GAIA: ORIGIN AND EVOLUTION OF THE MILKY WAY

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ABSTRACT

GAIA is the astrophysics candidate for the ESA Cornerstone 5 mission, which is to be selected in September 2000. The GAIA mission will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group. This amounts to about 1 per cent of the Galactic stellar population. Combined with astrophysical information for each star, provided by on-board multi-colour photometry, these data will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way Galaxy. Additional scientific products include detection and orbital classification of tens of thousands of extra-solar planetary systems, a comprehensive survey of objects ranging from huge numbers of minor bodies in our Solar System, through galaxies in the nearby Universe, to some 500 000 distant quasars. It will also provide a number of stringent new tests of general relativity and cosmology. A complete satellite design has been developed, including the proposed payload, corresponding accuracy assesments, and results from a prototype data reduction development. GAIA can be launched in 2009, within the specified budget for the next generation ESA Cornerstone missions.

Keywords: GAIA, Milky Way Galaxy, Stellar Populations, Extrasolar Planets, Solar System, Fundamental Physics, Space Astrometry, spacecraft

1. GAIA: AN OVERVIEW

GAIA is the astrophysics candidate for the fifth cornerstone mission of the ESA science programme, CS5. The GAIA mission, which has been under study by ESA, industry and a very wide community of European astrophysicists over the past two years, arose from the recommendations of the Horizon 2000+ Survey Committee in 1994. Selection of the CS5 mission will be made in September 2000, with the choice between GAIA and a mission to the planet Mercury, BepiColombo, with the approved mission scheduled for launch in 2009.

GAIA builds upon the observational techniques pioneered and proven by ESA's Hipparcos mission to solve one of the most difficult yet deeply fundamental challenges in modern astronomy: to create an extraordinarily precise three-dimensional map of about one billion stars throughout our Galaxy and beyond. In the process, by combining positional data with complementary radial velocities, GAIA will map the stellar motions, which encode the origin and subsequent evolution of the Galaxy. Through comprehensive photometric classification, GAIA will provide the detailed physical properties of each star observed: characterizing their luminosity, temperature, gravity, and elemental composition. This massive multi-parameter stellar census will provide the basic observational data to quantify the origin, structure, and evolutionary history of our Galaxy, the primary science goal of the GAIA mission.

GAIA will achieve this by repeatedly measuring the positions and multi-colour brightnesses of all objects down to $V = 20$ mag. On-board object detection will ensure that variable stars, supernovae, transient sources, micro-lensed events, and minor planets will all be detected and catalogued to this faint limit. Final accuracies of 10 microarcsec at 15 mag, comparable to the diameter of a human hair at a distance of 1000 km, will provide distances accurate to 10 per cent as far as the Galactic Centre, 30 000 light years away. Stellar motions will be measured even in the Andromeda galaxy.

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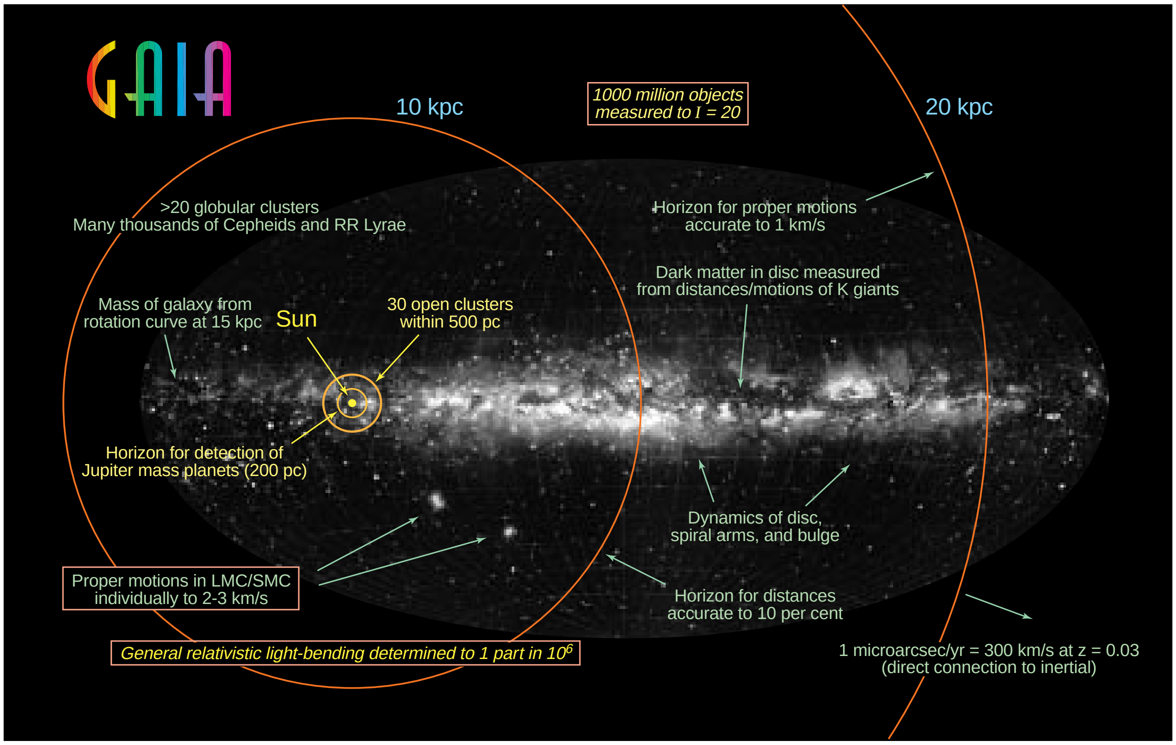


Figure 1. An overview of the GAIA scientific performance, superimposed on the Lund map of the sky. The Milky Way Galaxy, and the other galaxies of the Local Group, are the primary scientific targets for the GAIA mission.

1.1. GAIA: the science

GAIA's expected scientific harvest is of almost intimidating extent and implication. The primary science goal is to clarify the origin and history of our Galaxy, quantifying tests of galaxy formation theories, and also our knowledge of star formation and evolution. This is possible since low mass stars live for much longer than the present age of the Universe, and retain in their atmospheres a fossil record of the chemical elements in the inter-stellar medium at the time of their formation. The orbits of these stars similarly encode their dynamical histories, so that the GAIA results will precisely identify relics of tidally-disrupted accretion debris, and probe the distribution of dark matter. The GAIA survey will establish the luminosity function for pre-main sequence stars, detect and categorize rapid evolutionary stellar phases, place unprecedented constraints on the age, internal structure and evolution of all stellar types, establish a rigorous distance scale framework throughout the Galaxy and beyond, and classify the star formation, kinematical and dynamical behaviour across the Local Group of galaxies.

GAIA will pinpoint exotic objects in colossal numbers: many thousands of extra-solar planets will be discovered, and their detailed orbits and masses determined; brown dwarfs and white dwarfs will be identified in their tens of thousands; some 100 000 extragalactic supernovae will be discovered in time for ground-based observers to implement follow-up observations; Solar System studies will receive a massive impetus through the detection of many tens of thousands of new minor planets; inner Trojans and even new trans-Neptunian objects, including Plutinos, will be discovered. In addition to astrophysics and solar system studies, GAIA will contribute to fundamental physics: GAIA will quantify the bending of star light by the Sun and the major planets over the entire celestial sphere, and therefore directly observe the structure of space-time—the accuracy of GAIA's determination of General Relativistic light bending is comparable to that required to detect the long-sought scalar correction to the tensor form. The PPN parameters γ and β, and the solar quadrupole moment J_2, will be determined with unprecedented precision. New constraints on the rate of change of the gravitational constant, $\dot{G}$, and on gravitational wave energy over a certain frequency range, will be obtained.

1.2. GAIA: the mission

GAIA will be a continuously scanning spacecraft, accurately measuring one-dimensional coordinates along great circles, and in two simultaneous fields of view, separated by a well-defined and well-known angle. These one-dimensional coordinates are then converted into the astrometric parameters in a global data analysis, in which distances and proper motions 'fall out' of the processing, as does information on double and multiple systems, photometry, variability, metric, planetary systems, etc. The payload is based on a large but feasible CCD focal plane assembly, with passive thermal control, and a natural short-term (3 hour) instrument stability due to the sunshield, the selected orbit, and a robust payload design.

The telescopes are of moderate size, with no specific design or manufacturing complexity. The system fits within a dual-launch Ariane 5 configuration, without deployment of any payload elements. A 'Lissajous' orbit at the outer Lagrange point L2 has been identified as the preferred operational orbit, from where an average of 1 Mbit of data per second is returned to the single ground station throughout the 5-year mission. The 10 microarcsec accuracy target has been shown to be realistic through a comprehensive accuracy assessment programme; this remarkable accuracy is possible partly by virtue of the (unusual) instrumental self-calibration achieved through the data analysis on-ground. This ensures that final accuracies essentially reflect the photon noise limit for localisation accuracy: this challenge, while demanding, has been proven deliverable by the Hipparcos experience.

During the GAIA study, the Science Advisory Group, whose members are the authors of this paper, has studied the main elements of an 'end-to-end' programme. The analysis demonstrates that star selection can be effectively undertaken autonomously on-board, which has the far-ranging scientific implications noted earlier, and which also eliminates the need for a complex and costly pre-launch programme of observation definition: the Science Operations Centre activities associated with the mission will also be correspondingly greatly simplified.

Extant studies include a detailed assessment of the storage, computational processing and algorithmic demands of the resulting satellite data stream, which will total some 20 Tbytes of raw data. These simulations have supplied confidence that rapid and efficient data reduction is feasible, assuming conservative projections of recent developments in storage devices, computational capabilities, and state-of-the-art concepts of object-oriented data bases.

1.3. GAIA: the observatory

GAIA will record more than just huge volumes of positional data on a vast number of astrophysical targets. GAIA will also provide a complementary range of data, with a diversity of applications. Every one of the 10^9 GAIA targets will be observed typically 100 times, each time in a complementary set of photometric filters, and a large fraction also with a radial velocity spectrograph. The available spatial resolution exceeds that available in ground-based surveys. Source detection happens on-board at each focal-plane transit, so that variable and transient sources are detected. All these complementary datasets, in addition to the superb positional and kinematic accuracy which is derivable from their sum, make GAIA an optimal observatory mission: every observable source will be observed every time it crosses the focal plane.

These data allow studies from asteroids to distant supernovae, from planets to galaxies, and naturally interest almost the entire astronomical community. Because of this enormous interest, GAIA will be an open observatory mission, directly making available its rich scientific resource to the sponsoring communities. The scale of the GAIA data is such that many analyses can be undertaken during operations, some will require the whole mission calibration information, while others again will await final data reduction. The GAIA observatory will provide exciting scientific data to a very wide community, beginning with the first photometric observations, and rapidly increasing until the fully reduced GAIA data become available. The resulting analyses will provide a vast scientific legacy, providing a wealth of quantitative data on which all of astrophysics will build.

The ESA Concept and Technology Study has demonstrated that these scientific goals are feasible by means of an ESA-only mission, technically achievable on the time-scale of a 2009 launch, and within a budget profile consistent with the current cornerstone envelope. While challenging, the entire GAIA design is within the projected state-of-the-art: the satellite can be developed in time for launch in 2009. By combining current technology with the demonstrated Hipparcos measurement principles, GAIA will deliver an orders of magnitude improvement in our knowledge of our Galaxy, in terms of accuracy, number of objects, and limiting magnitude. With such a schedule, a complete stereoscopic map of our Galaxy will be available within 15 years. The successful completion of this programme will characterise the structure and evolution of stars and our Galaxy in a manner completely impossible using any other methods, and to an extent inconceivable even a decade ago.

2. GAIA: THE SCIENTIFIC CASE

The range of scientific topics which will be addressed by the GAIA data is vast, covering much of modern astrophysics, and fundamental physics. In this section we present a few illustrative examples, to give the flavour of the mission capabilities, with scientific applications ranging from the Milky Way Galaxy, stellar astrophysics, Solar System minor bodies, and extra-galactic studies, to fundamental physics. Further details are available on the GAIA www site `http://astro.estec.esa.nl/GAIA`. Documents there contain references to the original work briefly summarised here, as well as details of the many other exciting scientific projects which GAIA will address, but which space precludes discussion of here.

2.1. Structure and Evolution of the Milky Way Galaxy

Understanding the Galaxy in which we live is one of the great intellectual challenges facing modern science. The Milky Way contains a complex mix of stars, planets, interstellar gas and dust, radiation, and the ubiquitous dark matter. These components are widely distributed in age (reflecting their birth rate), in space (reflecting their birth places and subsequent motions), on orbits (determined by the gravitational force generated by their own mass), and with chemical element abundances (determined by the past history of star formation and gas accretion). Astrophysics has now developed the tools to measure these distributions in space, kinematics, and chemical abundance, and to interpret the distribution functions to map, and to understand, the formation, structure, evolution, and future of our Galaxy. This potential understanding is also of profound significance for quantitative studies of the high-redshift Universe: a well-studied nearby template underpins analysis of unresolved galaxies with other facilities, and at other wavelengths.

Understanding the structure and evolution of a galaxy requires three complementary observational approaches: (i) a census of the contents of a large, representative, part of the galaxy; (ii) quantification of the present spatial structure, from distances; (iii) knowledge of the three-dimensional space motions, to determine the gravitational field and the stellar orbits. That is, one requires complementary astrometry, photometry, and radial velocities. Astrometric measurements uniquely provide model independent distances and transverse kinematics, and form the base of the cosmic distance scale. Photometry, with appropriate astrometric and astrophysical calibration, gives a knowledge of extinction, and hence, combined with astrometry, provides intrinsic luminosities, spatial distribution functions, and stellar chemical abundance and age information. Radial velocities complete the kinematic triad, allowing determination of gravitational forces, and the distribution of invisible mass. The combination of vast continuing ground-based radial velocity projects and Hipparcos did this for one location in the Milky Way, the Solar neighbourhood; GAIA will accomplish this for a large fraction of our Galaxy.

GAIA will measure not only the local kinematics with much improved accuracy, but the full six-dimensional stellar distribution function throughout a large part of the Galactic disk. This will allow not only a determination of the gravitational potential of the Galaxy and its distribution function, but also reveal how much a given stellar population deviates from dynamical equilibrium. This in turn will constrain the formation history of the Galactic disk and its components, e.g., the past variations of pattern speed and strength of the central bar and spiral arms.

We note here a few of the many important and challenging science cases, all of which require GAIA's faint limiting magnitude, and which illustrate GAIA's study of the Galactic Bulge, Disk, and Halo.

2.1.1. The Galactic Bulge

Bulge stars are predominantly moderately old, unlike the present-day disk; they encompass a wide abundance range, peaking near the Solar value, as does the disk; and they have very low specific angular momentum, similar to stars in the halo. Thus the bulge is, in some fundamental parameters, unlike both disk and halo. What is its history? Is it a remnant of a disk instability? Is it a successor or a precursor to the stellar halo? Is it a merger remnant? It is not clear whether the formation of the bulge preceded that of the disk, as predicted by 'inside-out' scenarios; or whether it happened simultaneously with the formation of the disk, by accretion of dwarf galaxies; or whether it followed the formation of the disk, as a result of the dynamical evolution of a bar. Large-scale surveys of proper motions and photometric data inside the bulge can cast light on the orbital distribution function. Knowing the distance, the true space velocities and orbits can be derived, thus providing constraints on current dynamical theories of formation. GAIA data for bulge stars, providing intrinsic luminosities, metallicity, and numbers, can be inverted to deduce star formation histories. A simulation of such an analysis is provided in figure 2.

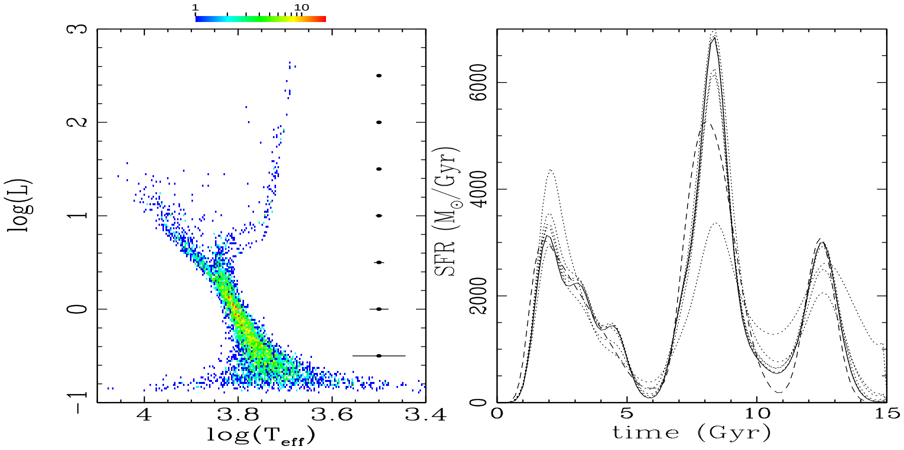


Figure 2. Left: a synthetic H-R diagram appropriate for GAIA. Right: the derived star formation history following inversion of the data in the left panel. The true input star formation history is shown by the long dashes. The dotted lines are the successive 2, 4, 6, 8 and 9 iterations of the inversion method. The 10th iteration is given by the solid curve, showing rapid convergence and a good recovery of the input star formation history, when suitable quality data are available.

The highly accurate parallaxes, proper motions and magnitudes acquired by GAIA for more than 10^6 stars per square degree, will allow the vast majority of red and asymptotic giant branch stars, and a significant fraction of the clump stars in Baade's Window to be measured with a precision higher than 10–15 per cent. With $V = 20$ as the limiting magnitude, red and asymptotic giant branch stars can be detected over a range of 5 mag.

There is substantial evidence that the bulge is not axisymmetric, but instead has a triaxial shape seen nearly end-on. Indications for this come from the asymmetric near-infrared light distribution, star counts, the atomic and molecular gas morphology and kinematics, and the large optical depth to micro-lensing. The actual shape, orientation, and scale-length of the bulge, and the possible presence of an additional bar-like structure in the disk plane, however remain a matter of debate. The reason why it is so difficult to derive the shape of the Galactic bar is that three-dimensional distributions cannot be uniquely recovered from projected surface brightness distributions such as the COBE/DIRBE maps. In addition, bars with the same density distribution could have different pattern speeds. No unique solution can be found using only one-velocity component diagrams, unless the gravitational potential is known, since the velocity dispersion in the star motions smears out the effects of the bar on the distribution function.

GAIA proper motions to faint magnitudes, in particular in a number of low-extinction windows, will allow unambiguous determination of the shape, orientation, tumbling rate mass profile and star formation history of the bulge. The large-scale kinematics of the Galaxy also contains an imprint of the non-axisymmetric central potential.

2.1.2. The Galactic Halo

The stellar halo of the Galaxy contains only a small fraction of its total luminous mass, but the kinematics and abundances of halo stars, globular clusters, and the dwarf satellites contain imprints of the formation of the entire Milky Way. The most metal-deficient stars, with [Fe/H] < -3.5, represent a powerful tool to understand primordial abundances and the nature of the objects which produced the first heavy elements.

Halo Streams The halo of the Milky Way is likely to be the most important component that may be used to distinguish among competing scenarios for the formation of our Galaxy. The classical picture of inner monolithic collapse with later accretion in the outer Galaxy, predicts a smooth distribution both in configuration and velocity space for our Solar neighbourhood, which is consistent with the available observational data. The currently popular hierarchical cosmologies propose that big galaxies are formed by mergers and accretion of smaller building blocks, and many of its predictions seem to be confirmed in high-redshift studies.

Those merging and accretion events leave signatures in the phase-space distribution of the stars that once formed those systems (Figure 3a). Helmi etal have shown that, after 10 billion years, the spatial distribution of stars in the inner halo should be fairly uniform, whereas strong clumping is expected in velocity space. This clumping appears

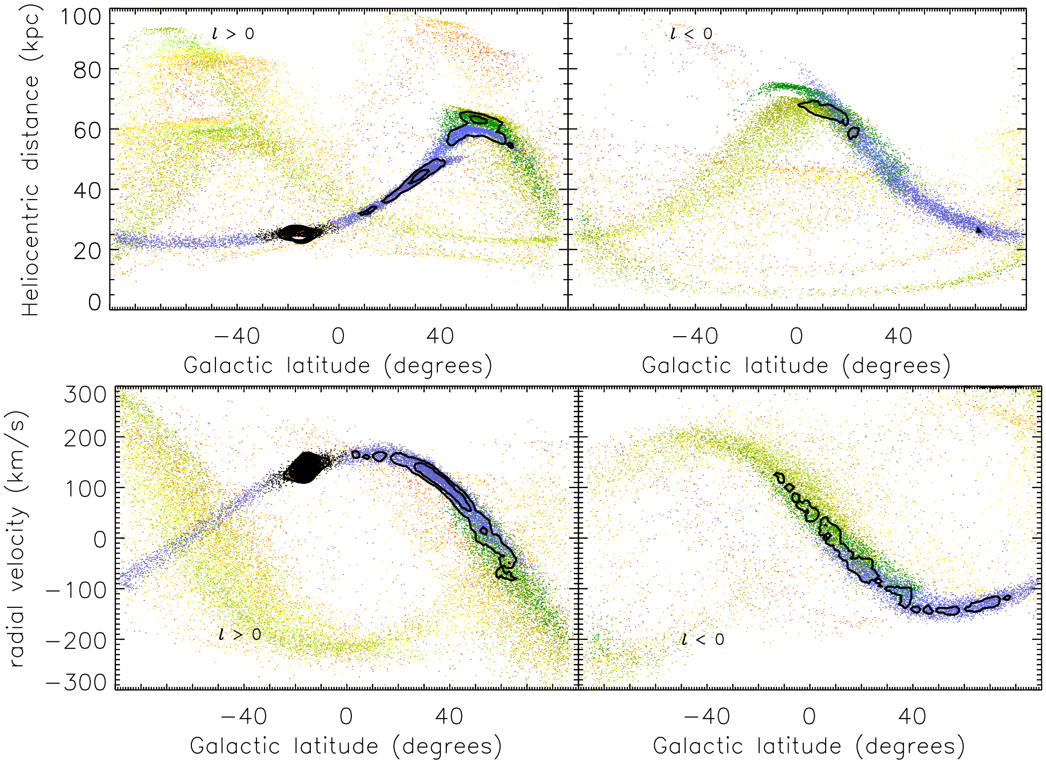


Figure 3. An example of the phase-space distribution of stars originating in a disrupted satellite for the case of Sagittarius. Top: the predicted distribution in heliocentric distance versus latitude. Bottom: the predicted distribution in radial velocity versus latitude. Different colours indicate material lost in different pericentric passages. Streams as coherent structures in phase-space are clearly visible even after 10 Gyr of evolution, and will be easily picked out by GAIA.

in the form of a very large number of moving groups (several hundred in a 1 kpc^3 volume centered on the Sun, if the whole stellar halo were built in this way) each having very small velocity dispersions and containing several hundred stars. The required velocity accuracies to detect individual streams are less than a few km s^{-1}, requiring measurement precision of order μas.

The space of adiabatic invariants allows better identification of the different merging events. Here clumping should be stronger since all stars originating from the same progenitor have very similar integrals of motion, resulting in a superposition of the corresponding streams. The plane defined by the total angular momentum and its z-component is suitable for finding such sub-structures, both because lumps remain coherent even after complete phase-mixing and also because of GAIA's accuracy.

The Outer Halo GAIA will find several million individual stars in the outer halo (defined here as galactocentric distance $R > 20$ kpc). These will mostly be G and K giants and red and blue horizontal branch stars. G and K giants are intrinsically bright, they form in all known old stellar population types, they have easily measurable radial velocities, and they are historically well studied because they are the most easily accessible stars in the globular clusters. Horizontal branch stars have been the preferred tracer stellar type for the outer halo to date, because they can be much more easily identified amongst field stars than G and K giants. In particular, blue horizontal branch stars have been very easy to locate, since almost all faint ($14 < V < 19$ mag), blue ($0.0 < B-V < 0.2$) stars are halo blue horizontal branch stars. However these stars are a biased tracer of the halo population in the sense that they do not always form in old metal weak populations (viz. the second parameter problem in globular clusters). Redder horizontal branch stars and G and K halo giants are drowned out by the huge numbers of foreground turnoff and dwarf stars in the Galactic disk.

GAIA will circumvent all these difficulties. The late-type foreground dwarfs are much closer than the background late-type giants, so that at faint magnitudes ($V < 19$ mag) the dwarfs have a measurable parallax while the background giants do not. It will be possible to lift the veil of foreground stars and reveal of order millions of background halo stars, on the giant branch, and the red and blue horizontal branch.

2.1.3. Large Scale Structure of the Galactic Disk

A summary of the photometric and kinematic requirements defined by the GAIA science case is shown in Table 1, from which it may be seen that GAIA addresses many aspects of disk structure and dynamics. We note here just two of these examples.

Table 1. Summary of selected Galactic kinematic tracers, and the limiting magnitudes and astrometric information necessary to study them. Columns 7–8 demonstrate that the faint magnitude limit of GAIA is essential for probing these different Galaxy populations, while columns 11–12 demonstrate that GAIA will provide data of adequate precision to meet the scientific goals.

(1) Tracer	(2) M_V mag	(3) ℓ deg	(4) b deg	(5) d kpc	(6) A_V mag	(7) V_1 mag	(8) V_2 mag	(9) ϵ_T km/s	(10) σ_{μ_1} μas/yr	(11) σ'_{μ_1} –	(12) σ'_{π_1} –
Spiral arms:											
Cepheids	–4	all	< 10	10	3–7	14	18	7	5	0.03	0.06
B–M Supergiants	–5	all	< 10	10	3–7	13	17	7	4	0.03	0.05
Perseus arm (B)	–2	140	< 10	2	2–6	12	16	10	3	0.01	0.01
Thin disk:											
gK	–1	0	< 15	8	1–5	14	18	40	6	0.01	0.06
gK	–1	180	< 15	10	1–5	15	19	10	8	0.04	0.10
Disk warp (gM)	–1	all	< 20	10	1–5	15	19	10	8	0.04	0.10
Disk asymmetry (gM)	–1	all	< 20	20	1–5	16	20	10	15	0.14	0.4
Thick disk:											
Miras, gK	–1	0	< 30	8	2	15	19	50	10	0.01	0.10
HB	+0.5	0	< 30	8	2	15	19	50	20	0.02	0.20
Miras, gK	–1	180	< 30	20	2	15	21	30	25	0.08	0.65
HB	+0.5	180	< 30	20	2	15	19	30	60	0.20	1.5
Gravity, $\mathcal{K}_\mathcal{Z}$:											
dK	+7–8	all	all	2	0	12	20	20	60	0.01	0.16
dF8-dG2	+5–6	all	all	2	0	12	20	20	20	0.01	0.05
Bulge:											
gM	–1	0	< 20	8	2–10	15	20	100	10	0.01	0.10
HB	+0.5	0	< 20	8	2–10	17	20	100	20	0.01	0.20
MS turnoff	+4.5	1	–4	8	0–2	19	21	100	60	0.02	0.6
Halo:											
gG	–1	all	< 20	8	2–3	13	21	100	10	0.01	0.10
HB	+0.5	all	> 20	30	0	13	21	100	35	0.05	1.4
Globular clusters (gK)	+1	all	all	50	0	12	21	100	10	0.01	0.10
internal kinematics (gK)	+1	all	all	8	0	13	17	15	10	0.02	0.10
Satellite orbits (gM)	–1	all	all	100	0	13	20	100	60	0.3	8

Key: (1) tracer of a specific sub-population. HB: signifies blue and red horizontal branch as appropriate; for globular clusters, the cluster itself is used as tracer, with its proper motion the mean of many cluster star motions; globular cluster kinematics refers to the internal kinematics of globular clusters of our own Galaxy; (2) absolute visual magnitude of a typical tracer star; (3–4) appropriate Galactic coordinates; (5) optimal or practical distance; (6) typical visual extinction along the line of sight; for low latitudes the extinction in a Galactic window is given; (7–8) typical range of apparent visual magnitudes; (9) expected velocity dispersion for tracer stars of the sub-population, in the proper motion direction; (10) expected GAIA proper motion standard error, σ_{μ_1}, for a single star at representative magnitude; (11) relative proper motion error; (12) expected relative error on GAIA astrometric distances at representative magnitudes.

Galactic Disk Warps Galactic disks are thin, but they are not flat. Approximately one-half of all spiral galaxies have disks which warp significantly out of the plane defined by the inner galaxy. Remarkably, there is no realistic explanation of this common phenomenon, though the large-scale structure of the dark matter, and tidal interactions, must be important, as the local potential at the warp must be implicated. Neither the origin nor the persistence of galaxy warps is understood, and insufficient information exists to define empirically the relative spatial and kinematic distributions of the young (OB) stars which should trace the gas distribution, and the older (gKM) stars which define a more time-averaged gravitational field.

The expected kinematic pattern (at least, in existing plausible models) is most strongly constrained by the straightness of the line of nodes: these should wind up in at most a few rotation times, typically less than 2 Gyr. A relevant shear pattern corresponds to systematic motions dependant on warp phase and galactocentric distance superimposed on Galactic rotation. A plausible velocity amplitude associated with the warp at the optical disk edge is significantly less than 0.1Ω, with Ω the disk rotation angular velocity. This will be distributed between latitude and longitude contributions depending on the local geometric projection.

At $R = 15$ kpc, for a flat rotation curve, the systematic disk rotation corresponds to 6 mas yr^{-1}. The kinematic signature from a 1 kpc-high warp corresponds to a systematic effect of ~ 90 μas yr^{-1} in latitude and ~ 600 μas yr^{-1} in longitude. For such a signal to be detected the reference frame must be rigid to better than a few microarcsec on scales of $\sim 10^\circ$ (i.e. matching the high-frequency warp structure) and on scales of 2π radians, requirements well within the GAIA capabilities. The corresponding distance requirements are more demanding: at the warp a mean parallax is less than 100 μas, so that resolution of the warp within 10 per cent implies distance accuracies of 10 μas at $I \sim 15$ mag. Along lines of sight with typical reddening, the study of the Galactic warp will be within the limits of GAIA's performance.

Dark Matter in the Disk The distribution of mass in the Galactic disk is characterized by two numbers, its local volume density ρ_o and its total surface density $\Sigma(\infty)$. They are fundamental parameters for many aspects of Galactic structure, such as chemical evolution (is there a significant population of white dwarf remnants from early episodes of massive star formation?), the physics of star formation (how many brown dwarfs are there?), disk galaxy stability (how important dynamically is the self-gravity of the disk?), the properties of dark matter (does the Galaxy contain dissipational dark matter, which may be fundamentally different in nature from the dark matter assumed to provide flat rotation curves, and what is the local dark matter density and velocity distribution expected in astroparticle physics experiments?), and non-Newtonian gravity theories (where does a description of galaxies with non-Newtonian gravity and no dark matter fail?).

The most widely referenced and commonly determined measure of the distribution of mass in the Galactic disk near the Sun is the local volume mass density ρ_o, i.e. the amount of mass per unit volume near the Sun, which for practical purposes is the same as the volume mass density at the Galactic plane. This quantity has units of $M_\odot$ pc^{-3}, and its local value is often called the 'Oort limit'. The contribution of identified material to the Oort limit may be determined by summing all local observed matter – an observationally difficult task. The uncertainties arise in part due to difficulties in detecting very low luminosity stars, even very near the Sun, in part from uncertainties in the binary fraction among low mass stars, and in part from uncertainties in the stellar mass–luminosity relation. All these quantities will be determined directly, to extremely high precision, by GAIA.

The second measure of the distribution of mass in the Solar vicinity is the integral surface mass density. This quantity has units of $M_\odot$ pc^{-2}, and is the total amount of disk mass in a column perpendicular to the Galactic plane. It is this quantity which is required for the deconvolution of rotation curves into 'disk' and 'halo' contributions to the large-scale distribution of mass in galaxies. If one knew both the local ρ_o and $\Sigma(\infty)$, one could immediately constrain the scale height of any contribution to the local volume mass density which was not identified. That is, one could measure directly the velocity dispersion, i.e., the temperature, of the 'cold' dark matter.

2.2. Stellar Astrophysics

GAIA will provide distances of delightful accuracy for all types of stars of all stellar populations, even the brightest, or those in the most rapid evolutionary phases which are very sparsely represented in the Solar neighbourhood. With the parallel determination of extinction/reddening and metallicities by the use of multi-band photometry and spectroscopy, this huge amount of basic data will provide an extended basis for reading *in situ* stellar and galactic evolution. All parts of the Hertzsprung–Russell diagram will be comprehensively calibrated, including all phases of stellar evolution, from pre-main sequence stars to white dwarfs and all existing transient phases; all possible masses, from brown dwarfs to the most massive O stars; all types of variable stars; all possible types of binary systems down to brown dwarf and planetary systems; all standard distance indicators (pulsating stars, cluster sequences, supergiants, central stars of planetary nebulae, etc.). This extensive amount of data of extreme accuracy will stimulate a revolution in the exploration of stellar and Galactic formation and evolution, and the determination of the cosmic distance scale.

Table 2. GAIA observations: limiting apparent magnitude and distance for stars with a relative parallax error smaller than 10 percent, for zones with no extinction. The last column indicates the limiting factor: the GAIA magnitude limit (G) or the distance (d).

Mv [mag]	Stellar type	$\langle V-I \rangle$ [mag]	$V_{\rm lim}$ [mag]	$V_{\rm lim}$ [mag]	$d_{\rm lim}$ [pc]	Limiting factor
	O V	–0.3	12.2	12.2		
–5	B0-G0 Ib	to			27 000	d
	all Ia and Ia0	4.7	12.2	8.5		
0	A0 V	0.01	15.0	15.0	10000	d
	K3 III	1.19	15.2	14.7	11000	d
5	G5 V	0.8	17.6	17.3	3300	d
10	M2 V	2.0	20.3	19.2	1150	d
	DB	0.0	19.7	19.7	870	d
15	M7 V	3.0	22.5	20.6	320	d
	DG	0.8	21.3	21.0	180	G
17	M8 V	3.2	23.1	21.0	170	G
20	brown dwarfs	4.5	24.5	21.0	80	G

Clusters and their Mass Functions One of the most direct products of GAIA will be a complete and homogeneous census of the stellar content of a large number of clusters and associations or moving groups. This will enable a statistically significant study of the initial mass function within each group separately and a meaningful intercomparison of the results for different groups. GAIA's astrometric capabilities will allow kinematic member selection of stars in both open clusters and Galactic globular clusters, to $V \leq 20$ mag. This will separate field stars from the cluster members, allow internal dynamical studies, derivation of very accurate distances and space motions for the clusters, and will also provide much-improved colour-magnitude diagrams. Establishing the initial mass function for groups of all ages over a large volume will greatly advance the understanding in detail of the origin of the field-star population and its mass function.

Stellar Structure One of the triumphs of stellar evolution theory is a detailed understanding of the preferred location of stars in the physical Hertzsprung–Russell diagram, which plots luminosity versus temperature. However, there remain a number of uncertainties associated with stellar evolution models, and hence age estimates based on the models.

Probably the least understood aspect of stellar modeling is the transport process of matter, angular momentum and magnetic field at macroscopic and microscopic levels, including in particular the process of convection. Numerical simulations hold promise for the future, but at present one must view properties of stellar models which depend on the treatment of convection to be uncertain, and subject to possibly large systematic errors. Main sequence stars and red giants have surface convection zones. Hence, the surface properties of the stellar models (such as its effective temperature, or colour) are rather uncertain. Horizontal branch stars have convective cores, so the predicted luminosities and lifetimes of these stars are subject to possible systematic errors. Other domains such as the statistical physics at high density and/or low temperature or the nuclear reaction rates of heavy nuclei also require improvement. This lack of knowledge has consequences on topics as fundamental as the chemical evolution of the Universe, the rate of formation of heavy elements and of dust in the interstellar medium, and on the measurement of the age of the Universe. Understanding the dynamics of stellar interiors remains a key challenge for astronomy.

The agreement between predicted and observed properties of stars has remained qualitative due to the modest accuracy and relative scarcity of the relevant observed quantities. Luminosity estimates are based exclusively on determinations of stellar distances, which can be determined directly only by measurement of the trigonometric parallax. GAIA will provide distances to an unprecedented 0.1 per cent for 7×10^5 stars out to a few hundred pc, and to 1 per cent accuracy for a staggering 2.1×10^7 stars up to a few kpc. Distances to 10 per cent will reach beyond 10 kpc, and will cover a significant fraction of our Galaxy, including the Galactic centre, spiral arms, the halo, and the bulge, and—for the brightest stars—to the nearest satellites. The faint limiting magnitude allows investigation of white dwarfs as well as the bottom of the main sequence down to brown dwarfs. For the first time, this will provide an extensive network of accurate distance measurements for all stellar types. The number of stars of different types which will be discovered, and accurately measured by GAIA is summarised in the Table below.

Cosmic Distance Scale GAIA will provide accurate distances (and proper motions) for such huge numbers of each category of stellar distance indicators that, again in this domain, the analysis methods can be drastically changed. The sampling of open and globular clusters in age, metal, oxygen or helium content will be complete all over the Galaxy. Parallel improvement in the transformation between the observational and the theoretical H-R diagram will be required to take full benefit of these accuracies in terms of stellar evolution and age determination: photometric and/or spectroscopic data should allow the determination of the bolometric magnitude and of the effective temperature from the observed magnitudes and colours. For pulsating variables, the sampling versus period, populations, colours, and metal content will be as good as possible as excellent distance determinations will be obtained for all observable galactic stars, and a first reliable estimation of the intrinsic dispersion of the period-luminosity relations will be possible. Moreover, a first check of the universality of these relations (not only the slopes, but also the zero-points) will be possible, directly for LMC Cepheids, or using GAIA mean distances for the closest galaxies of the Local Group, at least LMC, SMC and Sagittarius.

2.3. Binaries, Brown Dwarfs and Planetary Systems

GAIA will detect a majority (59 per cent) of the 10 million binaries closer than 250 pc from the Sun. While this fraction drops to 35 per cent out to 1000 pc, this represents key information on 64 million binaries. This huge sample can be subdivided in, e.g., age-groups, and the variability and possible evolutionary trends of the binary frequency at different orbital periods can be studied.

The number of detected astrometric binaries will be larger than the number of actual orbit determinations. The success rate has been checked by simulations, and the number of 'good' orbits determined. The absolute numbers (again some 10 million orbits) are seen to be dominated by the 15–17.5 mag interval. To determine starting elements for all these unknown orbits (enabling a subsequent least-squares refinement as used in the simulations) will be a formidable task, which will require significant experimentation and development of algorithms. The reward however is huge: accurate determination of the binary fraction, the distribution of semi-major axes, and its evolution, and most of all, quantification of the stellar mass-luminosity relationship.

Sub-stellar binary companions can be divided in two classes, namely planets and brown dwarfs. There exist three major genesis indicators that can help classify sub-stellar objects as either brown dwarfs or planets: mass, shape and alignment of the orbit, and composition and thermal structure of the atmosphere. It is thought that stars form from large-scale dynamical instabilities, while planets form by core accretion or dynamical instability of protoplanetary disks. It has recently been shown that correlations between eccentricity and the logarithm of orbital period for pre-main sequence (and main-sequence) binaries and for objects thought to be the result of accretion in a disk (like the giant planets in the Solar system) are significantly different. The majority of the candidate planets discovered so far by the radial velocity programmes appear to follow the $(e, \log P)$ relation that can be established for pre-main sequence binaries. Low eccentricity alone is not sufficient to classify as planet a newly discovered low-mass companion, as low eccentricity is expected for stellar companions orbiting close to the other star.

The large-scale GAIA observations will also clarify the statistics of multiple systems. For stability reasons, the period-ratio in hierarchical systems has to be above about 10:1, but the observed distribution goes from 10 to at least 10^6, with 1000 as a typical value. The '5-year' astrometric pairs can thus be expected to contain many spectroscopic and/or eclipsing subsystems, and GAIA will be able to provide reliable triple-star statistics. Although one will seldom be able to specify completely the geometry in a specific system, the fraction of eclipsing components is expected to vary with the astrometric inclination, shedding some light on the distribution of relative inclination between the two orbits. This is an important parameter in triple-star orbital dynamics, and it may also help discriminate between different theories of (multiple) star formation.

The ability to determine simultaneously and systematically the planetary frequency and distribution of orbital parameters for the stellar mix in the Solar neighbourhood is a fundamental contribution that GAIA will uniquely provide. The only limitations are those intrinsic to the mission, i.e., the actual sensitivity of the GAIA measurements to planetary perturbations. GAIA's strength will be its discovery potential, following from the combined photometric and astrometric monitoring of all of the several hundred thousand bright stars out to distances of $\sim$ 200 pc.

GAIA's potential has been assessed by simulating observations of a homogeneous set of extra-solar planetary systems, to establish the expected sensitivity to the presence of planets and the potential for accurate estimation of orbital parameters, as a function of semi-major axis, period, and eccentricity, and the distance from the Sun. These simulations put the number of astrometric detections of Jupiter-mass planets somewhere between 10,000–50,000, depending on details of the detection and orbital distribution hypotheses. Photometric detections of planetary transits will of course also be a natural product of the GAIA photometry.

2.4. Solar System

Solar system objects present a challenge to GAIA because of their significant proper motions, but they promise a rich scientific reward. The minor bodies provide a record of the conditions in the proto-Solar nebula, and their properties therefore shed light on the formation of planetary systems. We present just two examples of relevant GAIA science.

Trojans in the Inner Solar System In addition to known asteroids, GAIA will discover a very large number, of the order of 10^5 or 10^6 (depending on the uncertainties on the extrapolations of the known population) new objects. It should be possible to derive precise orbits for all the newly discovered objects, since each of them will be necessarily observed many times during the mission lifetime. These will include a large number of near-Earth objects.

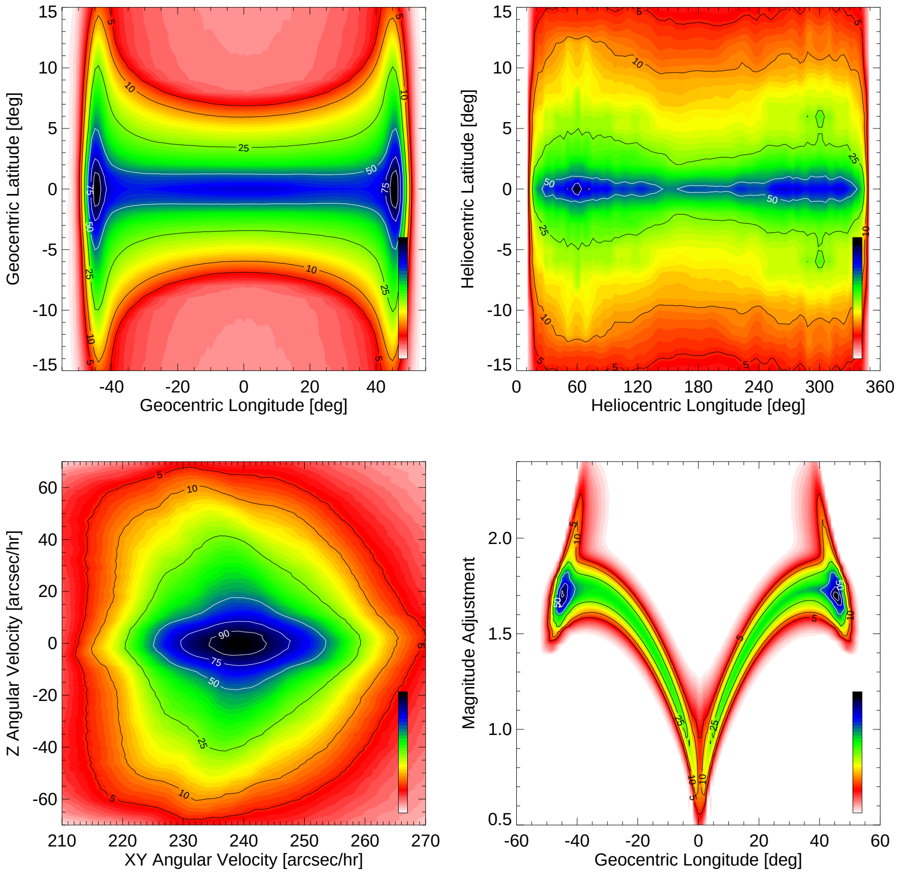


Figure 4. Predictions of the expectation of co-orbiting asteroids: (a) in the plane of geocentric ecliptic latitude and longitude; (b) heliocentric ecliptic latitude and longitude; (c) the distribution as a function of proper motions in the plane of, and perpendicular to, the ecliptic; (d) the distribution of magnitude adjustment versus geocentric longitude.

GAIA is ideal to look for these objects because of the enormous area of sky that must be searched. Co-orbiting satellites like Trojans librate about the Lagrange points, but the amplitude of libration can be very large. Figure 4(c) shows the distribution as a function of proper motions in the plane of, and perpendicular to, the ecliptic. The average velocity in the plane of the ecliptic is 238 arcsec/hr with a full-width half maximum of 28 arcsec/hr. Figure 4(d) shows the distribution of magnitude adjustment versus geocentric longitude. The brightest objects occur close to the Sun. These are the asteroids on horseshoe orbits at superior conjunction. Even though they are furtherest away from the Earth, this is outweighed by the effects of the almost zero phase angle. The broadest range of magnitude adjustments occurs at the greatest eastern and western elongations $\sim \pm 45°$. Here, the phase angle changes quickly for small changes in the longitude. This portion of the sky is accessible to GAIA. The average value of the magnitude adjustment here is 1.7, i.e., these objects are typically 1.7 mag fainter than their absolute magnitude (at zero phase angle and at unit heliocentric and geocentric distance). For the same distribution of magnitudes, Venusian Trojans are on average brighter than terrestrial or Martian Trojans.

Trans-Neptunian Objects: the Kuiper Belt The old view of a vast region of empty space extending from Pluto (~40 AU) to the Oort Cloud (~10 000 AU) has been conclusively replaced by a picture of a volume richly populated by unexplored new worlds. Ground-based surveys in the past few years have discovered over 100 icy bodies beyond Neptune, members of a population called the 'Kuiper Belt'. Kuiper Belt bodies are related to a wide range of outer Solar system bodies, such as the short-period comets, the Neptunian satellite Triton, and the Pluto-Charon system — indeed, Pluto is now recognized as the largest known member of the Kuiper Belt. The Kuiper Belt is also our closest link to the circumstellar disks found around other main sequence stars, and an understanding of the physical processes operative in the Belt (both now and in its early stage) will mark a key step forward in understanding the problem of planetary formation.

GAIA will detect a significant number of Kuiper Belt objects during its 5-year mission. The angular motion of a typical object at $\sim 90°$ elongation (where GAIA will be looking) is small: the known KBOs have $d\alpha/dt = 0.02 - 1.0$ arcsec hr^{-1} and $d\delta/dt = 0.002 - 1.2$ arcsec hr^{-1}. The surface density of the Kuiper Belt at $V = 20$ mag is 8×10^{-3} objects per square degree (2×10^{-2} at $V = 21$ mag, implying that GAIA should discover some number up to ~ 300 KBOs with $V \leq 20$ (~ 800 KBOs with $V \leq 21$).

Scientific objectives regarding the Kuiper Belt that can be answered only with GAIA include binarism, new Plutinos, and the good orbits essential to understand the system dynamics.

2.5. Galaxies, Quasars, and the Reference Frame

GAIA will not only provide a representative census of the stars throughout the Milky Way, but it will also make unique contributions to extragalactic astronomy. These include the structure, dynamics and stellar populations in the Magellanic Clouds and other Galactic satellites, and in M31 and M33, with scientific consequences comparable to those noted above for the Milky Way. In addition, the faint magnitude limit and all-sky survey of GAIA allows unique cosmological studies, from the space motions of Local Group galaxies, and studies of huge numbers of supernovae, galactic nuclei, and quasars.

Orbits in the Local Group: Gravitational Instability in the Early Universe The orbits of galaxies are a result of mildly non-linear gravitational interactions, which link the present positions and velocities to the cosmological initial conditions. Non-gravitational (hydrodynamic) or strongly non-linear gravitational interactions (collisions, mergers) are sometimes significant. It is uniquely possible in the Local Group to determine reliable three-dimensional orbits for a significant sample of galaxies, in a region large and massive enough to provide a fair probe of the mass density in the Universe. Such orbital information provides direct constraints on the initial spectrum of perturbations in the early Universe, on the global cosmological density parameter Ω, and on the relative distributions of mass and light on length scales up to 1 Mpc.

Radial velocities are known. The required measurements are distances and transverse velocities for the relatively isolated members of the Local Group, those more distant than ~100 kpc from another large galaxy. Improved distances will be derived from the GAIA-calibrated standard distance indicators, such as Cepheids and RR Lyraes, as described in The transverse motions will be derivable uniquely from the GAIA proper motion.

Large Scale Structure `Galaxies, Quasars and Supernovae:`
`Galaxies:` Growth of structure in the Universe is believed to proceed from small amplitude perturbations at very early times. Growth from the radiation-dominated era to the present has been extensively studied, particularly in the context of the popular hierarchical clustering scenario. Many aspects of this picture are well-established. Others are the subject of active definition through redshift and imaging surveys of galaxies, and the microwave background experiments. There are several aspects of this research which require very wide area imaging surveys with high spatial resolution, to provide high-reliability catalogues of galaxies and quasars extending to low Galactic latitudes. Here GAIA will contribute uniquely, by detecting and providing multi-colour photometry with ~0.3 arcsec spatial resolution for all sufficiently high-surface brightness galaxies. This provides a valuable and unique data set at two levels: for statistical analysis of the photometric structure of the central regions of many tens of thousands of galaxies; and for study of the large-scale structure of the local Universe. The scientific value of this huge and homogeneous database will impact all fields of galaxy research, naturally complementing the several redshift surveys, and the deeper pencil-beam studies with very large telescopes. Among the most important unique GAIA science products will be determination of the colour and photometric structure in the central regions of a complete, magnitude-limited sample of relatively bright galaxies.

`Supernovae:` GAIA will detect all compact objects brighter than $I = 20$ mag, so that in principle supernovae can be detected to a modulus of $m - M \sim 39$ mag, i.e., to a distance of 500 Mpc or $z \sim 0.10$. Simulations show that in 4 years, GAIA will detect about 100 000 supernovae of all types. Of these, the most useful as cosmological-scale distance indicators are the Type Ia supernovae, whose light curves are very accurate distance indicators, ±5 per cent. Rapid detection of such transient sources will allow detailed ground-based determination of lightcurves and redshifts.

`Quasars:` The astrometric programme to $V = 20$ mag will provide a census of $\sim$ 500 000 quasars. The mean surface density of $\sim 25\,\mathrm{deg}^{-2}$ at intermediate to high Galactic latitudes will provide the direct link between the GAIA astrometric reference system and an inertial frame. They are also of direct astrophysical interest.

Existing ground-based studies of gravitational (macro) lensing among the quasar population are restricted to resolutions of $\sim$ 1 arcsec. GAIA will provide sensitivity to multiply-imaged systems with separations as small as $\sim$ 0.2 arcsec. For the brighter quasars, $V < 18$ mag, with a surface density of $\sim 1\ \mathrm{deg}^{-2}$, where examples of lensing are most common, GAIA's sample of $\sim$ 500 000 quasars represents an increase of two orders of magnitude over existing surveys. Pushing the sensitivity to image separations of a few tenths of an arcsec will access systems where most of the lensing due to individual galaxies is expected. In particular, the GAIA survey will provide new constraints on lensing by the bulk of the galaxy population, including spiral galaxies, rather than the high-mass tail of ellipticals to which existing surveys are predominantly sensitive. GAIA also offers intriguing possibilities in the field of gravitational microlensing of the quasar population. Assuming that the data transmission allows identification of quasars showing a complex structure within a field of 3 arcsec, the observations will lead to the detection of a complete sample of several thousand gravitational lenses. This homogeneous sample would provide decisive astrophysical information, including constraints on the cosmological parameters Ω and λ_0. Photometric variability of multiply lensed quasars is of course also a proven method to determine $\mathrm{H_o}$.

Reference Frames At present, the International Celestial Reference System (ICRS) is primarily realized by the International Celestial Reference Frame (ICRF) consisting of positions of 212 extragalactic radio-sources with an rms uncertainty in position between 100 and 500 μas. The extension of the ICRF to visible light is the Hipparcos Catalogue with rms uncertainties estimated to be 0.25 mas yr^{-1} in each component of the spin vector of the frame (ω) and 0.6 mas in the components of the orientation vector (ε) at the catalogue epoch, J1991.25. The GAIA catalogue will permit a definition of the ICRS more accurate by three orders of magnitude than the present realizations. GAIA will define the ICRS to better than 60μas in the orientation of the frame.

The spin vector can be determined very accurately by means of the many thousand faint quasars picked up by the astrometric and photometric survey. Several observational properties of quasars can be combined to extract samples that are very clean (i.e. without stars), but need not be complete for this purpose in identifying every extragalactic compact source. These methods include use of all of the traditional criteria, distinctive colour indices, photometric variability, and negligible parallax and proper motion. Cross identification with radio and spectroscopic surveys will of course also provide exciting astrophysics.

Table 3. Residual spin of the GAIA reference frame estimated from a simulation of quasar observations. The columns contain, for each range of B magnitudes: P = assumed probability that a quasar is unambiguously recognised as such from photometric indices; N_{QSO} = expected number of recognised quasars with $z < 2.2$ and $|b| > 20°$; $\sigma_{\mu,tot}$ = mean standard errors in the proper motion per object and coordinate, including an assumed contribution of $\sigma_0 = 10$ μas yr^{-1} from source instability; $\sigma(\omega_i)$ = resulting precision of the spin components about the Galactic axes (i = 1 towards the Galactic centre, i = 3 towards the Galactic pole); $\sigma(a_i/c)$ = resulting precision of the acceleration of the Solar system Barycentre along the Galactic axes.

B	P	$N_{\rm QSO}$	$\sigma_{\mu,\rm tot}$	$\sigma(\omega_1)$	$\sigma(\omega_2)$	$\sigma(\omega_3)$	$\sigma(a_1/c)$	$\sigma(a_2/c)$	$\sigma(a_3/c)$
(mag)			(μas yr^{-1})		(μas yr^{-1})			(μas yr^{-1})	
14 – 15	1.0	40	12	2.2	2.2	2.7	2.2	2.2	2.7
15 – 16	1.0	230	14	1.05	1.05	1.28	1.05	1.05	1.26
16 – 17	0.9	1 230	18	0.59	0.59	0.73	0.60	0.60	0.71
17 – 18	0.8	11 500	27	0.28	0.28	0.35	0.28	0.29	0.34
18 – 19	0.6	60 000	44	0.20	0.20	0.24	0.20	0.20	0.24
19 – 20	0.3	97 000	78	0.27	0.27	0.33	0.27	0.27	0.32
all		170 000		0.13	0.13	0.16	0.13	0.13	0.16

In order to quantify GAIA's determination of the reference frame, we have completed simulations using realistic quasar counts. These show that an accuracy of better than 0.4 μas yr^{-1} will be reached in all three components of ω, the spin vector, even with very pessimistic assumptions about intrinsic source jitter.

2.6. Fundamental Physics

The Space-Time metric The dominating relativistic effect in the GAIA measurements is gravitational light bending. Accurate measurement of the parameter γ of the Parametrized Post-Newtonian (PPN) formulation of gravitational theories is of key importance in fundamental physics. The Pound-Rebka experiment verified the relativistic prediction of a gravitational redshift for photons, an effect probing the time-time component of the metric tensor. Light deflection depends on both the time-space and space-space components. It has been observed, with various degrees of precision, on distance scales of $10^9 - 10^{21}$ m, and on mass scales from $1 - 10^{13} M_\odot$, the upper ranges determined from the gravitational lensing of quasars. GAIA will extend the domain of observations by two orders of magnitude in length, and six orders of magnitude in mass.

The astrometric residuals, after fitting to a fully relativistic standard GR metric, can be tested for any discrepancies with the prescriptions of General Relativity. This provides a constraint on the PPN term γ. Detailed analyses indicate that the GAIA measurements will provide a precision of about 5×10^{-7} for γ, based on multiple observations of $\sim 10^7$ stars with $V < 13$ mag at wide angles from the Sun, with individual measurement accuracies better than 10 μas. This accuracy is close to the values predicted by theories which predict that the Universe started with a strong scalar component, which relaxes to the general relativistic value with time.

White Dwarfs as Laboratories for Fundamental Physics One example of an application of GAIA to fundamental physics is analysis of old white dwarfs. White dwarfs are well suited to test any departure from standard physics, since even small changes in physical constants can result in prominent effects when the relevant time scales of white dwarf cooling are taken into account. Such is the case, for example, of a hypothetical change in the gravitational constant, G. The known white dwarf luminosity function provides an upper bound of $\dot{G}/G \leq -(1 \pm 1) \times 10^{-11}$ yr^{-1}, which is comparable to bounds derived from the binary pulsar PSR 1913+16. Since this is a statistical upper limit, improvement in our knowledge of the white dwarf luminosity function of the Galactic disk will translate into a more stringent upper bound for $\dot{G}/G$. This method is very powerful but demands error bars as small as possible and this can only be achieved through a deep ($V \sim 20$ mag) and all sky survey.

Gravitational Waves Other interesting applications of the GAIA include determination of the solar oblateness, from analysis of suitable asteroid orbits, and limiting any gravitational wave backgrounds, from determinations of coherent jitter in the quasar reference frame. Gravitational waves passing over the telescope will cause a time-varying shift in the apparent position of a source; i.e., the waves cause apparent proper motions. The fact that the apparent motions are determined by the local gravitational wave field at the telescope implies that the motions are coherent across the whole sky; the relative motion of two nearby sources is proportional to their angular separation. GAIA could set, in the $10^{-12} < f < 10^{-10}$ Hz band, the best upper limit on $\Omega_{\rm gw}$.

3. GAIA: THE PAYLOAD

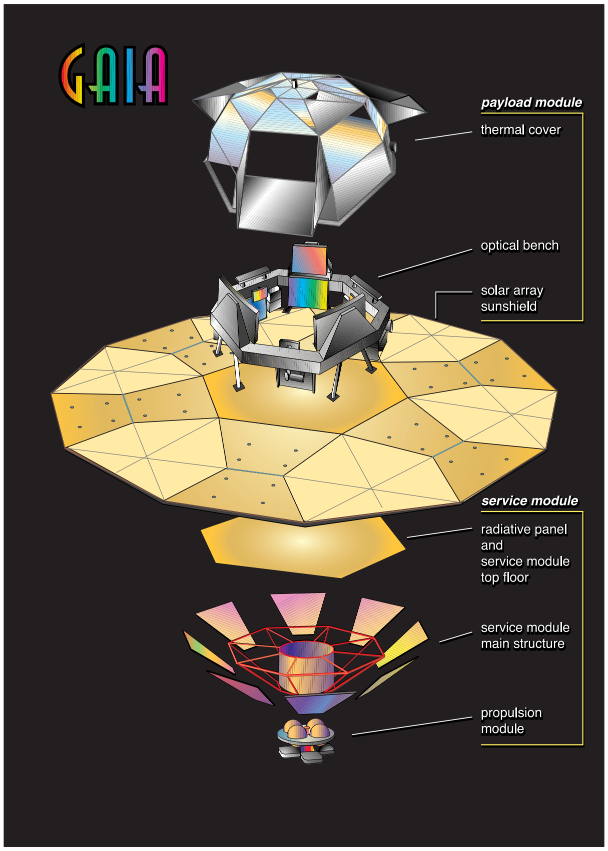


Figure 5. An exploded view of the GAIA satellite, with the primary payload and service module features identified. A more detailed view of the science payload, three telescopes mounted on a single SiC optical bench, is shown on the right.

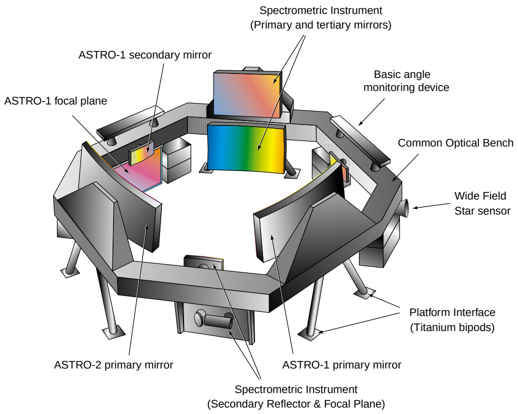


Figure 6. The GAIA science payload consists primarily of three 3-mirror telescopes. Two of the telescopes are identical astrometric instruments separated by the 106° basic angle. The third telescope provides the orthogonal motion, radial velocity, from spectroscopic doppler shift measurements.

3.1. General Design Considerations

The ultimate accuracy with which the direction to a point source of light can be determined is set by the dual nature of electromagnetic radiation, namely as waves (causing diffraction) and particles (causing a finite signal-to-noise ratio in the detection process). Consider the observation of a distant monochromatic point source by means of an optical telescope or interferometer equipped with an idealized detector. The instrument generates a diffraction image in the focal plane and the detector records the precise location of each detected photon in the diffraction pattern. If λ is the wavelength and D the overall size of the instrument aperture (diameter or base length), then the characteristic angular size of features in the diffraction pattern that can be used to localise the image is of order λ/D radians. If a total of N detected photons are available for localizing the image, then the theoretically achievable angular accuracy will be of order $(\lambda/D) \times N^{-1/2}$ radians.

A realistic size figure for non-deployable space instruments is of order a few metres, say $D \sim 2$ m. Operating in visible light ($\lambda \sim 0.5$ μm) then gives diffraction features of order $\lambda/D \sim 0.05$ arcsec. To achieve a final astrometric accuracy of (say) 10 μas it is therefore necessary that the diffraction features are localised to within 1/5000 of their characteristic size. Two obvious requirements follow: firstly, that at least some 25 million detected photons are needed to beat down the statistical noise by this factor; secondly, that extreme care is needed to achieve such a huge improvement in practice. Elementary calculations show that the first requirement (number of photons) can be satisfied for objects around 15 mag with reasonable assumptions on collecting area and bandwidth (see below). The second requirement is clearly a technical challenge, but the conclusion from the GAIA study is that this condition, too, can be met with two general constraints: two telescopes, and a scanning satellite.

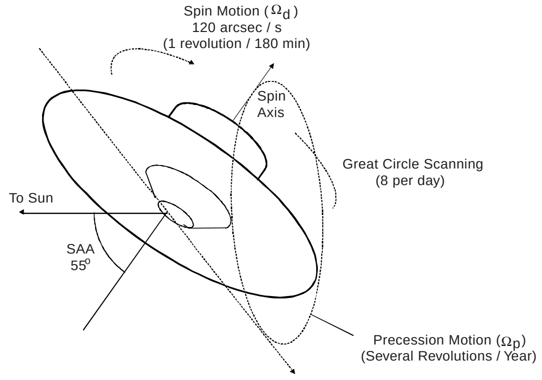
A wide separation of two individual viewing directions is a fundamental pre-requisite of the payload, since this leads to the determination of absolute trigonometric parallaxes, and thereby circumvents the problem which has plagued ground-based parallax determinations, namely the transformation of relative parallaxes to absolute distances.

The measurements conducted by a continuously scanning satellite can be shown to be almost optimally efficient, with each photon acquired during a scan contributing to the precision of the resulting astrometric parameters. Pointed observations cannot provide the over-riding benefit of global astrometry using a scanning satellite, which is that a global instrument calibration can be performed in parallel, and the interconnection of observations over the celestial sphere provides the rigidity and reference system, immediately connected to an extragalactic reference system.

Quantifying and generalising from these basic design considerations, the general principles of the proposed mission can be summarized as follows: (i) it is a continuously scanning instrument, capable of measuring simultaneously the angular separations of thousands of star images as they pass across a field of view of about 1° diameter. Simultaneous multi-colour photometry of all astrometric targets is a necessary and integral part of the concept; (ii) high angular resolution in the scanning direction is provided by a monolithic mirror of dimension ~ 1.7 m, (a Fizeau interferometer option was also studied, and discarded); (iii) the wide-angle measuring capability is provided by two viewing directions at large angles to each other and scanning the same great circle on the sky. The precise 'basic angle' between two viewing directions is determined from the 360° closure condition on each great-circle scan, while short-term (< 3 hours) variations are passively controlled, and monitored by internal metrology; (iv) the whole sky is systematically scanned in such a manner that observations extending over several years permit a complete separation of the astrometric parameters describing the motions and distances of the stars. A longer temporal baseline permits the determination of additional parameters, for example those relevant to binary systems, and to the detection of extra-solar planetary companions.

Scanning law and pointing requirements summary.

Parameter	Value
Satellite scan axis tilt angle	55° wrt the Sun
Scan rate	120 arcsec s^{-1}
Absolute scan rate error	1.2 arcsec s^{-1} (3σ)
Precession rate	0.17 arcsec s^{-1}
Absolute precession rate error	0.1 arcsec s^{-1} (3σ)
Absolute pointing error	5 arcmin (3σ)
Attitude absolute measurement error	0.001 arcsec (1σ)
High-frequency disturbances:	
power spectral density at 0.05 Hz	≤ 1000 $\mu\mathrm{as}^2$ Hz^{-1}
for $f > 0.05$ Hz	decreasing as f^{-2}



Within this general outline a multitude of options exist which have been extensively explored, optimized and weighed against each other. These include, for instance, the number and optical design of each viewing direction, and the choice of wavelength bands, detection systems, basic angle, metrology system, satellite layout, and orbit. The proposed payload design (Figures 5,6) consists of:

(a) two astrometric viewing directions. Each of these ‘Astro’ instruments comprises an all-reflective three-mirror telescope with an aperture of 1.7×0.7 m^2, the two fields separated by a basic angle of 106°. Each astrometric field comprises an astrometric sky mapper (ASM), the astrometric field proper (AF), and a broad-band photometer (BBP). Each sky mapper system provides an on-board capability for star detection and selection, and for the star position and satellite scan-speed measurement. The main focal plane assembly employs CCD technology, with about 250 CCDs and accompanying video chains per focal plane, a pixel size 9 μm along scan, TDI operation, and an integration time of ~ 0.9 s per CCD;

(b) an integrated radial velocity spectrometer and photometric instrument (‘Spectro’), comprising an all-reflective three-mirror telescope of aperture 0.75×0.70 m^2. The field of view is separated into a dedicated sky mapper, the radial velocity spectrometer (RVS), and a medium-band photometer (MBP). Both instrument focal planes are also based on CCD technology operating in TDI mode: with at least 3 large CCDs butted together for the radial velocity spectrometer; and two large CCDs, with a total of 11 medium-band filters, for the medium-band photometer.

(c) the opto-mechanical-thermal assembly comprising: (i) a single structural torus supporting all mirrors and focal planes, employing SiC for both mirrors and structure. There is a symmetrical configuration for the two astrometric viewing directions, with the Spectro system accommodated within the same structure, between the two astrometric viewing directions; (ii) a deployable sunshield to avoid direct Sun illumination and rotating shadows on the payload module, combined with the solar array assembly; (iii) control of the heat injection from the service module into the payload module, and control of the focal plane assembly power dissipation in order to provide an ultra-stable internal thermal environment; (iv) an alignment mechanism on the secondary mirror for each astrometric instrument, with micron-level positional accuracy and 200 μm range, to correct for telescope aberration and mirror misalignment at the beginning of life; (v) a permanent monitoring of the basic angle, but without active control on board.

(d) although the optical design only employs mirrors, diffraction effects with residual (achromatic) aberrations induce a small chromatic shift of the diffraction peak. This effect is usually neglected in optical systems, but was relevant for Hipparcos and becomes even more critical for GAIA. The chromaticity image displacement depends on position in the field, and on the star’s spectral energy distribution (colour), but not on its magnitude. The overall system design must minimise these chromatic displacements to levels below those relevant for the final mission accuracies, and demonstrate that they can be calibrated as part of the data analysis: one purpose of the broad-band photometry is to provide colour information on each observed object in the astrometric field to enable the chromaticity bias calibration on ground.

3.2. CCD and Focal Plane Design

Design of the GAIA focal plane CCD arrays provides a good example of the interplay between the science case and technological constraints during system optimisation.

Because of the very large number of CCDs and the relatively high image acquisition frequency (elementary integration time of approximately 0.9 s), the data rate at focal plane output is enormous, corresponding to several gigapixels per second if all pixels were readout and processed. It is therefore mandatory to implement suitable filtering of the data flow on board in order to reduce the complexity of the on-board hardware and software, and indeed to achieve feasibility at all. A corresponding consideration requires minimising the quantity of data to be stored between two consecutive ground station visibility windows (with the objective of minimising the capacity and related mass, size and power of the solid state recorder); and to minimise the quantity of data to be transmitted to ground (with a direct impact on the communication subsystem design complexity).

The natural solution to this limit comes directly from the science case, and the properties of the Galaxy: at the apparent magnitude and integration time limits appropriate for GAIA most of the pixel data do not include any useful information. There is a clear trade-off between reading too many pixels, with associated higher read-noise and telemetry costs, and reading too few, with associated lost science costs. This leads to the choice of on-board real-time detection, with definition of a window around each source which has sufficient signal to be studiable, and determination of the GAIA effective sensitivity limit to be that which saturates the telemetry, and which provides a viable lower signal. Combining all these constraints sets the limit near V=20 magnitude, for somewhat over one billion targets.

The windowing mode, and the implementation of the bright star measurement mode, are both driven by the detailed star data derived from the astrometric sky mapper transits. For each detected star and each CCD, a window is defined which identifies the pixels to be binned and readout at the serial register and output stages; all

Feature	Corresponding Information
Array size	25×58 mm^2 active area
Pixels per CCD	2150 cols $\times$ 2780 TDI stages
Dead zones	Top: 0.25 mm; sides: 0.6 mm; bottom: < 5 mm
Pixel size in image zone	9×27 μm^2
Phases in image zone	4
Pixel size in serial register	27×27 μm^2
Phases in serial register	4
Device thickness	10–12 μm
Si resistivity	20–100 Ωcm
Buried channel	n-type channel
Oxide thickness	Standard
Anti-blooming	Shielded at pixel level
Notch channel	Implanted for all CCDs
Output amplifiers	2 per device, 2-stage
Conversion factor	between 3 & 6 μV/e$^-$
Additional gates	5–10
Power dissipation	< 560 mW
Non-uniformity	$< 1\%$ rms local $< 10\%$ peak-to-peak global
Mean dark current	< 0.5 e$^-$s^{-1}pix^{-1} (200 K)
Non-linearity	< 1 per cent over 0–2V; < 20 per cent over 2–3.5V
CTI in image area	$< 10^{-5}$ at beginning-of-life; $\sim 10^{-4}$ after major solar flare
CTI in serial register	$< 10^{-5}$ at beginning-of-life; $\sim 5.10^{-4}$ after major flare
Quantum efficiency	trade with MTF and RON
MTF at Nyquist frequency	trade with QE and RON
Read-out noise	trade with QE and MTF

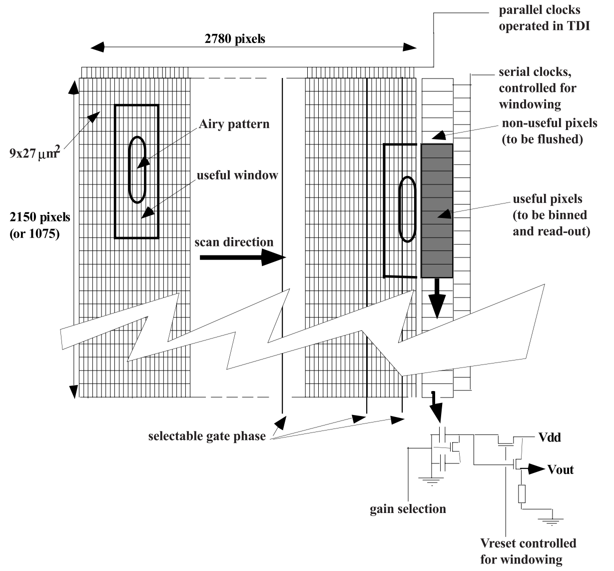


Table 4. Operating mode for the astrometric field CCDs. The location of the star is known from the astrometric sky mapper. A window is selected around the star to optimise the complex trade-off between minimising read-out noise, maximising scientific return, and demanding feasible communications.

other pixels are flushed at a higher frequency. The acquisition window includes appropriate margins to take into account the uncertainty on the scan rate and the focal plane geometry.

The CCD detectors form the core of the GAIA payload, and their development and manufacture will represent one of the key challenges for the programme. Although the CCD is well-known and widely used in optical astronomy, a large number of design possibilities must be collectively optimised. While separate characteristics can be individually tuned (for example, QE, red or blue response, MTF, read-out noise, read-out rate) figures for any individual parameter quoted in isolation can be highly misleading. Thus operating temperature may be lowered but at the expense of QE in the red; pixel sizes may be decreased to a few microns but at the expense of QE and MTF; read-out noise may be lowered considerably, but at the expense of read-out rate and signal dynamic range. Similarly, it is important to consider the effect of the total detection noise (including the effects of analogue video noise, quantization noise, and correct definition of the electrical bandwidth) and not just the CCD read-out noise.

3.3. Accuracy Assesments

The CCD discussion above is just one small part of a near-complete end-to-end simulation of the GAIA spacecraft, data acquisition, data reduction, and analysis which has been completed. This provides realistic accuracy values, as a function of magnitude for the parallax error, σ_π. An approximate analytic fit to these results is:

$$\sigma_\pi \simeq (7 + 105z + 1.3z^2 + 6 \times 10^{-10} z^6)^{1/2} \times [0.96 + 0.04(V-I)] \tag{1}$$

where $z = 10^{0.4(G-15)}$, and G is the natural broad-band GAIA magnitude, close to standard astronomical V. This formula is valid for the entire range of magnitudes and colours of relevance. For the position and proper motion errors σ_0 and σ_μ respectively, the following mean relation can be used:

$$\sigma_0 = 0.87\,\sigma_\pi\,, \qquad \sigma_\mu = 0.75\,\sigma_\pi \tag{2}$$

For all Galactic and astrophysical investigations it is however the *relative* parallax accuracy σ_π/π (equal to the relative distance error) which is the more relevant quantity. this quantifies the number of stars which will have their distances determined to a certain relative accuracy. This can be estimated by means of a Galaxy model, and is summarised in the table and figure below. In summary, GAIA will observe of order one billion stars, the majority of which will have quite well-determined properties. The table quantifies the total number of stars with relative distance error below a certain limit: $\sigma_\pi/\pi \le R$. For GAIA the numbers are estimated from a detailed accuracy analysis and realistic Galaxy model. For Hipparcos the numbers have been derived from Celestia 2000 (ESA SP–1220). The dependence of these limits on Galactic coordinates is illustrated in the figure.

The key conclusion from this analysis is that the GAIA spacecraft design is near optimal. The magnitude limit which is being reached is close to that at which useful distances can be derived with a spacecraft of diameter about 2-3m. This size limit is that set by the Ariane launcher shroud, and represents a practical upper limit for a spacecraft with non-deployed optics.

`Summary of the GAIA performance`

Maximum relative parallax error (R)	Number of stars GAIA	Hipparcos
0.01	20×10^6	188
0.02	40×10^6	878
0.05	100×10^6	6238
0.10	180×10^6	21014
0.20	290×10^6	49545
0.50	500×10^6	90186
1.00	680×10^6	104579

Figure 7. GAIA performance expectations. The numbers are estimated from a detailed accuracy analysis of the GAIA spacecraft, convolved with a realistic Galaxy model.

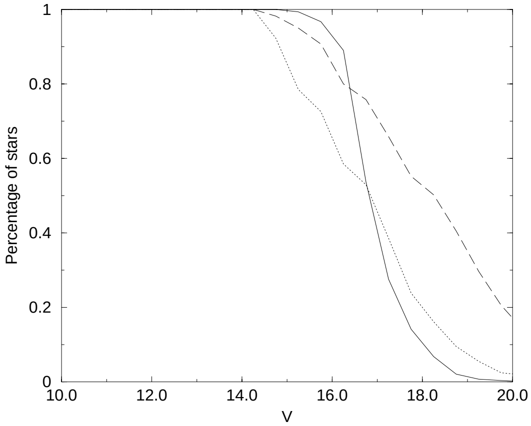


Figure 8. Percentage of stars with $G \le 20$ mag with relative error in parallax smaller than 10 per cent as a function of the V magnitude for three different galactic directions. Solid line: $(l,b) = (0°, 2°)$, dotted line: $(l,b) = (0°, 30°)$, dashed line: $(l,b) = (0°, 90°)$.

3.4. Data Reduction

The total amount of (compressed) science data generated in the course of the five-year mission is about 2×10^{13} bytes (20 TB). Most of this consists of CCD raw or binned pixel values with associated identification tags. Broadly speaking the data analysis aims to 'explain' these values in terms of astronomical objects and their characteristics. Successful implementation of the GAIA data analysis task will require expert knowledge from several different fields of astronomy, mathematics and computer science to be merged in a single, highly efficient system, including at least:

- accurate physical modeling of the observations in terms of detectors, optics, satellite attitude and the astrometric and photometric characteristics of the objects, including a fully general-relativistic treatment consistent to the 1 μas level;
- statistically efficient estimation methods, in order to utilize the information optimally;
- accurate calibration of the instruments, both geometrically and photometrically, including the celestial orientation (attitude) of the instrument axes;

- efficient procedures for generating and maintaining software, and for the management, processing and dissemination of data.

Considerable efforts have been invested to understand these challenges, building on recent work with neural network techniques and object-orientated data structures. Much remains to be learned. While the GAIA volume is not especially large compared to modern data sets in physics and astronomy, it is rather complex. Thus, effort has been focussed on assessing the data analysis challenge in terms of processing requirements. Certain basic algorithms that have to be applied to large data sets can be translated into a minimum required number of floating-point operations. For instance, an elementary process that will certainly be needed is the estimation of the location and amplitude of a stellar image from about eight successive CCD samples. A fairly straight-forward maximum-likelihood algorithm for this purpose has been used in Monte Carlo experiments designed to assess the precision of the estimates. From these experiments it appears that some 3000 floating-point operations are required for each estimation. For 10^9 objects, some 3×10^{12} such estimations will be needed, requiring $\sim 10^{16}$ floating-point operations. Since this is only a small part of the analysis, the entire effort can be estimated to be at least of order 10^{18} floating-point operations.

Many international efforts to develop efficient and effective techniques to handle large scientific databases are underway internationally, driven by particle physics, earth resources, and similar requirements, as well as by survey astronomy and cosmology, including the ESA Planck mission. We are aware that such developments are underway, and will ensure that whichever consortia of countries eventually develop the GAIA databases, and the analysis methodologies, they will include and build upon such expertise, rather than acting in isolation.

4. CONCLUSION

GAIA addresses science of vast general appeal, and will deliver huge scientific impact across the whole of astrophysics from studies of the Solar System, and other planetary systems, through stellar astrophysics, to its primary goal, the origin and evolution of galaxies, out to the large scale structure of the Universe, and fundamental physics.

GAIA is timely as it builds on recent intellectual and technological breakthroughs. Current understanding and exploration of the early Universe, through microwave background studies (e.g., Planck) and direct observations of high-redshift galaxies (HST, NGST, VLT) have been complemented by theoretical advances in understanding the growth of structure from the early Universe up to galaxy formation. Serious further advances require a detailed understanding of a ‘typical’ galaxy, to test the physics and assumptions in the models. The Milky Way and the nearest Local Group galaxies uniquely provide such a template.

While challenging, the entire GAIA design is within the projected state-of-the-art, and the satellite can be developed in time for launch in 2009. With such a schedule, a complete stereoscopic map of our Galaxy will be available within 15 years. In our working lifetimes, GAIA can provide a quantitative, stereoscopic movie of the Milky Way, and so unlock its origins.