Astronomy and Astrophysics in the Gaia sky
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Tribute to François Mignard's research

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It is a great pleasure for me to report about your colleague and my friend François Mignard. I know him since now 43 years and shared with him some scientific adventures. If, because of my age, I had to leave the Gaia project, I have followed the tremendous work done since by François Mignard and noticed that, despite his masterly played role as the conductor of the Gaia orchestra, he kept an important scientific activity. Actually, Gaia is far from being all his scientific achievements. And this is what I shall try to convince you.

In 1974, François Mignard graduated in Physics from the Ecole Normale Supérieure, a renown University level establishment in Paris which, in U.K. and USA would be called *College*. Then, he came to Nice with an assistantship at the University and decided to start his scientific career at the newly created CERGA in Grasse (Centre d'études et recherches géodynamiques et astronomiques). Progressing in his university third cycle curriculum, he had to make an original scientific research. I proposed him to work on the motion of a high eccentricity satellite and apply his results to the motion of Nereid. I thought that it would be a good preparation for a doctoral thesis, but the resulting paper astonishingly solved most of the difficulties. The tables derived from his theory were used by the international Ephemerides. This is how I discovered that François was an exceptionally gifted researcher.

He later proposed himself the subject of his doctoral thesis *Tidal phenomena in the evolution of planet-satellite system*, a very difficult and a new subject at that time,. The result was a remarkable piece of work whose application to the evolution of the lunar orbit was described in three articles in *The Moon and Planets* from 1979 to 1981. Using the same algorithms, he also studied the problem of the evolution of the motion of the satellites of Mars. He published a paper on the subject in the Monthly Notices. There he showed that the Laplace plane, used as an intermediary reference, allowed to understand the long-term evolution of the orbit of Phobos. He used a similar approach in the case of Pluto and Charon. In addition, in the frame of his duties in the observing service, he observed with an astrolabe, favouring the observation of planets (Mars and Jupiter).

In 1981, a new period of his activity started with a one year post-doc in Cornell University with J.A. Burns and one year professorship in Marseille. Then, he returned to CERGA. He was interested in many aspects of dynamical planetology, general relativity, data analysis, reference systems and frames. During the ten year period (1982-1992), he published on a large variety of subjects. Let us present some of them.

- He was particularly interested in radiation pressure and dust particle dynamics in the interplanetary medium as well as in the higher atmosphere with emphasis on LAGEOS which was then a major tool of geodesy.
- He studied the dynamics of grains in rings under radiation pressure force. Realizing that the direction of this force varies with time, he gave an integrable solution.
- He worked on the rotation of Hyperion, showing that its oblong shape, together with the high eccentricity of its orbit and the one to one resonance between the orbital and rotational periods, lead to a chaotic rotation.

• Studying the dynamics of the bodies in the Oort cloud, he found that if a star approaches the Solar system by less than one parsec, chances are that the perihelions of some of the bodies become sufficiently low, so that they may be captured by the major planets.

• He also got interested in the dynamics of binary asteroids, although there were no such example at that time.

• One of his constant interests was General Relativity to which the advent of space astrometry opened the way to new practical applications.

Most of these subjects were later, and some even until now, the object of original studies and publications or reports in conferences. This large variety of subjects, encompassing most of Astrometry and Dynamical Astronomy, to which one may add his great interest and knowledge in history of astronomy, made François Mignard a rare example of an astronomer with a wide knowledge and personal achievements. It is with such a background that he entered into space astrometry.

I dragged him into it in 1985, when I realized that some members of the FAST Consortium preparing the Hipparcos data reduction were not in a situation to perform some of the tasks in time. These were photometry and double star reduction. François was the only man in my environment I could trust to redress the situation, and he did it perfectly. He took up the tasks, directed people engaged, but actually did most of the work himself.

In photometry, he showed how to compare the variable amplitude of signals and to establish their eventual periodicities so as to recognize eclipsing variables, Cepheids, RR Lyr, etc.. While the HIPPARCOS mission was originally foreseen to be strictly astrometric, the work of François Mignard showed that each observation gave a mean uncertainty of 0.01 magnitude and the final calibrated combination presented an accuracy of 0.001mag. So, the resulting photometric catalogue and the light-curves of variable stars appeared to be a major improvement to earlier expectations.

In his approach to double stars, he faced a great variety of situations, making the work particularly difficult. He discovered a specific property of photon counts that opened the way to the resolution of binary systems. This led him, using all the observations accumulated during the mission, to obtain the relative astrometry (separation and direction) together with the magnitude difference. This work presented many difficulties, and F. Mignard wrote a very large and complex software that took into account all the possible situations. In this way, he treated 25,000 objects, discovering 10,000 new double stars out of which 70% astrometric data were obtained, and for 85% of them, the difference of magnitudes. Of course, the final catalogue takes into account the results obtained by both reduction consortia, but it is not exaggerating to state that François Mignard was the main contributor. Actually, he continued to work on the data, and extended the results, using ground-based astrometry, so as to determine the parallax of systems and obtain masses and absolute brightnesses of the components of some thirty double star systems.

Progressively he got interested in all the reduction procedure and became a major member of the Consortium FAST. For instance, the FAST software on astrometry had some difficulties with stars that happened to be far from their actual position in the Input Catalogue. François wrote a different and independent software that proved to be very useful in those difficult cases and, in addition, it contributed globally to the improvement of the solution. Among his involvement in other tasks contributing to the final catalogue, one may mention the astrometry of minor planets and the efforts to render the catalogue absolute.

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In 1991, he became member of the Hipparcos Science Team and, later, he progressively replaced me as the coordinator of the FAST consortium. He became responsible of a working group of the Hipparcos Science Team in charge of constructing the final catalogue of double stars. In addition to the specific articles on photometry and double stars, the presence of his name in several publications describing the intermediate and final reduction procedures, as well as in the presentation of the final catalogue, prove his wide views of the mission. In addition, he was responsible of seven chapters of the volume describing the methods used in both consortia to construct the catalogue.

Once the Hipparcos catalogue was published, he naturally started to work on the astronomical implications of such rich and precise data. In particular, he made a very deep and detailed analysis of the local galactic kinematics using proper motions from the Hipparcos catalogues.

Let me say that Hipparcos was not the only activity of François Mignard during this time: he continued to work in the fields of atmospheric drag and radiation pressure and published several papers on these subjects. In addition, his long lasting interest in General Relativity led him to be associated to a proposal of an ensemble of four helio-synchronous satellites to test the principle of equivalence. This first proposal was not accepted by ESA. It was however presented again in an improved configuration and, under the new name MICROSCOPE, successfully launched last year and works now very satisfactorily.

Finally, let me mention that, when I retired from my administrative duties, he became director of CERGA in 1993 until 2004. However, at that time for François, Hipparcos was already the past. As early as 1993, together with a few colleagues, the concept of what could be Gaia was presented. Since then, he was advocating it and participating in various groups working on the feasibility and the expected science of this mission. In 1997, a first draft of a scientific proposal was presented by this group to ESA. Interested, ESA created a Scientific Advisory group that included François Mignard, while first technical studies, based on this report, were initiated by ESA.

At that time, NASA was also considering to enter space astrometry and François was called in 1996 to become a member of the Science Working Group on SIM, a space interferometer with a limited number of stars, but very precise even at high magnitudes. I mention this fact to emphasize that, already at that time, he gained a world-wide recognition as a scientist.

During the hectic period in the beginning of this century, during which, the actual future of Gaia was questioned, he strongly defended the scientific quality of the mission, as President of the ESA Gaia Data Analysis Coordination Committee. His major role in the preparation of the treatment of the data was recognized so that when, in 2006, the DPAC (Data Processing and Analysis Consortium) was created, he was naturally chosen as the chairman of its executive Committee for two three years mandates.

During this period ranging from 1997 to 2006, his scientific activities did not weaken but were essentially directed towards General Relativity and reference frames to which Gaia was expected to bring completely new results. Among these, he studied the relativistic effects of Jupiter, in the frame of classical as well as quantum gravity. More generally, he analysed the various aspects of fundamental physics in the framework of Gaia mission. He also examined the best way to attach the Gaia catalogue to an absolute reference frame, the objective being to achieve better than 0.01 microarcsecond per year. He was also interested in the science that could be obtained from the observations of asteroids by Gaia: for instance the determination of their masses or the eventual detection of the Yarkovsky effect in the motion of close to Earth asteroids.

His activity as chairman of DPAC was fantastic. He was present in all the general meetings of the consortium and many of the thematic ones. Actually, he was President of two of them (Solar system and Relativity and reference frames). In this way, he co-ordinated, and was the driving force of the whole group. This was not a simple task because on one side he had to be the voice of the scientific community within ESA and, on the other side, to ensure within DPAC that every one has a part of responsibilities in the most favourable conditions for the success of the mission. Later, he was still very much involved in the preparation and in the follow up of the launch. Most of you were witnesses of his formidable energy in this context. This hectic activity of François is, I am sure, partly responsible of the major health problems he suffered.

During this meeting, the first remarkable results of Gaia much better than I could expect at first will be presented. It appears to be only a glimpse in comparison with what François will present you at the end of the colloquium and for which he has had a major share. You will judge by yourselves.

So, I shall stop here and hope that I convinced you that François Mignard is one of the most gifted and hard working astronomer of our time.

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The Gaia Project Scientist, Timo Prusti.

Alejandra Recio-Blanco opening the IAU symposium 330, as chair of the SOC.

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The Gaia mission status

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Abstract. Gaia is an ESA cornerstone mission conducting a full sky survey over its 5 year operational period. Gaia performs astrometric, photometric and spectroscopic measurements. The data processing is entrusted to scientists and engineers who have formed the Gaia Data Processing and Analysis Consortium (DPAC). The photometric science alerts started in 2014. The first intermediate data release (Gaia DR1) took place 14 September 2016 and it has been extensively used by the community. Gaia DR2 is scheduled for April 2018. Gaia is expected to be able to continue observations roughly for another 5 years after the nominal phase. The procedure to grant funding for the extension period has been initiated. In case funding is granted, the total operational time of Gaia may be 10 years.

Keywords. space vehicles, catalogs, surveys, astrometry, techniques: photometric, techniques: radial velocities

1. Introduction

Gaia is an ESA cornerstone mission building on the heritage of the Hipparcos mission as detailed in Gaia Collaboration *et al.* (2016b). Gaia covers the full sky making an astrometric, photometric, and spectroscopic survey. The spacecraft, including its payload, was built by industry with Airbus DS as the prime contractor. ESA has the overall management role as well as the spacecraft operations. The scientific community participation is through the Data Processing and Analysis Consortium (DPAC), which has been selected by ESA to produce the scientific catalogues for the community.

Gaia was launched 19 December 2013 from Kourou with a Soyuz rocket. Its nominal mission includes 5 years of operations and 3 years of post-operations to finalise the catalogues. The photometric science alerts, commenced 2014, were the first products provided to the community. The first intermediate release (Gaia DR1) took place 14 September 2016 (Gaia Collaboration *et al.* 2016a). The Solar system alerts for new asteroids also started 2016. The next data release, Gaia DR2, is planned for April 2018.

2. Operations

After a commissioning period lasting about half a year, Gaia has been conducting routine observations. On average Gaia detects and measures 70 million objects per day. On top days, when the scanning is parallel to the Galactic Plane, the count can exceed 300 million. In total, at the moment of this Symposium (24 April 2017), Gaia has observed 70 billion transits. Overall the Gaia operations are nominal.

Astrometry. By 24 April 2017 Gaia has made 688 billion astrometric measurements. Gaia has an automatic on-board detection to decide whether an object is celestial, point-like and brighter than 20.7 mag. The faint limit is not precise as the on-board magnitude

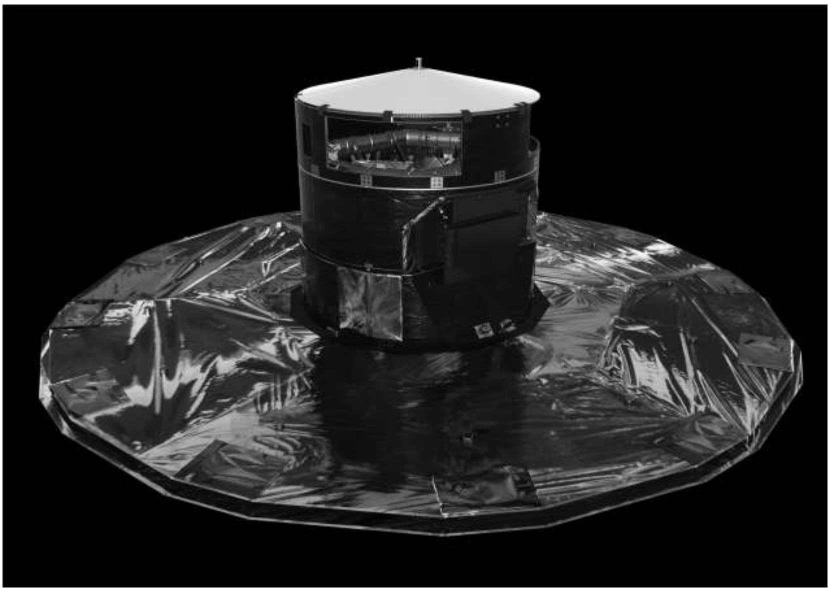

Figure 1. Gaia spacecraft. Copyright ESA

Figure 2. Gaia payload module at the time of vibration testing. Copyright Airbus DS

estimate for the faintest stars is of the order of 0.3 mag. The bright limit of Gaia is between 2 and 3 magnitudes. Brighter objects cause such a large saturation area on the detector, that Gaia cannot anymore determine the object as point like. The bright limit is not fixed as there are sensitivity variations across the CCDs and the brighter stars can be seen if they pass through a less sensitive part of a detector. In order to achieve full completeness, special observation are scheduled for the very brightest stars.

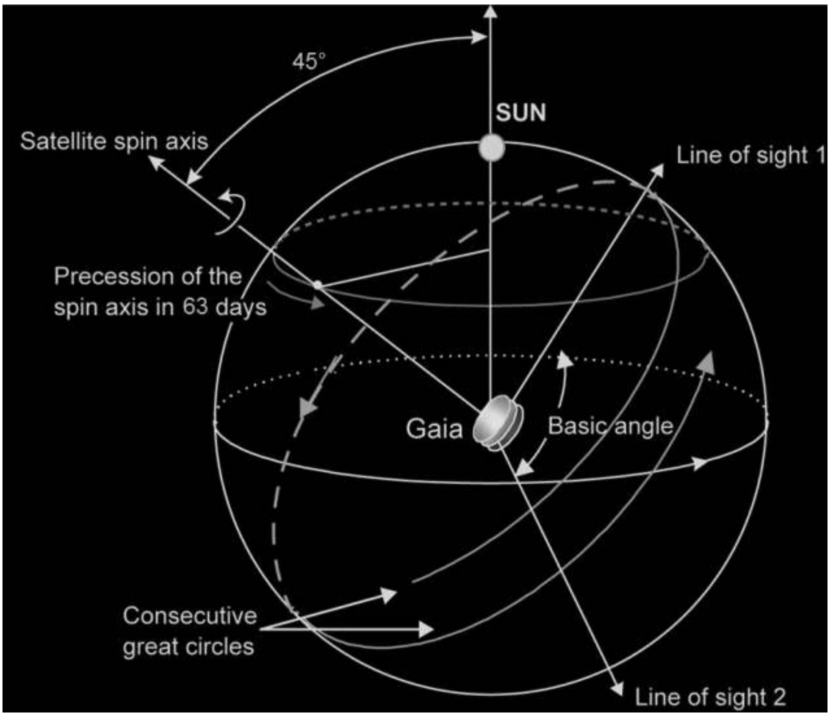

Figure 3. Gaia scanning. Copyright ESA

The ultimate accuracy of those measurements is not yet known, but will be of lower quality than measurements made in the regular way. In addition, selected dense regions are imaged with a special Gaia mode. This is done to compensate for the fact that in the most crowded parts of the sky, the Gaia on-board resources cannot cope with the stellar densities. By producing the images, some astrometric information can be gathered also for the faintest objects in these regions.

Photometry. All astrometric measurements of Gaia are also photometrically calibrated. Therefore for every astrometric measurements there is a corresponding photometric measurement. In addition Gaia has dedicated prisms and CCDs to record spectrophotometry of all objects detected by Gaia. The spectrophotometry is split into two ranges. BP covers wavelengths from 330 to 680 nm and RP from 640 to 1050 nm. The number of spectrophotometric measurements by 24 April 2017 is 147 billion. While the dispersed spectra can be used as narrow-band photometry, the BP and RP channels can also be integrated to provide more precise magnitudes for the wavelength ranges covered. Although every astrometric measurement has accompanying spectrophotometric measurement, it is important to note that in crowded regions, where the spectra overlap, deblending methods are needed to disentangle close-by sources from each other. In very crowded regions this leads to lower quality spectrophotometry than in nominal source density areas.

Spectroscopy. The spectrometer on-board Gaia is called Radial Velocity Spectrometer (RVS). The main task is to enable deducing radial velocities. The spectra cover wavelength range from 845 to 872 nm with resolution of the order of 11,000. In the on-board detection algorithm the limiting magnitude for gathering RVS spectrum is set to 16.2 in the RVS wavelength range. By 24 April 2017 about 13.7 billion spectra have been collected. For most of the objects the only astrophysical quantity that can be deduced is the radial velocity. However, for stars brighter than about 11 to 14 magnitudes also

Figure 4. Gaia focal plane assembly. Groups from left to right: 12 RVS CCDs, 7 RP CCDs, 7 BP CCDs, 62 astrometric CCDs and 14 sky mapper CCDs. The two most extreme CCDs in the corner are for the Basic Angle Monitor and the one out of the row of astrometric CCDs together with the one most to the right in the middle of the focal plane are for wavefront censors (the wavefront censor is missing still in this picture). Copyright Airbus DS

spectroscopy can be done (the brighter the star, the better the signal to noise and the more spectroscopic analyses are possible).

3. Intermediate data releases

Gaia DR1 took place 14 September 2016. The number of publications went very quickly up and many of the published (or close to publication) results can be found from these proceedings.

Gaia DR2 is scheduled for April 2018. The expected contents and precisions are detailed to some level in these proceedings and especially the scientific expectations are listed in many contributions.

4. Mission extension

The nominal Gaia mission will be completed by mid-2019. At that moment Gaia has been scanning the sky for 5 years. The operations are smooth and can continue beyond the nominal life time. If nothing unexpected happens, then the Gaia mission life time will be limited by the consumable, cold gas, for the micro propulsion system. The cold gas is used to keep the spin matching exactly the readout speed of the CCDs. The consumption is very regular, but with an expectation, that the consumption will increase as the satellite surfaces age and the Solar wind causes more torque on Gaia. The current best estimate of cold gas exhaustion is mid-2024. After cold gas exhaustion the spin control is not anymore sufficient for precision astrometry work.

In order to continue operations beyond the nominal end of mission to the real, functional end of the mission, additional funding is required for the 5 years from mid-2019 till mid-2024. As mission extensions are not unusual for ESA spacecrafts, there is a procedure that is followed up within the science programme. Every two years there is a