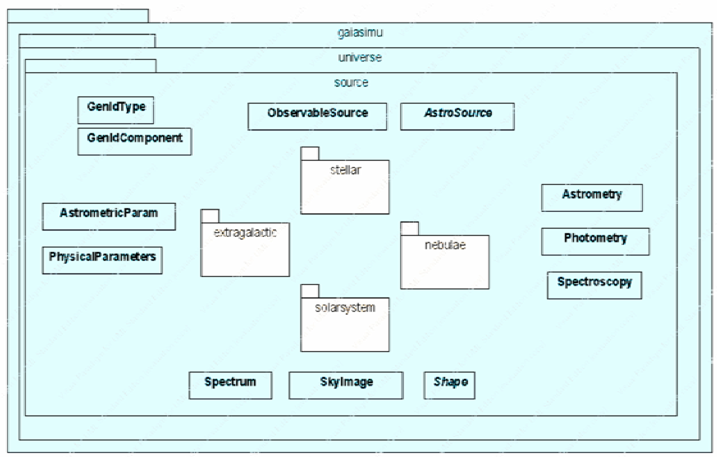

Fig. 1. Main classes describing an AstroSource.

3 Object generators

The "astrosources" have to be built from a set of generators which generate in any given direction of observations the objects which are present in the field of view of the instrument and their characteristics. Details on the various object generators can be found in Robin et al. (2009). The main aspects are described below.

Most of the objects in Gaia instruments are stars. To generate the stars in the Milky Way we use a version of the Besançon Galaxy Model which have been rewritten is Java. This version possess several improvements with regards to the standard model (Robin, et al, 2003). They are : full simulation of stellar multiplicity, inclusion of several stellar variability (delta Scuti, ACV, cepheids, RRab, RRc, roAp, semi-regular, dwarf novae), rare objects (Wolf Rayet, planetary nebulae). It also includes the computation of the microlensing towards the Galactic bulge, and uses the Drimmel & Spergel (2001) model as 3D extinction map for computing the extinction along any line of sight.

At present no stellar populations in local group galaxies have been implemented in the UM. Plans are done to simulate at least the stars in the Magellanic Clouds. Unresolved galaxies are generated using the Stuff (catalogue generation) and Skymaker (shape/image simulation) codes from E. Bertin, adapted in Java for the DPAC purpose. The galaxy simulator generates a mock catalog of galaxies with a 2D uniform distribution and a distribution in each Hubble type sampled from Schechter's luminosity function. Each galaxy is assembled as a sum of a disc and a spheroid and is put at its redshift and luminosity and K corrections are applied. The algorithm returns for each galaxy its position, magnitude, bulge to disc ratio, disk size, bulge size, bulge flatness, redshift, position angles, and V-I. A corresponding spectrum is extracted from a spectral library established from PEGASE2 software (www.iap.fr/pegase and Livanou et al, 2009). A shape image can be associated to the galaxy through library of images taken from the HST, rescaled and resampled at the correct distance.

Quasars are simulated from the scheme proposed in Slézak and Mignard (2007). To summarize, lists of sources have been generated with similar statistical properties as the SDSS, but extrapolated to G = 20.5 (the SDSS sample being complete to i = 19.1) and taking into account the flatter slope expected at the faint-end of the QSO luminosity distribution. Since bright quasars are saturated in the SDSS, the catalogue is complemented by the Véron-Cety & Veron (2006) catalogue of nearby QSOs.

The Solar System objects (SSOs) are only a little sample of the total number of objects expected to be observed by Gaia, but their peculiarities strongly condition the design of this part of the Universe Model. The semi-empirical statistical approach (constrained by observations) considered in the other parts of the Universe Model is no longer valid (in this first version of the Solar System Module) due to the high apparent motions of the SSOs. The reason is quite simple: it is not possible to generate a catalogue of objects (along with their physical information) for a certain (static) sky region, since the observed objects in that direction depends on time. Therefore, to generate a catalogue of SSOs we would need to specify both the sky region and observation time. However, if the simulations are required to be done in a reasonable computational time, the computation of the ephemerides along the mission of a set of ($\sim 10^5$) SSOs is not feasible in this first approach.

To solve this problem, the simulation must not be based on a reliable statistical model, but on catalogues containing orbital elements of SSOs, stored on disk. By computing SSOs ephemerides in time, and crossing the obtained positions with the Gaia Scanning Law, only the transiting ones (i.e. the SSOs inside one of the FoVs) at any time along the mission are selected. This transits list contains all the candidates expected to be observed, and obviously, it contains also the transit time in the corresponding FoV, the astrometric data and the apparent magnitude of these objects. This is the basic input for the simulation of the Solar System.

4 Universe Model output and tests

The Universe Model produces output catalogues of astrosources with their astrophysical parameters and all necessary parameters allowing to compute their contribution to Gaia observations (positions, velocities, rotation, light curve, shape, low and high resolution spectra, etc.) to be used by the simulators GASS, GIBIS and GOG. The output can be given either as an ascii file or directly ingested in the Main Data Base for processing.

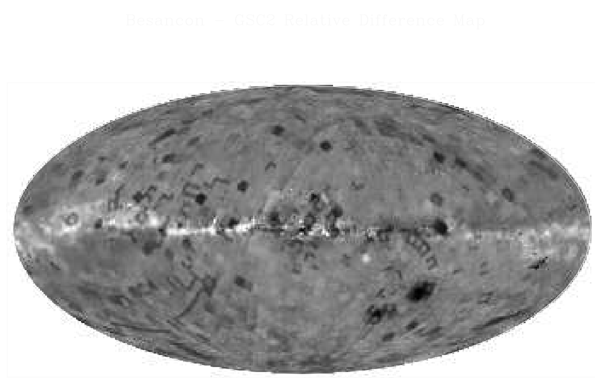

Fig. 2. Difference between GSC2 catalogue star counts at G=17 and galaxy model. Out of the Galactic plane the agreement is better than 10%. Significant excesses in the modelled star counts are found in the Galactic plane, that could be due to incompleteness in the data due to crowding, or to inappropriate model of extinction. Lack of counts in the model are found in the Magellanic cloud region (not included in the model) and in a few squared regions, most probably due to defects in the GSC2 photometric calibration.

In order to ensure that the model is reliable and realistic enough three level of tests are performed: unit tests on individual classes, integration tests on packages, and finally validation tests by comparison with real data. Concerning the third type, the validation of the stellar density has been done by comparing UM outputs with GSC-II catalogue over all sky (Drimmel et al, 2005). An example is given in fig 2. Moreover the Besançon Galaxy Model is extensively tested by comparison with many different data sets at various wavelengths (Robin et al, 2003). More tests are planned, for example on the number and separation of binaries, and by comparison of the model with the Hipparcos catalogue. We are also doing extensive kinematical tests by comparison of the simulations with Tycho-2 catalogue.

Figure 3 shows the predicted number of stars as a function of Galactic coordinates from the Gaia UM.

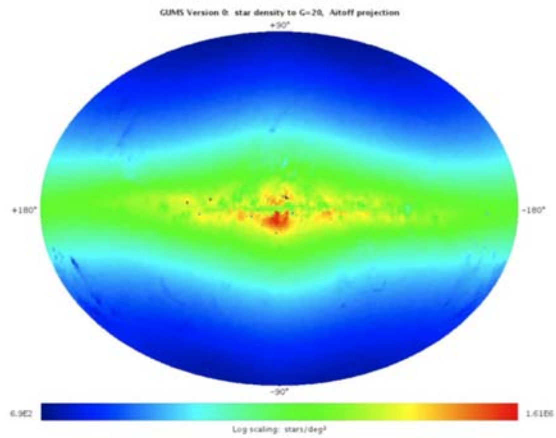

Fig. 3. Expected number of stars at magnitude G=20 from the Gaia DPAC Universe Model simulations GUMS.

5 Perspectives

The Gaia UM serves as providing simulations for testing purposes inside the DPAC. In the future and specially after launch the model will be maintained and will be further used for testing the analysis softwares. When waiting for real data, one will prepare the data interpretation using simulations in order to establish efficient methods for multivariate data analysis. Another application under study consists in doing a bayesian classifier based on prior probabilities computed from the simulations.

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PERSPECTIVES TO SIMULATE GALAXY DYNAMICS

Pfenniger, D.[1]

Abstract. The current practices of modeling the dynamics of galaxies can be projected for the next decade. The exponential growth of computer capabilities has reached a threshold where the particle representation is a superior way to capture subtleties of galactic dynamics than Boltzmann's perfect phase-space fluid representation. The up-to-now often neglected departures of strict symmetries and time invariance of the actual Milky-Way, and the impact on dynamics of stellar physics will need to be modeled in more detail in order to match the observational data and extract more information of it . This will be possible with the coming generation of computers which will allow to represent each individual star of a galaxy. Modeling the interstellar medium will remain a difficult problem for more time though.

1 Introduction

The continuous advances in observational techniques require sometimes to set back and re-examine whether current theoretical methods and assumptions need to be readjusted. The joined exponential growths of the amount of observational data and of the computer capabilities mean that some threshold may be reached beyond which radical changes must be made: this is a typical sign of a scientific "revolution", although this word sounds exaggerated when applied to a specialized field like Galactic astronomy. Indeed, the real major revolution impacting all the society comes from the continuous advances over 60 years of the technologies associated with semi-conductor electronics.

The question we want to address here is whether Galactic astronomy is close to such a threshold. The answer is clearly yes for the period 2010-2020 as argued below.

2 Moore's law

The growth of computing power is a historically unprecedented technological jump, where we have seen about a 30 times performance growth every 10 years over 60 years for electronic components based on semi-conductors. This is commonly called the Moore law, after Gordon E. Moore pointed out (1965) that the transistor density in integrated circuits doubled every year. This growth leads to technological and economical pressure on other technologies like data storage which are incited to follow a similar exponential growth. Almost all the sectors of the society are progressively transformed, including sciences. Most of the progress achieved for example in medicine, or astronomy, follows actually for a substantial part from this technological revolution, which allows pervasive computing.

The other essential aspect of Moore's law is economic. The growth of performance occurs not only in an absolute way, but also on the proportionate decrease of cost for a given performance. This means that a given computational capability is accessible to a larger and larger proportion of laboratories, scientists and people. The performance of the present top super-computers will become easy to afford for average scientists after about 5 to 15 years, and for the general public after 20 to 30 years. For example, a present-day laptop computer is comparable in power to a top high-performance computer of the 80's.

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3 Purpose of computer simulations

For sciences dealing with complex problems, like biology, earth-sciences, or astronomy, high performance computing plays the role that mathematics has fulfilled over the last centuries for physics: to provide tools for modeling the studied objects in a controlled and abstracted way. Physics could profit more of the tools of mathematics than other fields because the studied systems are selected to be as simple as possible. In complex fields the simplest systems are already too complicated to be handled by a pen and paper approach. In astronomy, already an isolated star or an isolated galaxy as a whole are too complicated to be described without computers. This is the reason why the understanding of these objects really progressed since the availability of computers.

Modeling with mathematics or computers is invaluable to reduce the apparent complexity of the studied problems to a level which can be grasped with our finite brains. Indeed, understanding a process is reaching a level of mental representation sufficiently intuitive for not requiring any calculation. As an example, practitioners of galaxy simulations can eventually figure out the outcome of particular initial conditions before performing the computation, like "seeing" in advance how the collision of two galaxies will proceed.

Thus computational science plays an increasingly important role in sciences, complementing traditional mathematics with new tools with no earlier counterpart. Once a complex process is understood, i.e., represented in a way manageable by a human brain, it is possible to think about it, and either find applications for applied sciences, or how to progress along the quest of knowledge in fundamental sciences. In astronomy, typically a better understanding allows to steer observations or instrument development in a more efficient, intelligent way than practicing blind search.

4 Change of paradigm

For a long time the best representation of a collisionless stellar system was thought to be Boltzmann's equation without collision term,

$$\partial_t f + \vec{v} \cdot \partial_{\vec{x}} f - \partial_{\vec{x}} \Phi \cdot \partial_{\vec{v}} f = 0, \tag{4.1}$$

where $f(\vec{x}, \vec{v}, t)$ represents the phase space mass density, and $\Phi(\vec{x}, t) = -G \int d^3x' \rho(\vec{x}', t)/|\vec{x} - \vec{x}'|$ is the gravitational potential generated by the spatial density distribution $\rho(\vec{x}, t) = \int d^3v f(\vec{x}, \vec{v}, t)$. This continuous representation of, in reality, a granular mass distribution was made on the model of gas or plasma kinetic where the number of particles is typically of the order of 10^{26}, suggesting to take the limit of an infinite number of particles and to represent the flow of particles as a smooth differentiable flow in phase-space. Note that in gas kinetic the molecule collisions, even if rare, are the essential ingredient making the path of molecules chaotic, rapidly unpredictable, and leading to a smooth f. In stellar dynamics, without collisions the star trajectories may preserve correlations and memory of the past that should lead, a priori, to irregular, non-differentiable f. This point, how and why f should be differentiable, is an open question in stellar and galactic dynamics. A smoothing mechanism is required. A possible candidate is Miller's (1966) exponential N-body system instability, but this remains to be better documented.

In a galaxy made of N stars, N is however never very large as for molecules in a gas container. If we adopt $N = 10^{11}$ and want to discretize phase space in a number of bins, we can have at most N populated bins, that is, at most $N^{1/6} \approx 68$ divisions per phase space coordinate, which is not a very smooth representation of the, in principle, differentiable function f. Actually, with 1 cell per particle the representation is like a sum of delta functions, far from representing a differentiable function; using, say, 100 particles per cell to smooth fluctuations brings down the number of divisions per phase space coordinate to 32: the averaged function is smoother but the bin resolution is then lower.

So the collisionless Boltzmann equation when applied to galaxies has conceptual difficulties to match well the intended systems. In contrast, the N-body model is a much more faithful representation of an ensemble of stars in mutual gravitational interaction. The problem in the past was that the description of the N-body evolution was leading to a unaccessible amount of computations. Contrary to gas kinetics, classical thermodynamics is not applicable to stellar systems since gravitation is a long ranged force, making gravitational systems non-extensive. Extensivity is an essential assumption with usual statistical mechanics. As a result, astronomers have been forced to use numerical simulations to describe self-gravitating systems, which they did as soon as computers became available.

There are several observational constraints which also demand to abandon the idea that a differentiable f is a good way to represent the distribution of stars:

1. The local stellar kinematics obtained from from Hipparcos and other sources (e.g. Dehnen 1998) shows that the velocity distribution of local stars is non-smooth, made of clumps in phase-space. Here we obtain an observational local evidence that f is not well represented by a differentiable function resembling a Maxwellian distribution.

2. Infrared view of the spiral stellar content (e.g. Seigar & James 1998) shows that spiral arms are strong non-linear density perturbations, so that self-gravity is locally not negligible in stellar arms. This raises doubt that axisymmetric static Milky-Way models where spirals are at most weak perturbations in a smooth potential assumptions for describing the stellar motions inside the Milky-Way.

3. Milky-Way CO surveys, such as the one of Dame et al. (2001), show that cold gas distribution is very clumpy and irregular, unlike what would be expected using classical gas dynamics of non-self-gravitating gases. The clumpiness of molecular clouds actually shows the evidence that the gas distribution at least is highly time-dependent at small scale, introducing a "noise" in the global potential. Again molecular clouds are at least partly self-gravitating over a range of scales, which raises doubt about a straight use of thermodynamics in such systems.

4. The stellar halos of the Milky-Way and nearby galaxies has been progressively mapped in sufficient detail (e.g. Ibata et al. 2005) to show a highly intricate structure made of stellar streams and dissolving dwarf galaxies contradicting the classical representation of these halos as virialized, steady structures. If we include in the stellar halo the galaxies orbiting the Milky-Way and also perturbing it, we obtain again another source of time-dependence.

Otherwise there are theoretical evidences that typical galactic potentials must be time-dependent:

1. Sellwood & Sparke (1988) showed first that barred galaxies are surrounded by spiral arms that rotate at one or several pattern speeds, but slower than the bar one. This breaks the time invariance that can be kept in barred galaxies when describing the galaxy in the bar rotating frame of reference. There is no way to avoid therefore time-dependence in barred galaxies with surrounding spiral arms.

2. Fux (1997,1999) could match several of the inner Milky-Way characteristics and fine details in the stellar and gas distribution by running N-body simulations and finding the best location of the Sun in the disk and at a given time in the run. Each of the best fits found is only valid over a very short time, of order of a few 10^6 yr, which means that the model is highly time-dependent with respect to the level of detail of the Milky-Way that we can use for constraining models. It means that if we would observe the Milly Way a few 10^6 yr earlier or later, we would observe substantial differences, especially in the gas distribution.

All these works point to the need to consider the Milky-Way as a time-dependent and non-axisymmetric system. Only self-consistent N-body models can achieve the detail level required by future observational data.

5 Future simulations

Moore's law has brought us today to reach the level where $N \sim 10^{10} - 10^{11}$ particles can be followed in a super-computer. This has been achieved recently in cosmological simulations (Teyssier et al. 2009; Boylan-Kolchin et al. 2009), because cosmological simulations require less integration time steps than typical galaxy simulations. However with the growth of computer power it is clear that the threshold of representing every star, or every star more massive than the Sun, in a Milky-Way type galaxy model is within reach, less than 10 years. The sensible problem of softening then almost disappears. Only in this way can phase space correlations such as streams be studied and compared with observations. At this level star formation and evolution can be followed too, first in simplified ways. Energy and momentum transfer between stars and the interstellar gas is an important aspect of the global dynamics, but also it will be important to follow the stellar mass loss from AGB stars that over several Gyr must have also a dynamical effect on the global galactic structure.

The effects of the environment such as accretion will be more and more taken into account in galaxy models, because from the cosmological context the environment appears as having played an especially important factor in the past, but will continue to impact the evolution of the Milky-Way for the next billions years. For example our version of the Milky-Way/Andromeda merging, is forecast for taking place during the next $\sim 3 - 8$ Gyr. A snapshot of a movie of the whole sky appearance made for educational purpose is shown in Fig. 1.

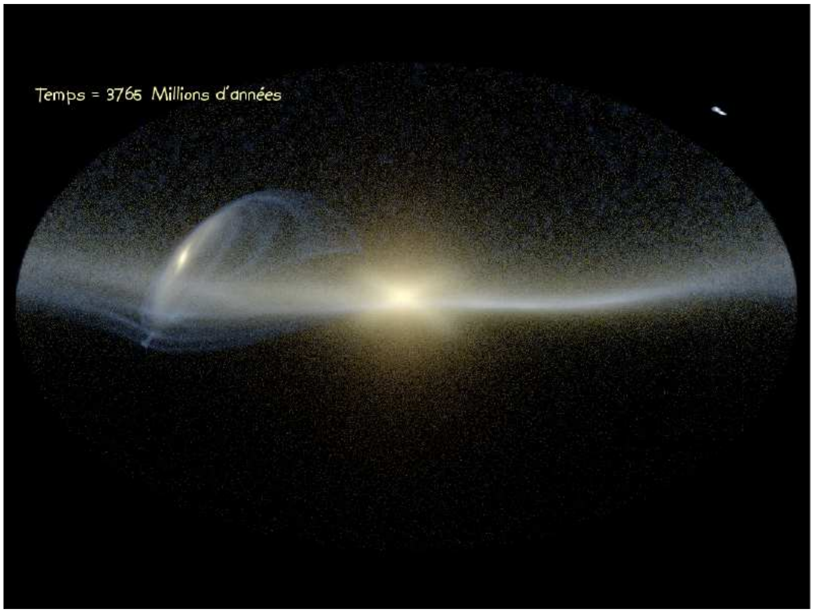

Fig. 1. The whole sky 3765 Myr from now as viewed from the Sun in a $30 \cdot 10^6$ particle simulation of the Milky-Way/Andromeda merging (Revaz & Pfenniger 2010). A drastic change of the Milky-Way appearance will occur illustrating how time-dependence then will still be a relevant property of the Milky-Way.

Interstellar gas dynamics will stay a very hard physical and computational problem though, due to the high dynamical and time ranges taking place in the interstellar medium. Springel (2009) using computational geometry methods (Voronoi cell spatial decomposition and finite volume scheme preserving flow invariants) has showed how to solve several pending problems in traditional Eulerian and Lagrangian hydrodynamical simulations. His scheme seems promising and removes in an elegant way shortcomings of both the Eulerian and Lagrangian approaches, at the expense of a larger software complexity.

In addition, the physics of the interstellar medium, and in particular of dust grains, is crucial for representing correctly cooling, chemistry and radiation transfer in the Galaxy. Presently the main barrier is more understanding the basic physics at play rather than modeling it on the computer. This is certainly an aspect that will need much more time than global dynamics for being mastered.

6 Conclusion

At the level of precision reached by present and future instruments, disk galaxies must be seen as time-dependent structures with multiple patterns rotating at different speeds. Modeling the optical part of the Milky-Way with N-body models containing as much particles as stars is feasible during the next decade. However gas and dust modeling will remain a difficult, not to underestimate problem for a longer time.

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TESTING GRAVITY IN THE MILKY WAY WITH GAIA

Famaey, B.[1] and Bienaymé, O.[1]

Abstract. With the advent of Gaia, it will be possible to design tests of gravity on the scale of the Galaxy. Observations of external galaxies indeed suggest a one-to-one analytic relation between gravity at any radius and the enclosed baryonic mass, a relation summarized by Milgrom's law of modified Newtonian dynamics (MOND). Within its modified gravity interpretation, MOND makes very specific predictions allowing to differentiate it from a spherical halo of dark matter. Here, we show that MOND can be tested with Gaia by measuring dynamically the disk surface density at the solar radius, the radial mass gradient within the disk, or the velocity ellipsoid tilt angle above the Galactic plane at various heights and various Galactocentric radii. However, these tests require an extremely accurate baryonic mass model for the Milky Way.

1 Introduction

The long-term goal of the Gaia mission is to get an accurate estimate of the Galactic gravitational potential by analyzing the motion of several hundreds millions stars up to ~ 15 kpc: the full dataset should be available around 2020. However, when the first releases of data will be available around 2015, it will already be possible to answer crucial questions about the dynamics of our Galaxy. Among them, a currently harshly debated question is whether the missing mass problem is due to the existence of dark matter or to a modification of the gravitational law on galaxy scales. Here, following the work of Bienaymé et al. (2009), we show how large-scale spectroscopic and astrometric surveys in general, and Gaia in particular, could help answer this question.

2 Cold Dark Matter or Modified Newtonian Dynamics?

The concordance cosmological model based on the existence of Cold Dark Matter (CDM) is very successful on large scales. However, the predictions of the model are in contrast with a number of observational facts on galaxy scales. A non-exhaustive list of issues is (i) the predicted overabundance of satellite galaxies; (ii) the prediction of cuspy dark matter halos, whereas observations point toward dark halos with a central constant density core; (iii) the problems to form large enough baryonic disks due to their predicted low angular momentum within simulations; and (iv) the departures from the CDM scenario recently found in tidal dwarf galaxies (e.g., Gentile et al. 2007). In addition to these discrepancies with observations, galaxies also follow tight scaling relations that are hard to explain without much fine-tuning of CDM. For instance, (i) the baryonic Tully-Fisher relation (relating the baryonic mass of a disk galaxy to the fourth power of its circular velocity), whic! h is valid for all disk galaxies with negligible scatter; (ii) the Faber-Jackson relation (relating the luminosity of an elliptical galaxy to the fourth power of its velocity dispersion), valid for elliptical galaxies, and more generally, the fundamental plane for elliptical galaxies; (iii) the universality of the dark and baryonic surface densities of galaxies within one scale-length of the dark halo (Gentile et al. 2009); and (iv) the mass discrepancy-acceleration relation (relating the dark-to-baryonic mass ratio to the gravitational acceleration), which holds for all disk galaxies at any galactocentric radius (McGaugh 2004). This last relation notably involves an acceleration scale $a_0 \sim 10^{-10}$ ms^{-2} whose significance is far from clear. Below this gravitational acceleration, the enclosed dark mass starts to dominate over baryons in galaxies, and this acceleration scale also fixes the slope and zero-point of the Tully-Fisher and Faber-Jackson relations. Final! ly, galactic rotation curves often display obvious features (bumps or wiggles) that are also clearly visible in the stellar or gas distribution ("Renzo's rule"), which is difficult to understand in galaxies dominated by collisionless dark matter.

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Table 1. Values predicted from the Besançon MOND model as seen by a Newtonist compared to observations, for the local surface density and the tilt of the velocity ellipsoid.

	Besançon MOND	Observations
$\Sigma_\odot(z = 1.1\,\mathrm{kpc})$	78 $M_\odot/\mathrm{pc}^2$	74 ± 6 $M_\odot/\mathrm{pc}^2$ (Holmberg & Flynn 2004)
Tilt at $z = 1$ kpc	6 degrees	7.3 ± 1.8 degrees (Siebert et al. 2008)

This could thus all point towards a modification of the gravitational law on galaxy scales: for instance, Milgrom (1983) postulated that for gravitational accelerations below a_0, the true gravitational attraction g approaches $(g_N a_0)^{1/2}$ where g_N is the usual Newtonian gravitational field (as calculated from the observed distribution of visible matter). This alternative paradigm is known as modified Newtonian dynamics (MOND), and uncannily explains all the scaling relations mentioned above (but it does not work for galaxy clusters). Such a modification of Newtonian dynamics could come at the classical (non-covariant) level from a modification of either the kinetic part or the gravitational part of the Newtonian action (with usual notations; ϕ_N being the Newtonian gravitational potential):

$$S = \int \frac{1}{2}\rho v^2 d^3x\, dt \; - \int \left(\rho\phi_N + \frac{|\nabla\phi_N|^2}{8\pi G}\right) d^3x\, dt, \tag{2.1}$$

where modifying the first term is referred to as "modified inertia" and modifying the second term as "modified gravity". Bekenstein & Milgrom (1984) have devised a modified gravity framework in which $|\nabla\phi_N|^2$ is replaced by $a_0^2 F(|\nabla\phi|^2/a_0^2)$ in Eq. 2.1, where $F(y)$ is a free function with defined asymptotic properties reproducing $g = (g_N a_0)^{1/2}$ in the spherically symmetric weak-field limit.

Within this Bekenstein & Milgrom modified gravity interpretation, MOND makes very specific predictions allowing to differentiate it from a spherical halo of dark matter. Here, we outline these predictions, that Gaia and other large-scale surveys could help to test.

3 How Gaia can help

We build these predictions using the free function $F(y)$ of Famaey & Binney (2005) and the MOND Milky Way model of Wu et al. (2008)[1]. This model is based on one of the most realistic possible baryonic mass models of the Milky Way, the Besançon model (Robin et al. 2003).

Once the MOND gravitational potential of the model is known, one can apply the Newtonian Poisson equation to it, in order to find back the density distribution that would have yielded this potential within Newtonian dynamics. In this context, as shown in Bienaymé et al. (2009), MOND predicts a disk of "phantom" dark matter allowing to differentiate it from a Newtonian model with a dark halo

(i) By measuring the force perpendicular to the Galactic plane: at the solar radius, MOND predicts a 60 percent enhancement of the dynamical surface density at 1.1 kpc compared to the baryonic surface density, a value not excluded by current data. The enhancement would become more apparent at large galactic radii where the stellar disk mass density becomes negligible.

(ii) By determining dynamically the scale length of the disk mass density distribution. This scale length is a factor ∼1.25 larger than the scale length of the visible stellar disk if MOND applies. Such test could be applied with existing RAVE data (Zwitter et al. 2008), but the accuracy of available proper motions still limits the possibility to explore the gravitational forces too far from the solar neighbourhood.

(iii) By measuring the velocity ellipsoid tilt angle within the meridional galactic plane. This tilt is different within the two dynamics in the inner part of the Galactic disk. However the tilt of about 6 degrees at z=1 kpc at the solar radius is in agreement with the recent determination of 7.3 ± 1.8 degrees obtained by Siebert et al. (2008). The difference between MOND and a Newtonian model with a spherical halo becomes significant at z=2 kpc.

[1]We use the model labelled "MOND $g_{\rm ext} = 0.1 a_0$" in Wu et al (2008), meaning that the modulus of the external gravitational field acting on the Milky Way is chosen to be $a_0/100$

Such easy and quick tests of gravity could be applied with the first releases of future Gaia data. To fix the ideas on the *current* local constraints, the predictions of the Besançon MOND model are compared with the relevant observations in Table 1. Let us however note that these predictions are *extremely* dependent on the baryonic content of the model, so that testing gravity at the scale of the Galaxy heavily relies on star counts, stellar population synthesis, census of the gaseous content (including molecular gas), and inhomogeneities in the baryonic distribution (clusters, gas clouds).

We thank HongSheng Zhao, Xufen Wu, and Dominique Aubert for their contribution to Bienaymé et al. (2009).

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POSTERS

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• Gaia RVS data reduction: the 6th dimension. F. Meynadier et al.

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SOME ASPECTS OF STELLAR MODELLING IN THE GAIA TEAM AT THE OBSERVATOIRE DE LA CÔTE D'AZUR

Merle, T.[1], Santoro, L.[1], Pichon, B.[1], Bigot, L.[1], Thévenin, F.[1] and Morel, P.[1]

Abstract. The objective of the Gaia mission (2012) is to provide the largest and most accurate astrometric survey of our Galaxy. From Gaia measurements, information will be derived about the history of our Galaxy, its early formation and its chemical composition. It is therefore of crucial importance to develop and test the methods and tools that will be used in the processing and analysis of the data. The derivation of the chemical abundances will impact on the formulation of the galactic evolutionary models. We present our investigations on –1– NLTE effects on atomic line profiles, the use of 1D or 3D modelling of the atmospheres and –2– radiative diffusion and rotation on stellar evolution models.

1 3D NLTE line formation

We are currently building new accurate and up-to-date atomic models that will be used with different model atmospheres to produce reliable line data to perform the chemical abundance determinations. Tests are performed in the framework of the SAM group which involves different institutes, namely Uppsala, Nice, Meudon, Oslo (Stellar Atmosphere Modelling : `http://www.astro.uu.se/~ulrike/GaiaSAM`).

The atomic models in progress are Ca I, Ca II, Mg I and II. They are important for the chemical evolution of the Galaxy because they are good α–elements tracers. Several studies modelizing Ca lines exist (one of the most recent is Mashonkina et al. 2007), demonstrating the importance of NLTE effects on Ca II IR triplet lines. These lines are essential for the Gaia RVS (Radial Velocity Spectrometer). In this respect, we are performing a very realistic and complete atomic model of Ca I & II. We will use these atomic models together with 3D models of stellar atmospheres to perform full 3D NLTE line synthesis with the code MULTI (Carlsson 1986).

We show on Fig. 1 a comparison between LTE (code MOOG) and NLTE (code MULTI) 1D line synthesis with a MARCS atmospheric model (Gustafsson et al. 2008) of Sun for the 8498 Å line of the CaII IR triplet. The synthetic profiles are compared with the integrated solar flux called FTS (Brault & Neckel 1987). The NLTE treatment fits better the line core of the observed flux than the LTE treatment. The line core cannot be fitted perfectly because of the absence of chromosphere in the MARCS atmospheric model. Indeed, the line core of Ca II triplet is formed in the upper layers of the atmosphere. Moreover, we can note the asymmetry in FTS data due to the convection that can be impossible to reproduce with 1D static atmospheric model.

We are also currently working on 3D models of the Sun and stars to get better fits (asymmetry, line shifts). The 3D approach gives a more realistic interpretation and prediction of the velocity fields in the atmosphere, something that 1D hydrostatic models are incapable of. Indeed, because of their hydrodynamical approach, the 3D models do not need any free parameters such as the macro-, micro- turbulence and mixing-length. The use of these time-dependent, 3D, hydrodynamical atmospheric models to compute stellar abundances has already proven to give significative differences compared with 1D modelling in particular for metal-poor stars and has already led to a significant revision of the solar abundances (Asplund et al. 2005), even if it is still debated (see, for instance, the last review of Aspund et al. 2009).

2 Improvements of stellar evolution models

We are testing the contribution of the rotation on the theoretical evolutionary tracks in the HR diagram for 1D models of stars. As a first application, we follow the work of Lebreton et al. (2001), using the Hyades

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cluster because there are 5 binary stars with estimated masses and the metallicity is well known. Moreover, the projected rotational velocities for the binary systems and for several single stars have been measured by several authors (Glebocki et al. 2000 and Nordstroem et al. 2004). For the binary systems we have an estimate of the rotational velocity V_{rot} and for the other stars we proceed with a statistical inversion approach (Chandrasekhar et al. 1950). The V_{rot} estimate will be used in the code Cesam2k (see `http://www.oca.eu/cesam`) with implemented theory of rotation described in Mathis & Zahn (2004) and the chemical element diffusion. In this manner, we investigate the contribution of these processes for the stellar evolution and their effect on chemical abundances concerning the determination of masses and ages. Now, we can build new theoretical isochrones of the Hyades cluster and determine its age. Several other clusters will be investigated with the same procedure to test the influences of the rotation on stellar age determination with the future Gaia data.

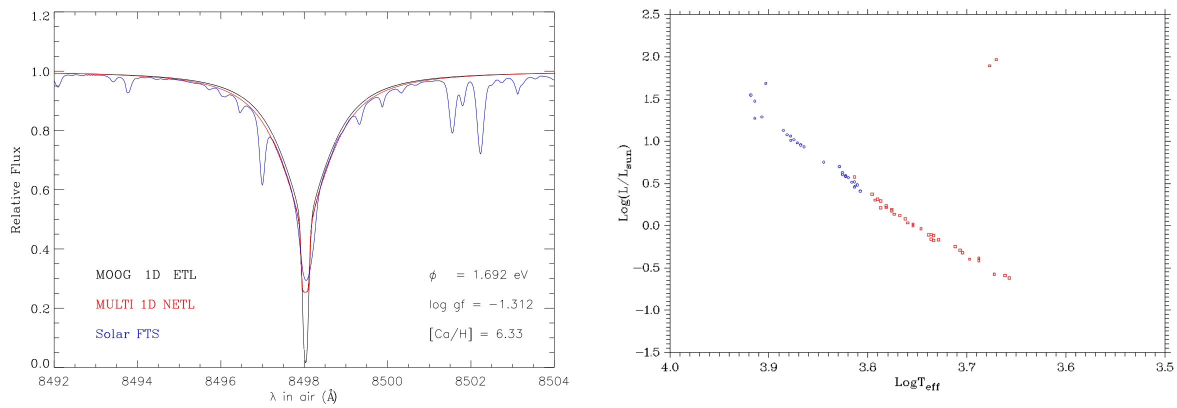

Fig.1. Left: comparison LTE / NLTE of a flux profile of the Ca II line at 8498 Å. Right: HR diagram of Hyades cluster. Red dots represent stars with $V_{rot} \leq 20$ km s^{-1} and blue dots stars with $V_{rot} \geq 20$ km s^{-1}.

3 Conclusion

The use of realistic stellar atmospheres (3D hydrodynamic LTE atmosphere + NLTE radiative transfer with accurate atoms) and stellar evolutions (evolution with radiative diffusion with/without rotation) would provide astrophysical analysis tools for a better determination of stellar parameters which will be of crucial importance for the interpretation of results of the Gaia mission. In particular, it will lead to:
- More realistic stellar abundances which will provide better Galactic abundances;
- Better constraints on ages and masses for the open clusters like the Hyades;
- Calculation of convective lineshifts for Zero-Point Radial velocities with applications to Gaia;
- New limb darkening calculations for stellar interferometry diagnostics providing more accurate stellar diameters using VLTI (Bigot et al. 2006) or the CHARA instruments;

which are the recent works in progress in our group.

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GAIA RVS DATA REDUCTION : THE 6^{TH} DIMENSION

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Abstract. This poster describes the current organisation of RVS data processing among the Gaia-DPAC (Data Processing & Analysis Consortium), with a particular focus on the French community's contribution.

1 Introduction

The Radial Velocity Spectrometer (RVS) is a slitless spectrometer which will operate in the Gaia satellite. As its name suggests it will, amongst other tasks, determine the radial velocity of a large number of sources (100 to 200 million) : this will give us access to the only component of the star's velocity which can not be determined by astrometry. It has to be noted that measuring radial velocity simultaneously with astrometric and photometric parameters measurements is a significant improvement over Gaia's precursor, the Hipparcos mission.

2 RVS Data reduction within the global GAIA data reduction scheme

The Gaia Data Processing & Analysis Consortium (DPAC) is organised into several coordination units which cover the whole data processing chain. One of these coordination units, CU6, is devoted to the RVS data processing, taking almost raw instrumental data as input. Its output is then directed to the Main Database (which will feed the catalogue) and to other scientific chains for further analysis.

In practice, the CU6 algorithms will be run at the CNES Data Processing Center which will also host CU4 (Object processing) and CU8 (Astrophysical Parameters) software. The CNES is responsible for integrating the software modules written by scientists in Java, and running them on dedicated hardware.

3 Processing chain

The processing chain is divided into 5 packages : Extraction, calibration, radial velocity zero-point, single transit analysis and multiple transits analysis.

The first step is to retrieve pixel blocks, disentangle overlapping objects, remove contaminants and perform appropriate geometric transformations in order to output a cleaned 1D spectrum.

The calibration step is indeed a self-calibration, as there is no internal calibration source. This self-calibration relies on redundant observations throughout the mission.

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Zero-point determination for radial velocities supposes a wide search for RV standard stars with homogeneous coverage of the sky. This is currently performed by several ground-based observation programmes, which data will be compared to RVS measurements in order to settle the RV zero-point (see poster by Crifo et al., this meeting).

"Single Transit Analysis" (STA) consists in fitting template spectra to the measured spectra, thus determining the source's radial velocity for each "transit" (meaning "each time the source passes across the focal plane").

"Multiple Transit Analysis" (MTA) gathers data from STA every 6 months and performs additional analysis (such as variability detection and basic modelling).

4 Scientific objectives

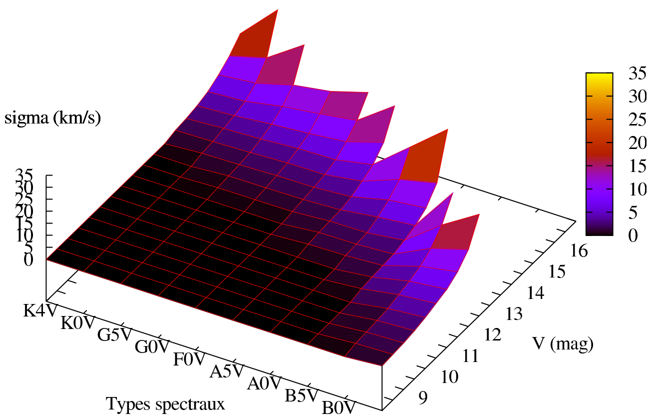

Fig. 1. Uncertainty on RV determination as a function of spectral type and V magnitudes, as derived from RVS performance simulations. This radial velocity survey will cover the whole sky up to 17th magnitude for late type stars, which show the strongest lines in the RVS spectral range. For a given magnitude, RV will therefore be more accurately determined for solar-type stars.

This survey will contribute to our knowledge of the Galaxy's kinematics and dynamics, but the spectra will also bring some information about effective temperature and surface gravity. Some emission lines will also be detected and will help characterizing B[e] stars or stars with envelopes or accretion discs. Other goals are reachable when analysing RVS data together with photometric data collected by the BP/RP instrument : chemical abundances will be determined for a large number of sources, which will allow to study their distribution and therefore bring insights about the dynamical and chemical of the galaxy, origin of the halo, the search for extremely metal-poor objects, studies of the thick disk. Open questions like the existence of a vertical chemical gradient in the disk may be addressed, and the chemical aspects of stellar associations and streams that Gaia will find will be studied.

5 French involvement

The French astrophysical community is strongly represented in the RVS data processing preparation, in collaboration with (mainly) UK (Mullard Space Science Laboratory) and Belgium (Observatoire Royal, Institut d'Astrophysique et de Géophysique).

David Katz (GEPI–Observatoire de Paris) is the coordinator of this unit, assisted by Mark Cropper (MSSL, UK) and Frédéric Meynadier (GEPI). The first two steps of the processing chain (extraction and calibration) as well as MTA are under MSSL responsibility; zero-point determination is led by Gérard Jasniewicz (GRAAL, Université de Montpellier) and STA is led by Yves Viala (GEPI). Specific CU6 simulations are realised by Paola Sartoretti (GEPI). On CNES side, technical coordinator Anne Jean-Antoine Piccolo and quality insurance manager Anne-Thérèse Nguyen are responsible for integrating and running the software for CU6.

Overall, the 26 persons whose names appear on this poster account for approximatively half of the people working for CU6 across Europe.

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DETERMINATION OF PLANETARY SYSTEMS WITH GAIA

Rambaux, N.[1], Couedtic, J.[1], Laskar, J.[1] and Sozzetti, A.[2]

Abstract. The astrometric performance of Gaia will allow to discover thousands of extrasolar planets. This work especially focuses on the detection of multiple-planet systems subject to strong gravitational interactions, for which the assumption of independent Keplerian orbits breaks down. We present the first results obtained by using a Bayesian approach to fit the numerous parameters of the systems.

1 Introduction

The astrometric performance of Gaia (few μas) will allow to discover thousands of extrasolar planets (Sozzetti et al. 2007; Casertano etal 2008). Therefore, in these papers it is shown that Gaia might detect massive planets (Mp 2-3 MJupiter) at an orbital distance from 1 to 4 AU.

In this large sampling of extrasolar planets, Gaia will detect systems with multiple companions and some of them will present complex dynamics through strong gravitational interactions and/or resonant orbits. For these systems independent Keplerian orbits break down. This work focuses on the detection of multiple-planet systems subject to strong gravitational interactions. We present the first results obtained by using a Bayesian approach in order to fit the numerous parameters of the planetary systems.

2 Model and Bayesian approach

We study perturbations induced by planetary companions on the barycentric motion of the star in the astrometric data. Therefore the astrometric signature for one planet is

$$\alpha = \frac{a_p}{d} \frac{M_{pl}}{M_\star} \tag{2.1}$$

where, M_p, $M_\star$ are masses of the planet and star, a_p semi-major axis of the orbit and d distance Earth-Extrasolar system.

The number of parameters to fit in this problem is 7 times the number of planets, where the 7 variables are the semi-major axis (or log(Period)), eccentricity, inclination, ascending node, argument of periastron, mean anomaly, and planetary mass.

Ford (2005), Ford etal (2005), and Gregory (2007) applied successfully the Bayesian approach to radial velocity measurements. Following these works we develop a Bayesian model to fit multi-planetary systems to Gaia astrometic data. Indeed, the Bayesian method is well designed to explore efficiently the parameter space and to avoid local minima inherent to Levenberg-Marquardt method or high number of iteration as in Genetic Algorithms (see discussion in Ford 2005). We use a Markov Chain Monte Carlo (MCMC) technique in order to compute the probability functions that is well suited for high-dimensional parameter spaces. The orbital problem is solved by numerical integration of the N-body problem in order to take into account the mutual interactions. Figure 1(a) is a simulation that illustrates the behavior of one (very short) Markov Chain and Figure 1(b) shows the corresponding probability distribution for the eccentricity. In this optimistic case the MCMC method converges towards the expected orbital values.

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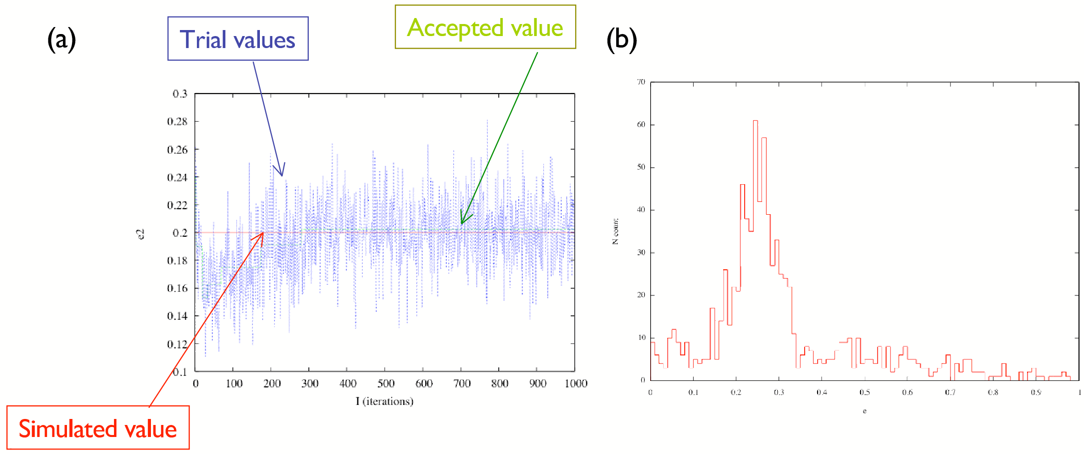

Fig. 1. (a) Example of Markov Chain (in practice the chain is around 10^5 iterations). (b) Probability distribution for the eccentricity.

We carry on to improve the model and to test the convergence process for various scenarios of orbital configuration. The first main difficulty in the Gaia framework is to develop an automatic scheme. Indeed, the efficiency of the Markov Chain depends on the correct ratio of rejected/accepted trial in order to sample well the parameter space (and to find the global minimum) in a relatively short computer-time. The second point is to introduce the Gelman-Rubin criteria in order to decide the convergence of the chain. The main challenge for the Gaia module is to obtain an automatic and efficient algorithm for measurements and at the same time an algorithm robust enough to avoid false detections.

3 Stability Criteria

In order to obtain realistic orbital parameters, we check the fit with stability criteria. One possibility is to use analytical (i.e. fast) stability criteria such as the Hill criterion (Marchall and Bozis 1982; Barnes and Greenberg 2007):

$$-\frac{2M}{G^2 M_*^3} c^2 h > 1 + 3^{4/3} \frac{m_1 m_2}{m_3^{2/3}(m_1+m_2)^{4/3}} - \frac{m_1 m_2 (11 m_1 + 7 m_2)}{3 m_3 (m_1+m_2)^2} \tag{3.1}$$

where M is the total mass of the system, m_1 is the mass of the more massive planet, m_2 is the mass of the less massive planet, m_3 is the mass of the star, G is the gravitational constant, $M_* = m_1 m_2 + m_1 m_3 + m_1 m_2$, c is the total angular momentum of the system, and h is the energy.

Nevertheless, this criteria is not efficient for resonant orbits or more than 3-body problem. Other criteria are studied as for example the chaotic diffusion of orbits.

This work inscribes in the module CU4-DU437 of Gaia. Its objective is dedicated to the search of the stability of the extrasolar planets and to characterize the existence of planetary companions (N2) with strong mutual interactions.

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THE GAIA-RVS STANDARDS: A NEW FULL-SKY LIST OF 1420 STARS WITH RELIABLE RADIAL VELOCITIES

Crifo, F.[1], Jasniewicz, G.[2], Soubiran, C.[3], Veltz, L.[4], Hestroffer, D.[5], Katz, D.[1], Siebert, A.[6] and Udry, S.[7]

Abstract. The Gaia-RVS is a integral-field spectrograph with no calibration device onboard. The instrument will be self-calibrated through the reduction procedure; but it needs a list of well-know stars to define the zero-point and to initiate the iterative reduction process. The IAU RV-standards are not numerous enough (some 140 objects; whereas some 1500 are needed), and many are too bright for the RVS. A new list has been defined, with criteria adapted to the RVS capabilities: magnitude and spectral range, no double stars, no variables, "clean" environment up to 80 arcsec, uniform sky coverage. The stars were taken from a few existing good lists, and each one needs to be reobserved at least 2 times before launch (2012), and also during the mission (end 2018). The list is now ready, and the reobservations are going on at high rate. This list should be released in a near future, so that everyone can use it, and eventually improve it.

1 The need for ground-based standards, and reference star selection

The RVS is designed mainly for measuring radial velocities of the brightest Gaia targets. Such a device had been missing on HIPPARCOS; however, due mainly to weight problems, it must be extremely light, and hence contains NO onboard calibration device for this slitless spectrograph. The wavelength calibration has to come from target stars for which the radial velocity is already known from ground- based measurements with a much higher accuracy. The expected final accuracy on the RVS stars is 1 to 15 km/s, depending on magnitude and spectral type.

Bright asteroids are the best references, as their velocity can be calculated theoretically with great accuracy; but they are not numerous enough and not well distributed on the sky; therefore stars have to be used too. These reference stars must be selected with care and verify a list of requirements, among them RV-stability within 100 m/s at the end, non-multiplicity, and lack of disturbing neighbours within the selection window (80 arc-sec), FGKM non-variable stars, etc. All these stars must have already several measurements available in the literature, and are all taken from the Hipparcos Catalogue for homogeneity reason. They are selected within the three following published lists: Nidever et al. (2002); Nordström et al. (2004; mostly CORAVEL data); Famaey et al. (2005; CORAVEL data). A list of 1420 stars (hereafter g8 list) well distributed over the sky is now defined, and each star must be reobserved at least two times before launch, and then during the mission, in order to insure that they are stable.

2 Status of ground observations

Three spectrographs are used: Sophie at OHP and Narval at Pic du Midi for the northern stars; and Coralie at La Silla (swiss Euler Telescope) for the southern ones. In addition, most spectra contained at OHP in the

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Elodie archive are also available. Figure 1 left shows the sharing between the spectrographs. Some stars are in common between the various spectrographs. Bright asteroids are systematically observed during each observing run. The Narval spectrograph is of special interest, as it is the only one covering the RVS spectral interval (847 - 874 nm): a same spectrum over the total available interval is reduced with 2 different procedures, the first using the Elodie-Sophie spectral interval (390 - 690 nm), and the second one over the RVS interval (see figure 2, right). As the spectral lines included are not the same, a small difference is expected, and is presently investigated.

In conclusion, the observations are going well, but need to be continuated at the present rate.

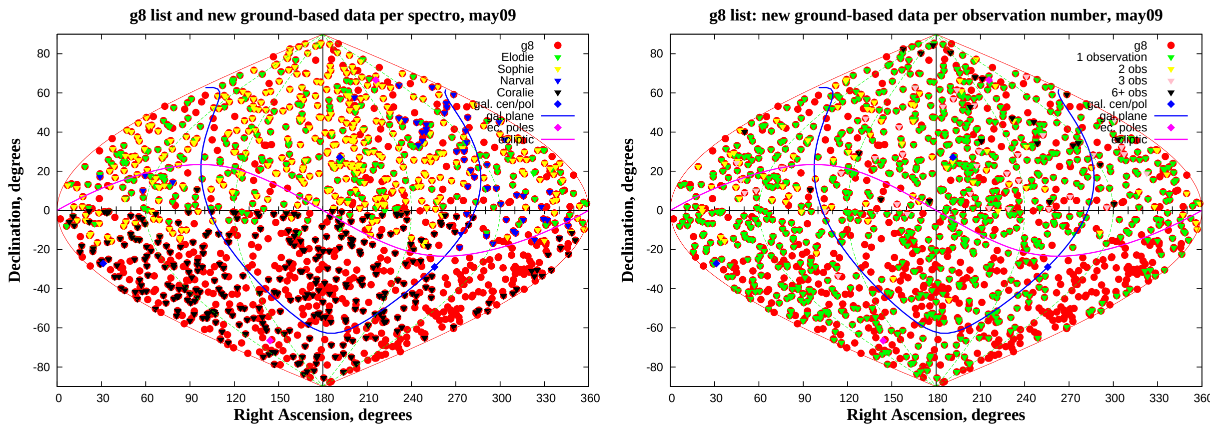

Fig. 1. Maps of reobservations. Left : Share-out of the stars between the spectrographs. **Right**: Number of reobervations per star with a SAME spectrograph. Red dots indicate stars not yet reobserved in May 2009.

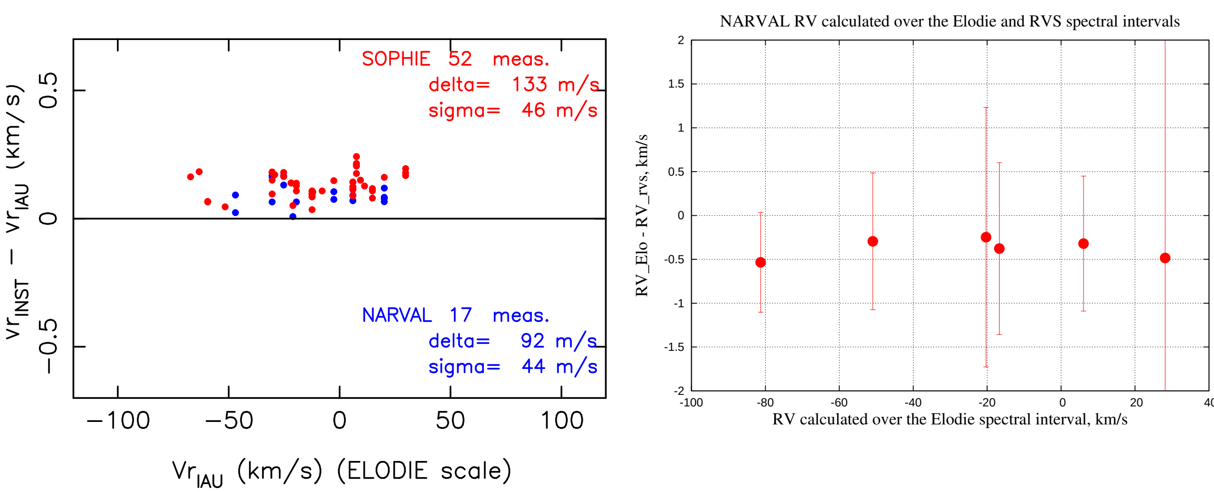

Fig. 2. Left : Comparison of RVs obtained by SOPHIE and NARVAL for several IAU standards, with the IAU value. **Right**: RV derived from the same NARVAL spectra over the Elodie and RVS spectral intervals; very preliminary values.

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