OVERALL SCIENCE GOALS OF THE GAIA MISSION

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ABSTRACT

This paper provides an overview of the science objectives of the Gaia mission, with deeper snapshots on specific areas not particularly covered in this volume. Starting with the expected performances I show how the combined and repeated information on each source will lead to a giant leap in our current knowledge of stellar and galactic physics, resulting both from the accuracy on individual objects but also from the statistical exploitation of the unbiased census over one billion stars. I then draw attention to the additional science output of the mission like the detection of extra-solar planetary systems, the determination of thousands of stellar masses, the massive impact on Solar System studies, the testing of the Einstein relativity theory to an unprecedented level together with the direct realisation of the primary inertial frame in the visible.

Key words: ESA; Gaia; Science.

1. INTRODUCTION AND PERFORMANCES

Following the success of Hipparcos, the Gaia project has been approved in October 2000, and confirmed two years later, as an ambitious experiment to probe with accurate astrometry, photometry and spectroscopy a very large number of stars of our Galaxy. Gaia will provide positional and radial velocity measurements of unprecedented accuracy to produce a stereoscopic and kinematic view of about one billion stars in our Galaxy. These geometric parameters will be supplemented by an on-board multi-colour photometry and low resolution spectroscopy with the required precision to address key questions of modern astrophysics regarding the formation and evolution of the Milky Way. Within the ESA science programme Gaia is a Cornerstone mission to be launched around 2011.

The Gaia payload consists of three distinct instruments mounted on a single optical bench, whose design is detailed by Pace (2005). Unlike HST and SIM, which are pointing instruments observing a pre-selected list of objects, Gaia is a scanning satellite that will survey in a systematic way, and repeatedly, the whole sky, tying together without regional errors widely separated sources.

The main performances of Gaia expressed with few numbers are just staggering and account for the vast scientific harvest awaited from the mission: survey to $V = 20$ of all point sources amounting to more than one billion objects with an astrometric accuracy of 10 μas at $V = 15$ and 4 μas for the few million stars brighter than $V = 13$; radial velocities down to $V = 17$, with an accuracy ranging from 1 to 10 $\mathrm{km\,s^{-1}}$; multi-epoch photometry in ~ 15 bands sampling the visible to the near IR.

Beyond its sheer measurement accuracy, the major strength of Gaia follows from (i) its capability to perform an all-sky and sensitivity limited absolute astrometry survey, (ii) the unique combination into a single spacecraft of the three major electronic detectors carrying out nearly contemporaneous observations, (iii) the huge number of objects and observations allowing to amplify the accuracy on single objects to large samples with deep statistical significance, a feature immensely valuable for astrophysics and not shared by a mission like SIM.

2. SPACE ASTROMETRY SCIENCE

The objectives of space astrometry are, in principle, the same as those of ground-based astrometry: to determine the apparent positions of celestial bodies and derive from them astrophysically important parameters such as distances, proper motions, movements within double and multiple star systems. However the current generation of CCD-based astrometric instruments can also be used as stable photometers and the photometric measurement in several bands appears in every proposal of scanning missions having astrometry as a first goal. In addition Gaia will carry also a dedicated spectrometer allowing to determine radial velocities for at least 100 million stars.

Whereas the direct product of the Gaia mission will be a highly accurate astrometric and photometric survey to V = 20 mag, the true science goals are much broader and account for the support of a large scientific community. They are summarised in few keywords below and some are discussed in more details in the rest of this paper.

- Mapping of the Milky Way
- Stellar physics (classification, M, L, $\ln g$, $T_{\rm eff}$, [Fe/H])

Table 1. Astrometric performances of Gaia compared to Hipparcos

	Hipparcos	Gaia	
Magnitude limit	12	20 – 21	
Completeness	7.3 – 9	20	
Number of objects	120 000	35×10^6	$V < 15$
		350×10^6	$V < 18$
		1.3×10^9	$V < 20$
Astometric accuracy	1 mas ($V < 9$)	4 μas	$V < 12$
	1 – 3 mas($V > 9$)	10 μas	$V = 15$
		200 μas	$V = 20$
$\sigma_\pi/\pi < 1\%$	150 stars	20×10^6 stars	
$\sigma_\pi/\pi < 5\,\%$	6200 stars	115×10^6 stars	
$\sigma_\pi/\pi < 10\%$	21 000 stars	220×10^6stars	
Radial velocity	–	2 – 10 km s^{-1}	$V < 17$
Broad band photometry	–	4-colour	$V < 20$
Medium band photometry	–	11-colour	$V < 20$
Low resolution spectroscopy	–	R = 11 500	$V < 16 – 17$

- Galactic kinematics and dynamics
- Distance scale (geometric to 10 kpc, HR diagram, Cepheids, RR Lyrae)
- Age of the Universe (cluster diagrams, distances, luminosity)
- Dark matter (potential tracers)
- Reference frame (quasars, astrometry)
- Planet detection ($\sim M_J$, astrometry and photometric transits)
- Fundamental physics ($\gamma \sim 5{\times}10^{-7}$, $\beta \sim 5{\times}10^{-4}$)
- Solar physics (solar J2 $\sim 5 \times 10^{-7}$)
- Solar System science (taxonomy, masses, orbits, 5×10^5 bodies)

Gaia will address virtually all these fields, covering a significant part of modern astrophysics (Perryman et al. 2001). As said earlier the understanding of the Milky Way is the primary objective of Gaia and the impact of the mission in this field is thoroughly covered in this volume. Hence I will just outline the science returns in this area, and cover in more detail topics that were not initially considered as central in the Gaia proposal, but have become more and more relevant during the study phase.

3. GALACTIC AND STELLAR PHYSICS

The main asset of Gaia comes from the complete and homogenous bulk of data, including proper motion, parallax, multi-band and multi-epoch photometry and radial velocity for all kinds of stars in every population and distributed in each component of the Galaxy. Astrophysically this translates into luminosity, temperature, chemical composition, gravity, that is to say the fundamental stellar parameters from which one can model the stellar engine and refine the evolutionary scenarios. Due to the large number of sources it will be possible to capture stars in transient states, or the rare specimen of very bright or very massive stars or to identify from the systematic survey the very metal poor (or rich) stars, that all harbour precious clues on the history of the Galaxy.

Thanks to the direct determination of the parallaxes and to the sampling of all the spectral types and classes, extensive calibrations of stellar luminosities will be undertaken. For the distant stars this implies that a mapping of the extinction should be achieved from the photometric data which puts a stringent requirement on the choice of the photometric bands. More rigorous age estimates would also follow from evolutionary models. Parallaxes with $\sigma_\pi/\pi < 1\%$ will be obtained up to distances of several kiloparsecs allowing luminosity calibration of early and late type main sequence stars and all the giants, including the Cepheids and RR Lyrae. With Gaia the distance of about 30 open clusters will be known to within one per cent and all galactic clusters to better than 10 per cent.

The understanding of the Milky Way will dramatically benefit from Gaia. The diverse components of the Galaxy will be surveyed, including the galactic centre, the thin and thick discs, the bulge and the halo. The space and velocity distribution functions of long-lived stars could be constructed on complete samples of various metallicities. All these achievements will help answer the key questions regarding the formation of the Galaxy, its structure and stellar content and its complex dynamical evolution. The space velocity deduced from the proper motions and distances will allow to constrain the rotation curve at large distance from the Sun and then to investigate the mass distribution and address the question of the presence of dark matter. The 3D velocity and distances will permit a clear recognition of the members of the thin and thick disc and also to map their respective 3D structure.

The Gaia multi-epoch photometric survey will have a significant astrophysical value by itself, because it is sensitivity limited and covers all categories of stars. All types of variability will be recognised with the accurate epoch photometry (individual measurement in the G-band will be better than 0.001 mag for $V < 15$ mag) and the repeated observations over 5 years. So far the only photometric all-sky survey is still the one made with Hipparcos which ended up with nearly 12 000 variables. It is estimated that Gaia could detect up to 18 million variable stars, including 70 000 RR Lyrae and several thousands pulsating Cepheids (Eyer 2005).

The Hipparcos mission has shown the capabilities of space astrometry to detect and resolve binary stars with a separation smaller than the size of the diffraction pattern. Gaia will have similar detection capabilities and then will be able to resolve binaries with an apparent separation less than 20 mas. For several 10^4 systems with periods of a few years the relative orbits will be determined together with the sum of the masses or the individual masses with 1% accuracy. Combined with the distance and luminosity calibration this will put the investigation of the M-L relation on much safer ground than with present masses. Gaia will detect a majority of the ~ 10 million binaries closer than 250 pc from the Sun, and further away an estimated 60 million will be identified. Unlike Hipparcos, Gaia will be able to measure resolved systems with large magnitude difference (up to $\Delta m \sim 10$ for wide pairs), thus providing material to investigate statistically the poorly known distribution of mass-ratios in the star formation.

In the case of open clusters, a 3-D picture will be provided along with a complete velocity field. The insight into the structure and dynamics of these systems and the variety of studies to be carried out will be dramatic. Much progress is also expected in the ages of the A–F stars of the galactic disc since they are based on comparison of theoretical isochrones to evolutionary sequences in which most of the uncertainty results from the mass and the luminosity, or equivalently distance (Lebreton 2005).

One could go on and on just mentioning the most outstanding expected returns in stellar and galactic physics. Many details are available in the Concept and Technology Study Report (ESA 2000) complemented by the latest updates in this proceedings.

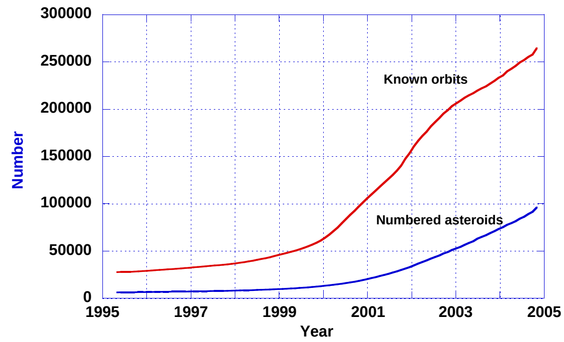

Figure 1. Recent evolution of the number of asteroids with known orbits up until November 2004. Numbered asteroids correspond to the subset with the most reliable orbits.

4. SOLAR SYSTEM SCIENCE

Solar System objects appear in the Gaia proposal at a high level in the science programme achievable within the current design, with an impact on virtually any category of minor planets. It was clear from the beginning that Solar System observations were not mere by-products of the mission, but held clearly as true scientific objectives belonging fully to the initial proposal, given the impact expected in this field. However the astrometric observation of the moving objects is very challenging for the data processing as a result of their significant proper motions and further investigations were needed to assess more accurately the actual capabilities of Gaia.

While the motion might be viewed as a source of concern for a mission optimised for stellar sources, whose displacements are negligibly small over few hours, the planet wandering against the stellar background is the key to their recognition as a non-stellar source at every field crossing. The velocity, albeit very small (between 5 to 100 mas s^{-1} according to the heliocentric distance) can be easily seen in the Gaia data, even within the limited timespan needed to cross a few CCD strips (Wolff 2005). From the positions and velocities obtained over successive transits a preliminary orbit should allow to track the planet down at crossings taking place much later or earlier (Muinonen 2005).

It is expected that Gaia will detect about 5×10^5 asteroids, primarily in the main belt. At the time of the publication of the Gaia proposal (ESA 2000), a little more than 50 000 objects were listed with an orbit and only 13 000 were numbered. The rate of yearly discoveries was slow and a straight extrapolation indicated that most of the objects to be detected by Gaia will be new. Therefore the Gaia survey was considered primarily as a discovery survey. During the last five years several ground-based searches for potentially hazardous near-Earth objects have led to a very significant increase in the detection rate and in the total number of identified asteroids, although their main goal is not directed toward the main-belt slow moving objects. The current number shown in Figure 1 stands at the end of 2004 at about 260 000 with reasonably good orbit, at least good enough to allow a recovery. The current trend extrapolated over the next few years indicates that the number of new objects in the Gaia survey will not be considerable, in contrast with the initial estimate made in 1999. However, the current surveys have their own bias, in particular by searching systematically during opposition, not far from the ecliptic and selecting the fastest moving sources. It is then clear that Gaia will detect a significant number (50 000? 100 000?) of new planets and one must be able to cope with this fact in the operations and data analysis.

Regarding the potential for the near-Earth objects (Høg 2005), this is again the ability to observe inside the Earth orbit at a rather small angular distance to the Sun (as close as 40 degrees) that gives Gaia its specific power, in addition to its unbeatable astrometric accuracy and the subsequent quality of the orbits.

This systematic survey, covering the whole celestial sphere and sensitivity limited will be the first and most direct result of Solar System science with Gaia. But the real impact lies elsewhere: Gaia will observe a given asteroid about 15 times per year with an accuracy better than 1 mas (per observation), 500 times better than that of most of the large current surveys and every observation will be supplemented by the photometric data in each of the $\sim$ 15 bands of the broad and medium band photometers. The following list gives the main area in which the combination of the Gaia measurements will most benefit to Solar System science:

- Orbits: virtually every object observed $\times 30$ better than now $\Rightarrow$ proper elements, dynamical families
- Masses from close encounters $\sim$ 100 masses expected
- Diameter for over 1000 asteroids $\Rightarrow$ shape, density
- Photometric data in several bands $\Rightarrow$ albedo, taxonomic classification
- Light curves over 5 years $\Rightarrow$ rotation, pole, shape
- Space distribution vs. physical properties
- Perihelion precession for 300 planets $\Rightarrow$ GR testing, solar J2

Several of these items are detailed in this volume (Tanga 2005; Cellino 2005; Muinonen 2005) and I just summarise the key features which make Gaia unique relative to ground-based surveys.

Most of the known asteroids have been discovered since 1980 (there were only 3000 known at that time). So the orbits are determined from observations that usually do not extend over more than 20 years in the best case and at most 6 oppositions. The typical standard quality of these observations are around 1 arcsec — limited either by the lack of good reference stars or the intrinsic quality of the photographic plate measurements of the early 1980s — and probably ten times better with the current CCD observations. This leads to orbit with $\sigma_a \sim 10^{-5} - 10^{-7}$au. With Gaia one can expect to have individual observations (one transit over the 11 Astro CCDs) in the mas range for the faint objects and about 100 μas for $V = 15$; typically 80 such transits will be obtained over 5 years. Gaia has a shorter time base (in fact not so much shorter), but a much higher astrometric accuracy. Combining the two, the improvement in orbit determination by going to space should be close to 100 in the best cases, and about 30 in most cases, at least for the osculating elements at the mid-mission time. Such a result opens the way for a precise investigation of the dynamical family based on the computation of the proper elements with a refined dynamical model including non-gravitational forces. An immediate output of the Gaia data base will be a correlation of physical properties with dynamical parameters bringing together key features in our understanding of the origin and evolution of the Solar System.

Similarly accurate orbits means that weak perturbations could be detected, and in particular those resulting from the tiny pull exerted by the largest asteroids. This is the key to the determination of the masses, provided sufficiently close approaches between a massive and a small planet happens during the mission. The distribution of close approaches during the Gaia mission is shown in Figure 2. The histogram gives the number of encounters at distance < 0.05 au between the 200 largest asteroids and any of the first 20 000 numbered planets over the years 2010.5–2017.5 (the distance is not the only criterion to be used to find the efficient encounters, but this is sufficient for this global statistic). One sees that multiple close encounters is the rule and that a global solution including $\sim$ 100 unknown masses will have to be developed. Determining these masses with an accuracy between 0.1 and 10 per cent would be a major scientific achievement given the extremely poor knowledge of the masses today and their utmost importance to the physical characterisation of any celestial body. Combined with the shape and size, this will lead to the determination of the density, an essential parameter to understand the collisional history of the main belt.

The photometric measurement in the G-band should have a millimagnitude accuracy at G = 16 for one transit. The magnitude variation over the transits follows primarily from the change of distance to the Sun and to the Earth, which is easily computed. The remaining scatter comes from the surface properties, the shape and the rotation (spin and pole direction). The photometric time series is strongly constrained by the period, which can be then quickly adjusted before the shape and pole coordinates are fitted to the data. Current experiments reported by Cellino (2005) indicate that the shape parameters could be fitted with few per cent errors and the pole directions within few degrees for many thousands of planets.

5. QUASARS AND REFERENCE FRAME

Gaia will contribute significantly to the knowledge of the quasars by providing for the first time an all-sky, flux-limited survey to $V = 20$, very difficult to carry out from the ground. Although there is no global survey of quasars

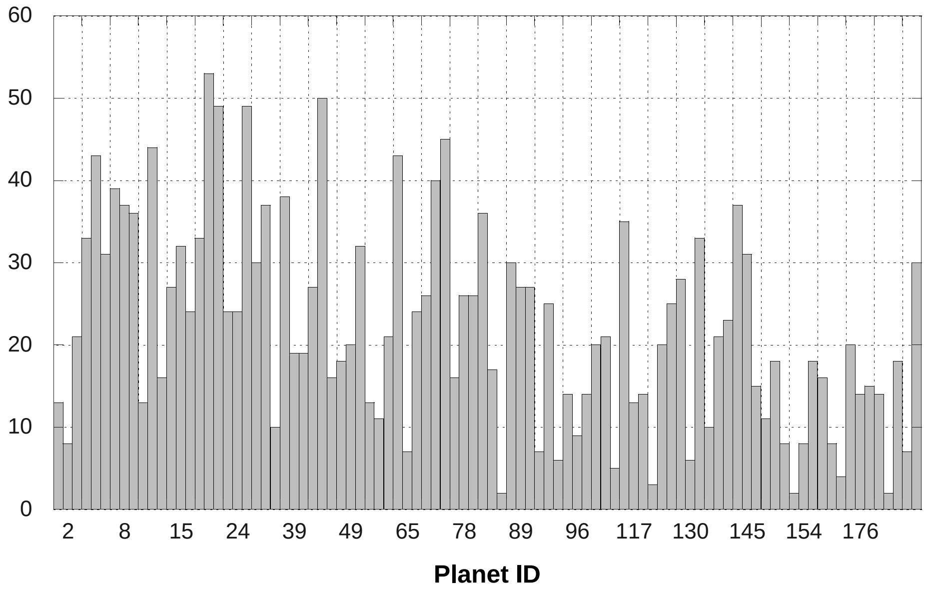

Figure 2. Statistics of close approaches between 2010.5 and 2017.0. The histogram gives for each of the first 200 planets the number of encounters at a distance $<$ 0.05 au with one of the first 20 000 planets. Each planet will be involved in several encounters with a small target from which accurate masses will be determined from a global solution with $\sim$ 100 masses as additional unknowns.

available at the moment, local surveys indicate that the typical surface density of quasars is about 20 sources $V < 20$ per square degree, much smaller than that of the stars at any galactic latitude. So at the end one may reasonably expect a census of about 500 000 quasars at galactic latitudes $|b| > 20^\circ - 25^\circ$. Closer to the galactic plane, we will face two difficulties: (i) the galactic extinction and reddening that will block off the light of these distant and rather faint sources, (ii) the difficulty to discriminate between the stars as their relative density to that of the quasars increases drastically at low galactic latitudes (this ratio is about 10 000 at $b = 10^\circ$ and $G = 19$).

However, the internal autonomous multi-colour detection will be very efficient in getting rid of the traditional contaminants like the white dwarfs and the very reddened stars and will permit the selection of a 99.9% star-free sample of QSOs (Claeskens et al. 2005). Such a clean sample should contain several 10 000s sources, largely enough to tie the Gaia astrometric solution to the non-rotating Universe. Simultaneously photometric redshift measurements will be feasible without additional effort for most of the detected sources with an accuracy of few per cents.

The extensive zero-proper-motion survey will provide a direct realization of the quasi-inertial celestial reference frame with a residual rotation less than 0.5 μas yr^{-1} (Figure 3) and a space density at least hundred times larger than that achieved by the radio version of the ICRF. Many more secondary sources (stellar or extragalactic) will also facilitate the access to this frame.

The random instability of the sources puts a serious limitation in the ultimate precision of the inertial frame and imposes a strict selection of the primary sources. Extragalactic radio sources display structure on spatial scales from hundreds to one mas with a variety of shapes. The variability at radio wavelengths is also correlated to structure change due to relativistic jets. The effect of source structure on position has been studied in radio and found as large as tens of mas yielding apparent motion in right ascension. Values of 10 to 30 μas yr^{-1} have been re-

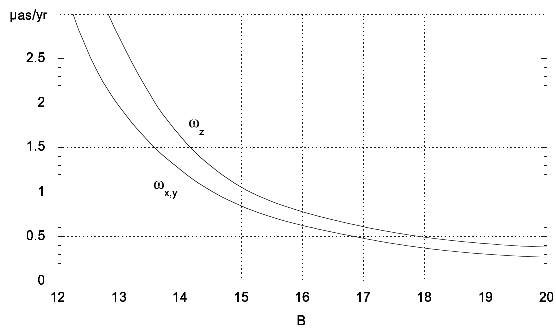

Figure 3. Precision of the spin rate of the inertial frame achievable with Gaia from the observations of the quasars. This is based on a simulation of 42 000 known sources (10 000 with $B < 18$) whose distribution with galactic latitude is similar to that expected from Gaia. The precision read for a B magnitude is computed with only sources brighter than B selected. Here galactic coordinates have been used and the random instability has been taken equal to 20 μas yr^{-1}. Though there are many more faint objects than bright ones, the frame is primarily determined by the brightest sources, because of the better astrometric precision. A similar situation should prevail in the real mission.

ported. Virtually nothing is known in the visible regarding the $\sim$ mas structure and its time change. However, the photometric variability in the optical bands might be an indication that photocentric random motions should not be excluded, in addition to the random microlensing. If relativistic jets seen in radio originated from synchrotron radiation of accelerated charges particles, the same mechanism should be seen in the optical band. Selection of a clean sample will be a difficult, but compelling for the primary realization of the inertial frame.

Dirty sources should not be simply dumped in the waste-basket but carefully scrutinized individually or collectively for jet motion (only for nearby AGNs) or structured transverse displacements. The lack of transverse motion of the extragalactic sources is the major assumption underlying the current paradigm of the kinematical reference frame. It is assumed that the visible Universe does not rotate as a whole, so that the most distant sources have no individual motion relative to each other. As a whole these sources define and materialise a kinematical non-rotating reference system. The construction of this ideal frame with a network of QSOs rests upon the fact that so far no systematic and unaccounted transverse motion has ever been detected. Thanks to its very accurate astrometry, Gaia will check this assumption by: (i) selecting candidate sources from criteria independent of their proper motion (large proper motion or parallaxes will be only used to reject contaminants, not to keep sources) and (ii) checking every source for small transverse motion. An interesting by-product of this analysis is the determination of the acceleration of the Solar System with respect to the background quasars resulting from the fact that any constant acceleration $\mathbf{\Gamma}$ translates into a spurious proper motion as,

$$\boldsymbol{\mu} = \frac{\mathbf{\Gamma}}{c} - \left(\frac{\mathbf{\Gamma}}{c}\cdot\mathbf{u}\right)\mathbf{u} \tag{1}$$

where $\mathbf{u}$ is the unit vector in the direction of a source. The largest expected effect of this kind will come from the motion of the Solar System around the galactic centre giving rise to a systematic proper motion field as large as 4 μas yr^{-1} (Kovalevsky 2003). Gaia will be able to separate these transverse motions of the quasars from the global rotation and then solve for the three components of the acceleration with $\sigma_\Gamma/\Gamma = 0.1$.

The lensing by intervening galaxies could be also a potential limitation. However a simple model shows that the optical depth is about 0.005 meaning that 99.5% of the sources will not be affected by macrolensing. This implies that about $\sim$ 2500 quasars will be multiply imaged by galaxies along the line of sight. Gaia has the potential to work in direct imagery mode over a very small field ($<$ 3 arcsec), wide enough to search for multiple imaged quasars with a resolution of $\sim$ 0.1 arcsec, achievable in AF11 by image stacking (Dollet et al. 2005). Surdej et al. (2002) have demonstrated that the fraction of multiply imaged quasars is a strong function of the cosmological parameters (Ω, λ_0), hence Gaia offers a good prospect of constraining independently the values of these important parameters, provided the close environment surrounding sources like quasars can be fully exploited. Photometric variability of multiply lensed quasars is also a proven method to determine H_0.

6. SUBSTELLAR COMPANIONS AND EXTRA-SOLAR PLANETS

An isolated brown dwarf, let alone a planet, is hardly observable in the visible light because of its quick fading after $\sim$ 1 Gyr. So far not a single planet has been convincingly directly observed and all detections have proceeded indirectly. At present more than 120 extra-solar planetary systems have been detected, primarily through the radial velocity measurements, although historically the astrometric method was considered as the most natural one. Based on these small statistics it is thought that about 5% of solar-type stars may be accompanied by at least one giant planet, and probably a much larger fraction may have planets of smaller mass. Extrapolated to the size of the Gaia survey this leads to an enormous potential of discovery, at least for Jupiter-like planets.

Through its high precision astrometry combined with a relatively regular time sampling over 5 years, Gaia will be able to detect the small reflex motion of a star due to the gravitational pull of a dark companion. The typical astrometric signature expected for a single planet of mass M_p around a star of mass $M_\star$ is given by,

$$\delta\theta = \frac{M_p}{M_\star}\,\pi a \tag{2}$$

where π is the parallax , a the orbital semi-major axis of the planet in au and the amplitude of the reflex motion $\delta\theta$ is expressed in the same angular units as π. A more convenient formula could be,

$$\delta\theta(\text{mas}) = \frac{1\text{pc}}{d}\,\frac{M_p}{M_J}\,\frac{M_\odot}{M_\star}\,\frac{a}{1\text{au}} \tag{3}$$

which gives an amplitude of 362 μas for 47 UMA with a period of three years, a wobble easily seen by Gaia. At 100 pc Jupiter orbiting the Sun would cause an astrometric amplitude of 50 μas, still detectable by Gaia on a solar-type star seen as a star of magnitude 10 at that distance. The principle of the astrometric detection is illustrated in Figure 4, where the actual path of the star (in solid line) departs from that of the barycentre (dashed line), or in other words, that of the same star without a planet.

The ability of Gaia to detect a planet is a function of the astrometric signature (it must be larger than a few times the final astrometric accuracy at the star magnitude) and of the periods. From recent simulations (Casertano et al. 2004) it appears that orbital periods larger than 8 years will be difficult for Gaia, at least for the orbit retrieval while detection from non-linear motion will be feasible up to about 30 years. On the other hand very short periods, shorter than the sampling rate will suffer from aliasing. McEvoy (1999) has estimated the number of detections achievable by Gaia by folding the probability of detection for different masses, distances and periods with the expected population of main sequence stars within 500 pc. She has assumed that 5% of the stars have planets of 1 Jupiter mass. The numbers range from 10 000 to 50 000, varying with the assumptions on the detection probability, SNR threshold, ... etc. Finding such a number of planets would provide a large statistical basis to

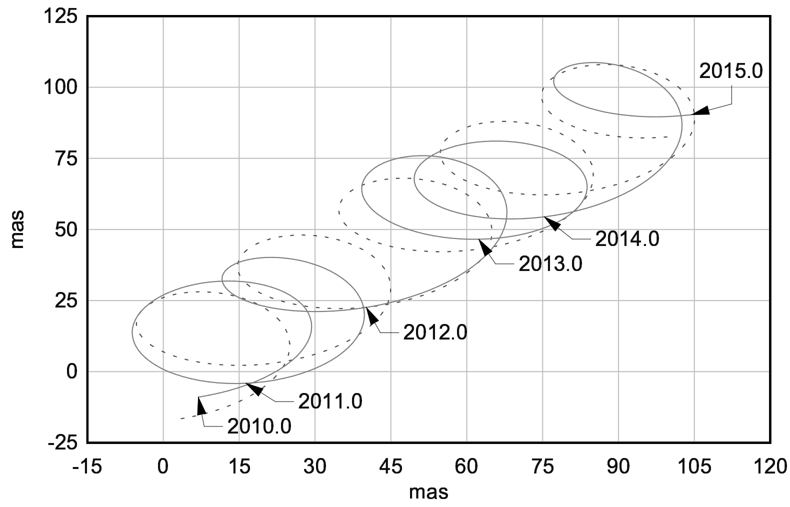

Figure 4. Absolute path on the sky of a star orbited by a single planet. In the plot the star is at 50 pc with a proper motion in both directions of 20 mas yr^{-1}. The dashed line represents the motion of the system barycentre while the solid line is that of the star including its displacement around the system barycentre. One has used $(m_p/m_\star)\,a$ = 0.5 au, and P = 2.5 yr. For visibility purposes the plot, while qualitatively correct for a planet, corresponds to a solar-type star with a low mass brown dwarf of 0.2 $M_\odot$.

discuss the scenarios of planetary formation and to relate the effect of stellar type and age to the distribution of orbital parameters in the solar neighbourhood. While Gaia is not likely to populate scarcely covered areas of the configuration space of the planetary systems, its strength shows up again with its capability to feed statistical analyses with samples of significant size.

The photometric detection has played a minor role so far in term of discoveries, but the few transits observed on systems known to have a planet have allowed to improve the orbital period and to lift the $\sin i$ ambiguity in the mass, and also to estimate the planet radius. In the near future the CNES-ESA Corot mission and the NASA Kepler mission will rely heavily on the photometric transits as a means to monitor a large preselected set of solar-type stars to discover rocky planets of the size of the Earth.

The magnitude dip during a transit is given by $(R_p/R_\star)^2$ and is about 0.01 for Jupiter transiting on the disc of a solar-type star. The accuracy of the epoch photometry of Gaia in the G-band will be in the millimagnitude range and will permit to detect such transits with a good SNR, large enough to identify the dimming of light and to apply the method to a very large number of stars. However the possibility for a transit to occur is constrained by the direction of the observer with respect to the orbital plane and by the size of the orbit. If i is the orbital inclination on the plane of the sky, a transit occurs at every revolution provided $\cos i < R_\star/a$ and for an isotropic orientation of the orbits the probability of this event is $R_\star/a$. This is negligibly small for Jupiter in the Solar System and gets of the order of 10% only with $a \sim$ 0.05 au. Therefore, the method will be strongly biased toward small orbits. Now, even in this case, the probability that a random observation takes place during a transit is equal to the fraction of the period needed by the planet to transit on the stellar disc and for a circular orbit is

$$\frac{\tau}{P} = 0.0015 \left[\frac{1\mathrm{au}}{a}\right] \left[\frac{R_\star}{R_\odot}\right] \left(1 - \frac{a^2}{R_\star^2}\cos^2 i\right)^{1/2} . \quad (4)$$

Even for orbits as small as 0.05 au this probability is close to 3%. However Gaia will observe the same system at about 30 different epochs (this is less than the number of field crossings, because the observations in successive fields within one or several revolutions are not independent trials given the fact that a transit lasts several hours) and the probability to observe at least one transit is about (Johansen (2002))

$$1 - (1 - \tau/P)^{30} \sim 0.6 \ \text{ for } a = 0.05\,\mathrm{au} \qquad (5)$$

while the probability to have at least 3 transits is 0.06. Note that for each epoch falling during a transit, the photometric data will provide several data points over ~half a day. Given these constraints the number of expected photometric transits to be detected during the mission lies somewhat between 5000 and 20 000 (Johansen 2002; Robichon 2002). The period will be predominantly small leading to little overlapping with the astrometric method.

7. FUNDAMENTAL PHYSICS

Even with the astrometry of Hipparcos, at the mas level, the signal modelling required that the second order term in aberration be included together with the relativistic treatment of the light deflection by the solar gravitational field. With an improvement of more than two orders of magnitude for the bright stars, the astrometric model of Gaia will be much more refined. The stringent demand of Gaia (and SIM) has pushed several individuals or groups to investigate relativistic modelling at the

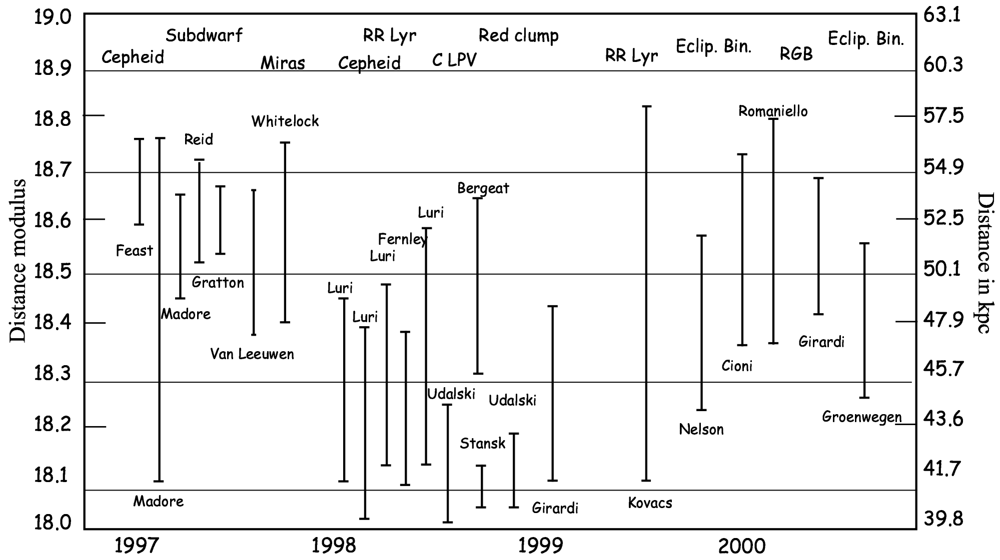

Figure 5. Recent determinations of the distance of the LMC. The different methods applied do not show systematic differences between them significantly larger than the random error of each determination. Two reviews by Walker (1999) and Feast (1999) give respectively for the distance modulus 18.55 $\pm$ 0.10 and 18.60 $\pm$ 0.10. Gaia should decrease the error bar to 0.02 (adapted from an earlier version of M. Perryman).

sub-microarcsecond level (Klioner 2003; Vecchiato et al. 2003; de Felice et al. 2004). Clearly Gaia provides a big incentive to examine with great care, and in several instances clarify, the meaning of old astronomical concepts like parallax, proper motions, radial velocity in the framework of high precision astrometry.

The first step into a relativistic modelling of the light path consists of determining the direction of the incoming photons as measured by an observer located in the Solar System, as a function of the barycentric coordinate position of the light source. The actual path is affected by the geometry of the spacetime in the Solar System and Gaia observations can be used to detect the minute changes in the direction of the incoming light to probe the space curvature and test the gravitation theory. It is customary and convenient since the work of Will and Nordvedt to express the departure of general metric theories from the standard General Relativity with ten additional parameters, each taking its reference values in Einstein theory.

The dominant relativistic effect well visible in the Gaia measurement is the gravitational light bending, primarily by the Sun, but also by the giant planets. In metric theory this is quantified by γ and the deflection is directly proportional to $(1 + \gamma)/2$. Gaia can observe at a distance of 40 degrees from the Sun where the light deflection reaches 12 mas, a sizeable effect for Gaia astrometry. Based on the repeated observations of the $\sim 10^7$ bright stars, detailed simulations have shown that Gaia measurements will provide precisions of few 10^{-7} for γ (Mignard 2002; Vecchiato et al. 2003). This will be an improvement by two orders of magnitude to the best determination of Cassini (Bertotti et al. 2003) which is not likely to be ameliorated by the time Gaia is launched. A similar determination, but much less accurate will be attempted with Jupiter using small field astrometry, that is to say less prone to unnoticed systematic effects. A new test proposed by Crosta & Mignard (2005) aims to evidence the deflection arising from the quadrupole moment of Jupiter, a prediction of General Relativity never observed and whose modelling is still subject to controversies as to the best way to handle the deflection by moving bodies (Klioner & Peip 2003).

The non-linearity in the superposition of gravitational fields will also be investigated with the precessional motion of well selected minor planets. Thanks to the sampling in semi-major axis there is for the first time the possibility to separate the relativistic effect from the contribution of the solar J2, which is impossible with Mercury alone. From simulated data on the actual asteroid population Hestroffer & Berthier (2005) have shown that β could be determined to within 1×10^{-4} and J2 to 1×10^{-8}. Because the two quantities remain strongly correlated, by assuming one of the two is sufficiently well known from independent sources, one can obtain a determination of the other five times better. Regarding the solar J2, compared to all other estimates, the Gaia determination will not be model-dependent (from internal structure model, relation between flattening and quadrupole moment, etc) and will be directly the dynamical J2. This could be injected back into the Mercury precession to improve β (Pireaux & Rozelot 2003).

8. COSMIC DISTANCE SCALE

Gaia will provide distances of unprecedented accuracy for all types of stars in every kind of population. Combined with the mapping of stellar extinction this will constitute the basic data for a full recalibration of stellar luminosity (Turon & Perryman 1999). This applies particularly well to galactic stars, including the bright giants, directly observable in the external galaxies. Based on recent galaxy models it is estimated that 18 million stars will have a distance known with a relative accuracy better than 1% and about 150 million better than 10%. On bright stars the Gaia astrometric accuracy translates into an error on M_V of 0.001 mag (for V = 10) at 100 pc, allowing a high resolution recalibration of the HR diagram, including most evolutionary phases, all types of variable stars or binary systems. Clearly the distances for all kinds of standard candles, will be the most valuable single type of data to explore stellar and galactic physics and investigate the cosmic distance scale.

Beyond our Galaxy, the parallaxes of individual objects will be negligible. Nonetheless by averaging over a population (globular clusters, nearby galaxies) useful results could be obtained and propagated to more distant galaxies. The impact of Gaia has been recently reviewed by Tammann (2002) from which I extract most of the information of this paragraph. The current state of the extragalactic distance scale rests upon the P-L calibration of the Cepheids and the intrinsic brightness of SNIa, and then on the distance of the Large Magellanic Cloud. Due to the lack of reliable distances for the galactic Cepheids the slope of the P-L relation has been based for decades on the analysis of LMC Cepheids. Recently the OGLE programme has provided multi-colour photometry for hundreds of LMC Cepheids and this indicates that not a single P-L relation can fit all the periods and that a significant change of slope takes place at a period of about 10 days (Udalski et al. 1999). The zero point of the standard P-L relation is determined from an adopted LMC distance modulus of $\mu = (m - M) = 18.56$, from a weighted mean between a large number of determinations relying on nearly as many methods. The recent reviews of Walker (1999) and Feast (1999) indicate that a reasonable uncertainty on μ is about 0.1, making the uncertainty of all the extragalactic distances of at least 5%. The most recent determinations are shown in Figure 5 with an indication of the methods employed. The dispersion is large, although there is no obvious systematic difference between techniques larger than the quoted uncertainties.

Gaia will improve the situation by providing direct indication of distance on individual stars. Admittedly at 50 kpc the accuracy on the individual bright giants will be rather poor, but by averaging over $\sim 10^6$ stars, this should fix the distance to 1 or 2% or equivalently the distance modulus between 0.02 to 0.04 mag. Then the whole extragalactic scale will benefit from this improved knowledge of the LMC modulus.

Gaia will allow for the first time to determine the trigonometric parallax of galactic Cepheids within 3 kpc with a relative error less than 1%. From Fernie et al. (1995) it is known that there are 15 Cepheids within 0.5 kpc, 65 within 1 kpc and 165 at a distance less than 2 kpc. Most of the Cepheids are very bright for Gaia ($V < 13$ mag) and rather red (like a K5V star) meaning that they will be very well measured by Gaia. The relative accuracy in parallax is plotted in Figure 6 for the $\sim$ 400 galactic Cepheids from the David Dunlap Observatory Cepheid data base with estimated distances and brightness. One sees that 100 of them will have $\sigma_\pi/\pi < 0.5\%$ and most

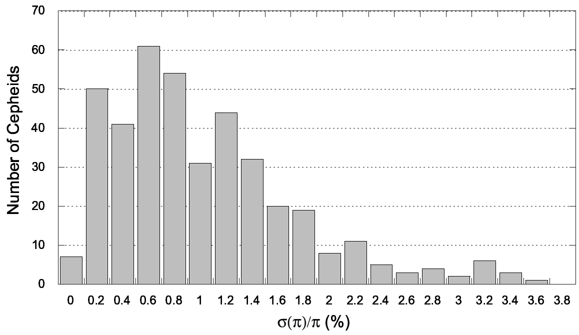

Figure 6. Expected relative accuracy in the distance of the galactic Cepheids.

of them will be garnered by Gaia with a relative distance better than 2% at the end of the mission. This will change dramatically the calibration of the P-L relation and given the relatively large number of stars, this should also allow to investigate the metallicity effect and test the universality of the P-L relation, both for the slopes and the zero-points.

The LMC Cepheids with a $13 < V < 16$ will be typically observed with a 30% accuracy allowing to check a possible difference between the LMC and galactic zero-point. In addition to the Cepheids, Gaia will bring also thousands of RR Lyrae and Miras with geometric distances accurate to 1 to 10 per cent, providing a large sample to determine the P-L relations as a function of colour and metallicity. As for the globular clusters, Gaia should give the distance (based on an average of several hundreds of stars) of most of the 140 galactic clusters to better than 1%, making them a valuable tool for the extragalactic scale based only on old objects. For the globular clusters the main output from the accurate distance will be the estimates of their absolute ages from the absolute luminosity of the main sequence turnoff. A precision of 3% on the distance is sufficient to determine an age with one billion year uncertainty and it is known that the distance modulus is the chief source of uncertainty in globular cluster ages (Krauss & Chaboyer 2003).

9. CONCLUSION

Gaia's main science objective is to clarify the origin and evolution of the Milky Way from a deep census of its stellar populations. Epoch-making advances are expected in stellar physics thanks to the combination of accurate astrometry, photometry and spectroscopy in a survey mode. Although this remains the main goal of the mission I have attempted to convey the message that a main characteristic of the mission is its versatility permitting the same observations to address many other science goals with the highest level of accuracy and statistical significance. Our hope is that the many scientists who have accepted to invest a considerable amount of their research time to make the mission possible and successful will not be disappointed by the results.

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REFERENCES

Bertotti, B., Iess, L., Tortora, P., 2003, Nature, 425, 374

Casertano, S, Lattanzi, M.G., Morbidelli, R. et al., 2004, Gaia technical report PSWG-OAT-002

Cellino, A., 2005, ESA SP-576, this volume

Claeskens, J.F, Smette, A., Surdej, J., 2005, ESA SP-576, this volume

Crosta, M. T., Mignard, F., 2005, ESA SP-576, this volume

Dollet, C., Bijaoui, A., Mignard, F., 2005, A&A, 426, 729

de Felice, F., Crosta, M. T., Vecchiato, A., et al, 2004, ApJ, 607, 580

ESA, 2000, Composition, Formation and Evolution of the Galaxy, ESA-SCI(2000)4

Eyer, L., 2005, ESA SP-576, this volume

Feast, M.W. 1999, PASP, 111, 775

Fernie, J.D., Beattie, B., Evans, N.R., and Seager, S. 1995, IBVS No. 4148

Hestroffer, D., Berthier, J., 2005, ESA SP-576, this volume

Høg, E., Mignard, F. 2005, ESA SP-576,this volume

Johansen, A., 2002, Gaia technical report GAIA-CUO-106

Klioner, S., Peip, M., 2003 A&A, 410, 1063

Klioner, S., 2003 AJ, 125, 1580

Kovalevsky, J., 2003 A&A, 404, 743

Krauss, L.M., Chaboyer, B., 2003 Science, 299, 65

Lebreton, Y, 2005, ESA SP-576, this volume

McEvoy, A.C., 1999, SAG-AC-001

Mignard, F., 2002, in Gaia: A European Space Project, eds. O. Bienaymé and C. Turon, p. 107

Muinonen, K. 2005,ESA SP-576, this volume

Pace, O., 2005, ESA SP-576, this volume

Perryman, M.A.C. et al., 2001, A&A, 369, 339

Pireaux., S., Rozelot, J.P., 2003 Astroph. Sp. Sci., 284, 1159

Robichon, N., 2002, in Gaia: A European Space Project, eds. O. Bienaymé and C. Turon, p. 215.

Surdej J., Claeskens, J.F., Smette, A., 2002, A complete sample of gravitationally lensed quasars to be detected with GAIA, presented at the RRFWG in Liège, November 2002

Tammann, G.A., Reindl, B., 2002, Baltic Astronomy, 11, 297-319

Tanga, P., 2005, ESA SP-576, this volume

Turon, C., Perryman, M.A.C., 1999, in Harmonizing Cosmic Distance Scale in a post-Hipparcos Era, D. Egret and A. Heck eds., ASP Conf. Ser. 167, 1-12

Udalski, A., Szymanski, M., Kubiak, M. et al., 1999, Acta Astronomica, 49, pp.201-221

Vecchiato, A., Lattanzi, M. G., Bucciarelli, B., et al., 2003, A&A, 399, 337

Walker, A., 1999, in Post-Hipparcos cosmic candles, eds. A. Heck and F. Caputo, p. 125

Wolff, S., 2005, ESA SP-576, this volume