Contents

Compiled by:
the GAIA Science Advisory Group
K.S. de Boer (Bonn), G. Gilmore (Cambridge),
E. Høg (Copenhagen), M.G. Lattanzi (Turin),
L. Lindegren (Lund), X. Luri (Barcelona),
F. Mignard (CERGA), P.T. de Zeeuw (Leiden)

ESA Study Scientist: M.A.C. Perryman

ESA Study Manager: O. Pace

Industrial Study: Matra Marconi Space (baseline design) and Alenia Aerospazio (interferometric design)

Published by:
ESA Publications Division
ESTEC, PO Box 299
2200 AG Noordwijk
The Netherlands

Editor: Bruce Battrick
Design and Layout: Leigh Edwards
Front cover: Richard Sword, Cambridge

ISBN No.: 92-9092-635-X
Printed in: The Netherlands
Price: 15 Dfl

Overview of the Concept and Technology Study

The GAIA Observatory 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, about 1 percent 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 and depth necessary to address the three key questions which underlie the GAIA science case:

- *When did the stars in the Milky Way form?*
- *When and how was the Milky Way assembled?*
- *What is the distribution of dark matter in our Galaxy?*

The accurate stellar data acquired for this purpose will have an enormous impact on all areas of stellar astrophysics, including luminosity calibrations, structural studies, and the cosmic distance scale. 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, including near-Earth objects, through galaxies in the nearby Universe, to some 500 000 distant quasars. GAIA 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 assessments, and results from a prototype data reduction development. The satellite can be launched in 2009, within the specified budget for the next generation ESA Cornerstone missions, and at a time ideally matched to complement other ESA missions and new ground-based observatories.

Science Profile

Science Goals:

- **the Galaxy:**
  origin and history of our Galaxy
  tests of hierarchical structure formation theories
  star formation history
  chemical evolution
  inner bulge/bar dynamics
  disk/halo interactions
  dynamical evolution
  nature of the warp
  star cluster disruption
  dynamics of spiral structure
  distribution of dust
  distribution of invisible mass
  detection of tidally disrupted debris
  Galaxy rotation curve
  disk mass profile

- **star formation and evolution:**
  in situ luminosity function
  dynamics of star forming regions
  luminosity function for pre-main sequence stars
  detection/categorization of rapid evolutionary phases
  complete local census to single brown dwarfs
  identification/dating of oldest halo white dwarfs
  age census
  census of binaries/multiple stars

- **distance scale and reference frame:**
  parallax calibration of all distance scale indicators
  absolute luminosities of Cepheids
  distance to the Magellanic Clouds
  definition of the local, kinematically non-rotating metric

- **Local Group and beyond:**
  rotational parallaxes for Local Group galaxies
  kinematical separation of stellar populations
  galaxy orbits and cosmological history
  zero proper motion quasar survey
  cosmological acceleration of Solar System
  photometry of galaxies
  detection of supernovae

- **Solar System:**
  deep and uniform detection of minor planets
  taxonomy and evolution
  inner Trojans
  Kuiper Belt Objects
  disruption of Oort Cloud
  near-Earth objects

- **extra-solar planetary systems:**
  complete census of large planets to 200-500 pc
  orbital characteristics of several thousand systems

- **fundamental physics:**
  γ to ~5 x 10^{-7}
  ß to 3 x 10^{-4} - 3 x 10^{-5}
  solar J_2 to 10^{-7} - 10^{-8}
  $\dot{G}/G$ to 10^{-12} - 10^{-13} yr^{-1}
  constraints on gravitational wave energy for $10^{-12}<f<4 \times 10^{-9}$ Hz
  constraints on Ω_M and Ω_Λ from quasar microlensing

- **specific objects:**
  10^6 - 10^7 resolved galaxies
  10^5 extragalactic supernovae
  500 000 quasars
  10^5 - 10^6 (new) Solar System objects
  50 000 brown dwarfs
  30 000 extra-solar planets
  200 000 disk white dwarfs
  200 microlensed events
  10^7 resolved binaries within 250 pc

Measurement Capabilities:

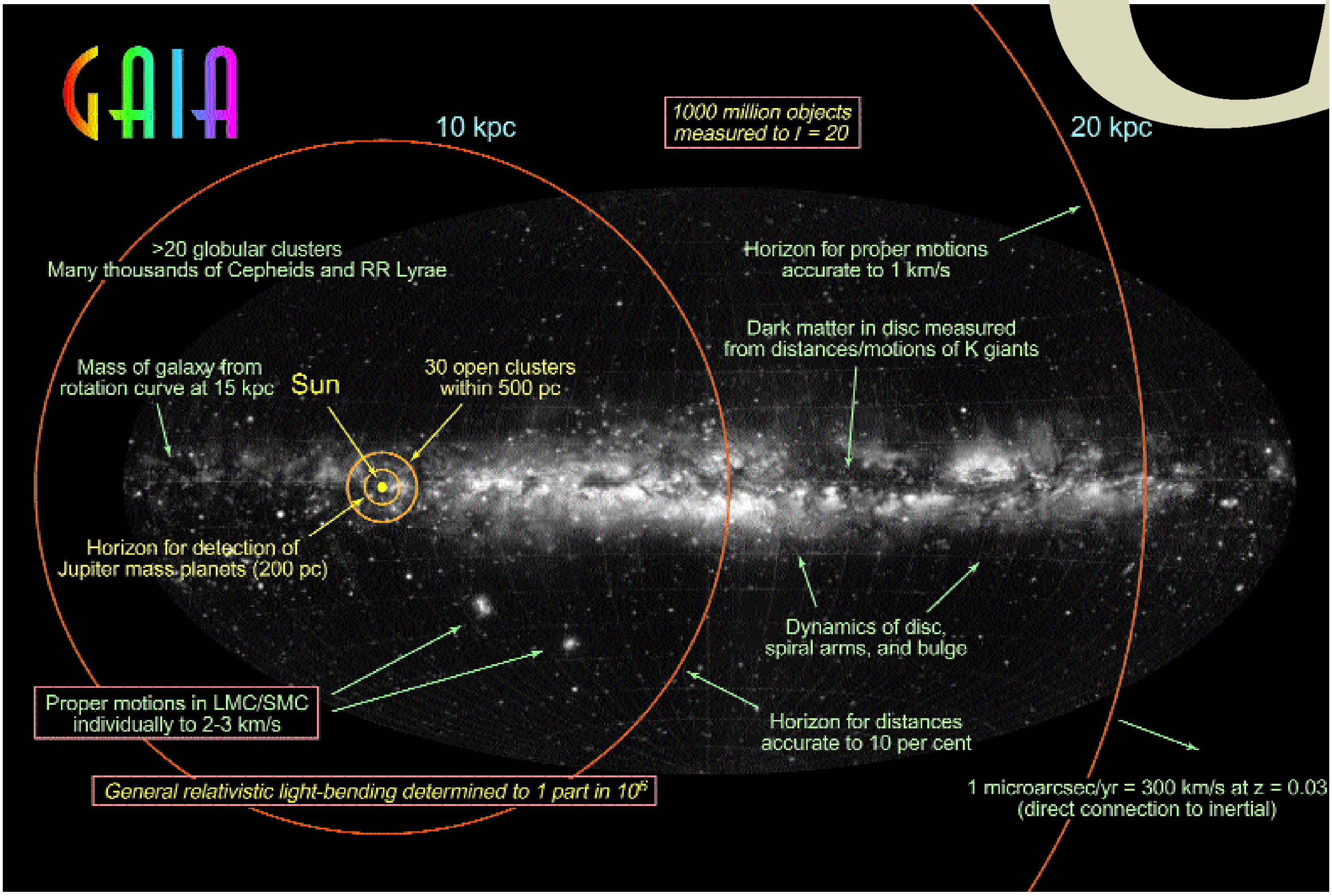
- **median parallax errors:**
  4 µas at 10 mag
  11 µas at 15 mag
  160 µas at 20 mag

- **distance accuracies:**
  2 million better than 1%
  50 million better than 2%
  110 million better than 5%
  220 million better than 10%

- **radial velocity accuracies:**
  1-10 km s^{-1} to V=16-17 mag, depending on spectral type

- **catalogue:**
  ~1 billion stars
  0.34 x 10^6 to V=10 mag
  26 x 10^6 to V=15 mag
  250 x 10^6 to V=18 mag
  1000 x 10^6 to V=20 mag
  completeness to about 20 mag

- **photometry:**
  to V=20 mag in 4 broad and 11 medium bands



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.

Mission Profile

Payload:

- **two identical astrometric telescopes:**
  fully-reflective 3-mirror silicon carbide optics
  separation of viewing directions: 106^0
  monolithic primary mirrors: 1.7 x 0.7 m^2
  field of view: 0.32 deg^2; focal length: 50 m
  wavelength range: 300-1000 nm

- **payload and focal plane assemblies:**
  thermally and mechanically decoupled from service module
  operating temperature: ~200 K
  focal plane detectors: CCDs operating in time-delayed integration mode
  pixel size along-scan: 9 µm

- **spectrometric instrument:**
  spectrometer for radial velocity measurements + medium-band photometry
  entrance pupil: 0.75 x 0.70 m^2
  field of view: 4 deg^2; focal length: 4.17 m
  focal plane detectors: CCDs operating in time-delayed integration mode

Orbit and Spacecraft:

- **orbit:**
  Lissajous, eclipse-free, around Sun/Earth L2
  220-240 day transfer orbit

- **revolving sky scanning:**
  scan rate = 120 arcsec s^{-1}
  precession period = 76 days

- **spacecraft:**
  3-axis stabilized
  autonomous propulsion system for transfer orbit
  electrical (FEEP) thrusters for operational attitude control
  6 deployable solar panels, integrated with multi-layer insulation to form the sun shield

- **science data rate:**
  1 Mbps sustained, 3 Mbps on down-link, using electronically steerable high-gain phased array antenna

- **launch mass:**
  3137 kg (payload = 803 kg, service module = 893 kg, system margin (20%) = 339 kg, fuel = 1010 kg, launch adaptor = 92 kg)

- **power:**
  2569 W (payload = 1528 W, service module = 641 W, harness losses= 76 W, contingency (10%) = 224 W)

- **dimensions:**
  payload: diameter = 4.2 m, height = 2.1 m
  service module: diameter = 4.2 m (stowed)/8.5 m (deployed), height = 0.8 m

- **launcher:**
  Ariane-5, dual launch, SPELTRA, 1666 mm interface

- **lifetime:**
  5 years design lifetime (4 years observation time)
  6 years extended lifetime

1 An Overview

GAIA is the astrophysics candidate for the fifth Cornerstone mission of the ESA science programme, CS5. The GAIA Observatory, 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 ESA Horizon 2000+ Survey Committee in 1994.

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 extremely precise three-dimensional map of a representative sample of 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 percent as far as the Galactic Centre, 30000 light years away. Stellar motions will be measured even in the Andromeda galaxy.

1.1 The Science

GAIA's expected scientific harvest is of quite remarkable 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: it will quantify bending of star light by the Sun and major planets over the entire celestial sphere, and therefore directly observe the structure of space-time - the accuracy of GAIA's determination of light bending is comparable to that required to detect the long-sought scalar correction to the tensor form. The Parameterized Post-Newtonian (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 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, 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, supported by a wide community across Europe, 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.

Studies undertaken 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 very large object-oriented databases.

1.3 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 data sets, 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 be able to 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 improvement by orders of magnitude in our knowledge of our Galaxy, simultaneously 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.

1.4 The Scientific Context

A key factor in selection of the ESA Cornerstone 5 mission is scientific timeliness. The scientific context in 2010 is known very well, will be dominated by a small number of major projects, and will be focussed on an understanding of the formation and evolution of galaxies and their contents.

Planck will be quantifying cosmology and large-scale structure. FIRST and ALMA will be providing detailed studies of star formation across the Universe. NGST will be imaging the most distant galaxies. All these missions require one crucial complementary ingredient: a well-studied template galaxy which can be used to model and analyse their observations. GAIA will provide that complementarity, and allow the synergy possible from the suite of ESA and ground-based facilities.

Operation in 2010 is also especially timely in terms of GAIA discovery potential: during its operational lifetime, GAIA will be providing a wealth of photometric data, much of which will motivate more detailed study with these other facilities, including major ground-based telescopes such as the ESO VLT.

The range of scientific topics which will be addressed by the GAIA data is vast, covering much of modern astrophysics, and fundamental physics. In the following section a few illustrative examples are presented, to give the flavour of the mission capabilities, with scientific applications ranging from the Milky Way Galaxy, stellar astrophysics, Solar System minor bodies, and extragalactic 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.

2 Science Case

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 simultaneously 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

(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) $\sigma_{\mu1}$ μas/yr	(11) $\sigma'_{\mu1}$ -	(12) $\sigma'_{\pi1}$ -
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
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	0.20	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
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
Gravity, Kz:											
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
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

Table 1: Summary of Galactic kinematic tracers, and corresponding limiting magnitudes and astrometric accuracy. Columns 7-8 demonstrate that the faint magnitude limit of GAIA is essential for probing these different Galaxy populations, while the astrometry accuracies in columns 10-11 demonstrate that GAIA will meet the scientific goals.

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.

A summary of the photometric and kinematic requirements defined by the GAIA science case is shown in Table 1, from which it is seen that GAIA addresses many aspects of disk structure and dynamics.

A few of the many important and challenging science issues are presented here, 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, through dynamical evolution of a bar.

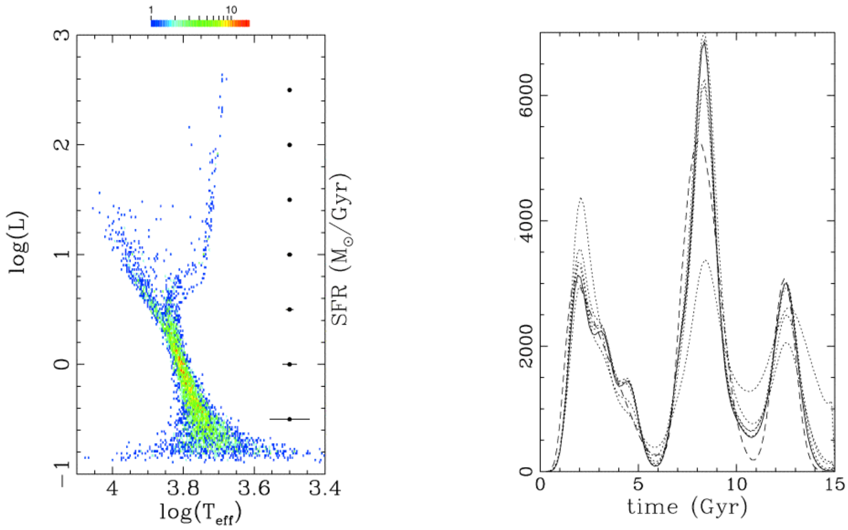


Figure 1: Left: a synthetic Hertzsprung-Russell diagram appropriate for GAIA. Right: the derived star formation history following inversion of the data in the left panel. The true input star formation history is shown by the long dashes. The dotted lines are the successive 2, 4, 6,8 and 9 iterations 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.

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 1.

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 percent. 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.

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

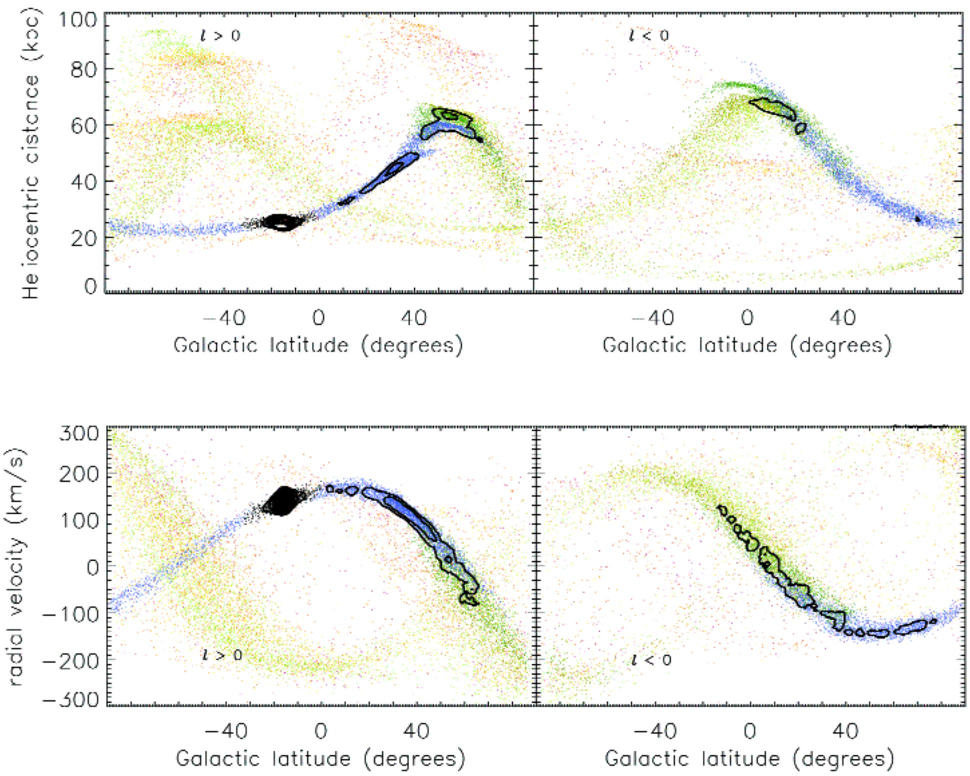
The stellar halo of the Galaxy contains only a small fraction of its total luminous mass, but the kinematics and abundances of halo stars, globular clusters, and the dwarf satellites contain imprints of the formation of the entire Milky Way. The most metal-deficient stars, with [Fe/H]< -3.5, are a powerful probe of 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 2). 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 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 microarcsec.

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

Figure 2: 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, and will be easily picked out by GAIA.



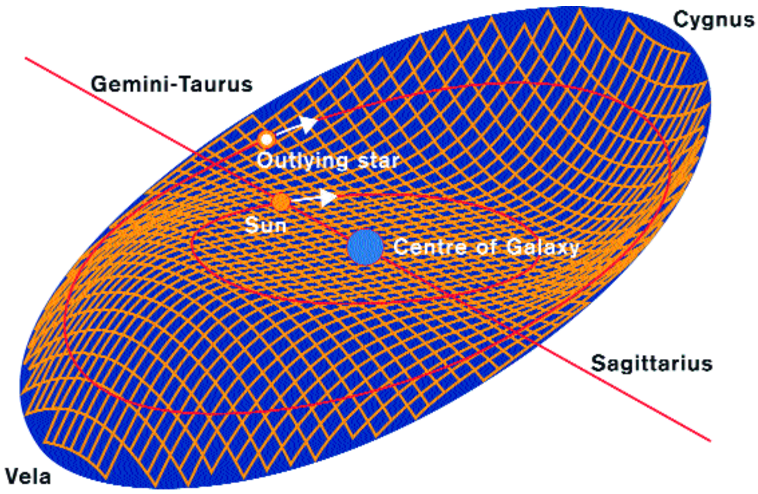


Figure 3: The disk of the Galaxy based on HI observations. The vertical axis is exaggerated by a factor of 10. The arrows show the motion of the Sun and an outlying star on their orbits in the Galaxy. The outlying star has an upward motion as seen from the Sun. Directions in the sky, as seen from the Earth, are indicated by the constellation names. The line indicates the locus of zero vertical displacement for the warped disk.

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. Redder horizontal branch stars and G and K halo giants are drowned out by the extremely large 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

Just two of the many areas of investigation of large-scale structure of the disk that GAIA will explore are presented here.

Galactic Disk Warps Galactic disks are thin, but they are not flat (Figure 3). 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 dependent 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, where Ω is 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 ~10^0 (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 percent implies distance accuracies of 10 µas at I~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, and its total surface density. 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, 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 mass distribution in galaxies. Knowing both the local volume and surface densities, one could 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 astonishing 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 determination of extinction/reddening and metallicities from 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

Mv (mag)	Stellar type	(V-I) (mag)	V_{lim} (mag)	V_{lim1} (mag)	d_{lim2} (pc)	Limiting factor
-5	OV, B0-G0 Ib, all Ia and Ia0	-0.3 to 4.7	12.2 12.2	12.2 8.5	27 000	d
0	A0 V	0.01	15.0	15.0	10000	d
5	G5 V	0.8	17.6	17.3	3300	d
10	M2 V DB	2.0 0.0	20.3 19.7	19.2 19.7	1150 870	d d
15	M7 V DG	3.0 0.8	22.5 21.3	20.6 21.0	320 180	d G
17	M8 V	3.2	23.1	21.0	170	G
20	brown dwarfs	4.5	24.5	21.0	80	G

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)

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.

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 modelling 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. 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 for 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 measurements are based exclusively on determinations of stellar distances and interstellar absorption. Absorption can be deduced from multi-colour photometry, obtainable with GAIA. The distances can be determined directly only by measurement of the trigonometric parallax. GAIA will provide distances to an unprecedented 0.1 percent for 7 x 10^5 stars out to a few hundred pc, and to 1 percent accuracy for a staggering 2.1 x10^7 stars up to a few kpc. Distances to 10 percent 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 range of stars of different types which will be discovered, and accurately measured by GAIA is summarised in Table 2.

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 Hertzsprung-Russell 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.

GAIA parallaxes will allow a definitive resolution of the controversy about the zero points of the period-luminosity-colour relationships by providing distance estimates to better than 1 percent for most galactic Cepheids and for RR Lyrae up to about 3 kpc, better than 10 percent for all galactic RR Lyrae and for Cepheids in the Sagittarius galaxy, and still between 10-30 percent for Cepheids in the Magellanic Clouds. Thus a first check of the universality of these relations (not only the slopes, but also the zero-points) will be possible.

2.3 Binaries, Brown Dwarfs and Planetary Systems

GAIA will detect a majority (59 percent) of the 10 million binaries closer than 250 pc from the Sun. While this fraction drops to 35 percent out to 1 000 pc, this represents key information on 64 million binaries (Figure 4). 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

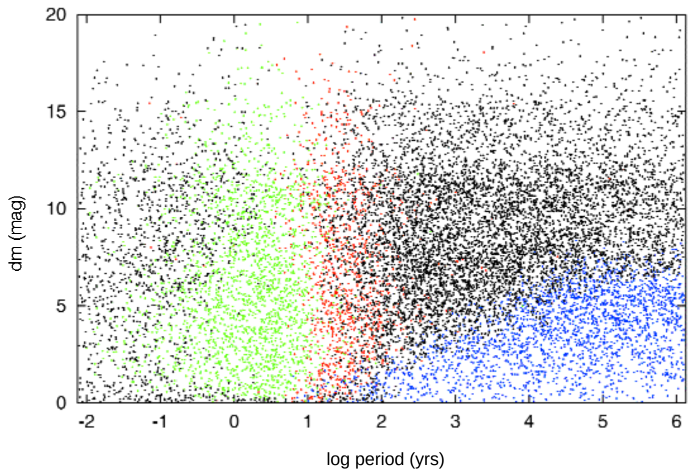


Figure 4: Simulated bright binaries (black) in a log P versus Δm diagram. The other colours denote systems detected as non-single by GAIA: blue for resolved system, red for 'quadratic', and green for 'stochastic' proper motion deviations.

by simulations, and the number of 'good' orbits determined. The absolute numbers (some 10 million orbits) are 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.

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 ~200 pc.

Detection of Giant Planets The results of the simulations are summarized in Figure 5. The solid lines express the empirical relationship between the amplitude of the astrometric perturbation and the orbital period for detection probabilities of 25, 50, and 95 percent. The curves show the behaviour of the astrometric signature as a function of the orbital period for a Jupiter-mass planet around a Solar-mass star at different distances from the observer. Essentially all Jupiter-mass planets within 50 pc and with periods between 1.5-9 years will be discovered by GAIA.

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 10000-50000, depending on details of the detection and orbital distribution hypotheses. Photometric detections of planetary transits will also be a natural product of the GAIA photometry.

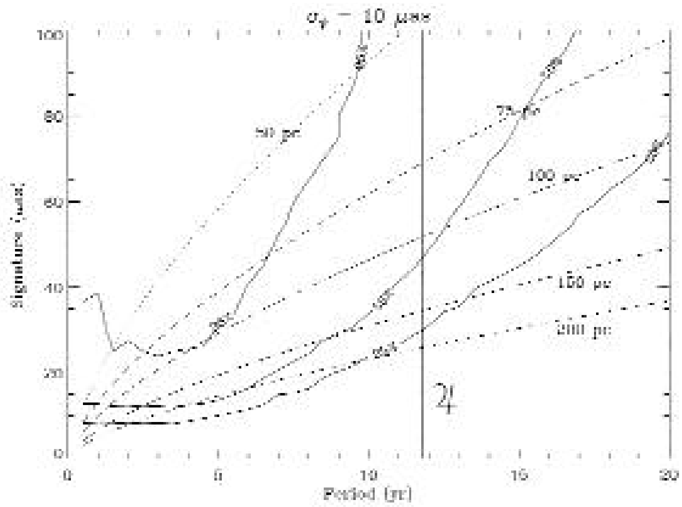


Figure 5: Iso-probability contours (solid lines) for 25, 50, and 95 percent of detection probability, compared with Kepler's third laws (dotted/dashed lines) for systems with Jupiter-Sun masses at D = 50, 75,100, 150, and 200 pc

2.4 Solar System

Solar System objects will be detected by GAIA in huge numbers. These minor bodies provide a record of the conditions in the proto-Solar nebula, and therefore shed light on the formation of planetary systems. Just two examples of relevant GAIA science are given, although many others, including the discovery and orbit determination of near-Earth objects, are also subjects of high scientific and public interest.

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 observed many times. These will include a large number of near-Earth objects.

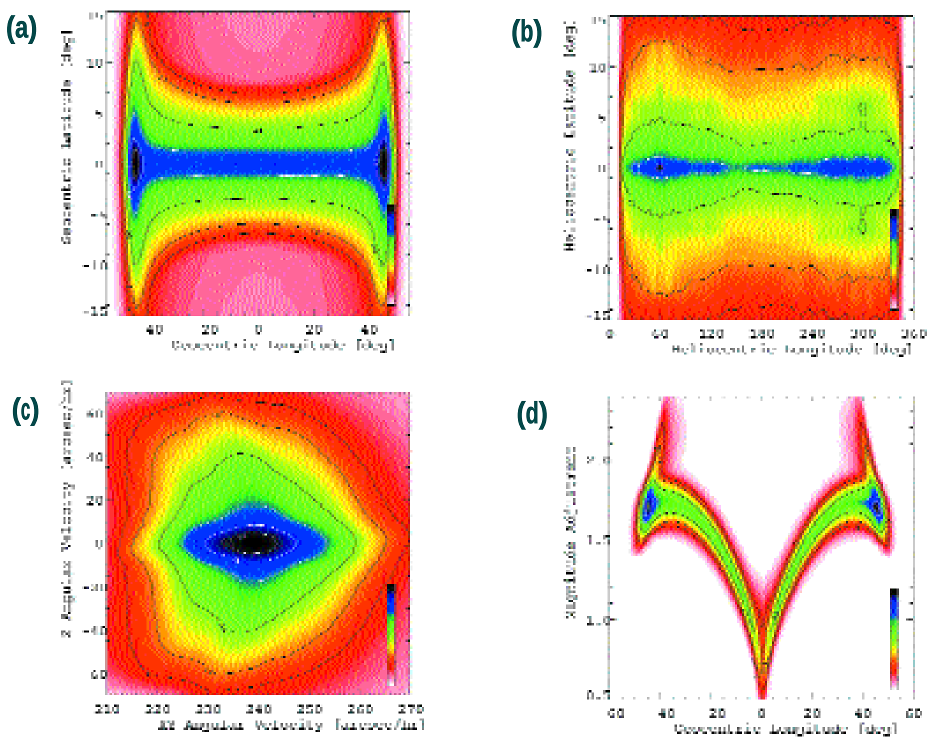


Figure 6: Predictions of the expectation of asteroids co-orbiting with Venus: (a) in the plane of geocentric ecliptic latitude and longitude; (b) heliocentric ecliptic latitude and longitude; (c) the distribution as a function of proper motions in the plane of, and perpendicular to, the ecliptic; (d) 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 6(c) shows the distribution of Venus Trojans as a function of proper motions in the plane of, and perpendicular to, the ecliptic. The average velocity in the plane is 238 arcsec hr^{-1} with a full-width half maximum of 28 arcsec hr^{-1}. Figure 6(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 furthest 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 ±45 degree. 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.

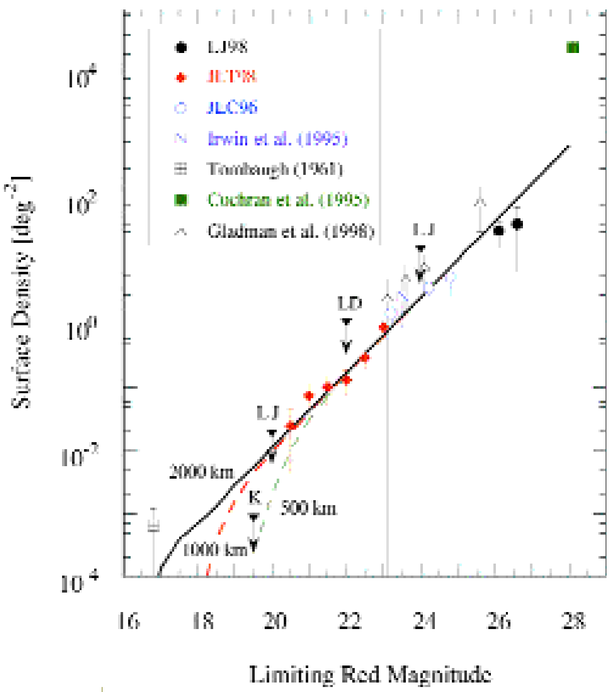


Figure 7: Surface density of Kuiper Belt objects as a function of R magnitude, based on the objects discovered before 1999.

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' (Figure 7). 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 ~90^0 elongation (where GAIA will be looking) is small: the known Kuiper Belt objects 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 x 10^{-3} objects per square-degree, implying that GAIA should discover some ~300 Kuiper Belt objects. Scientific objectives that can be answered only with GAIA include binarity, 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 (Figure 8) 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

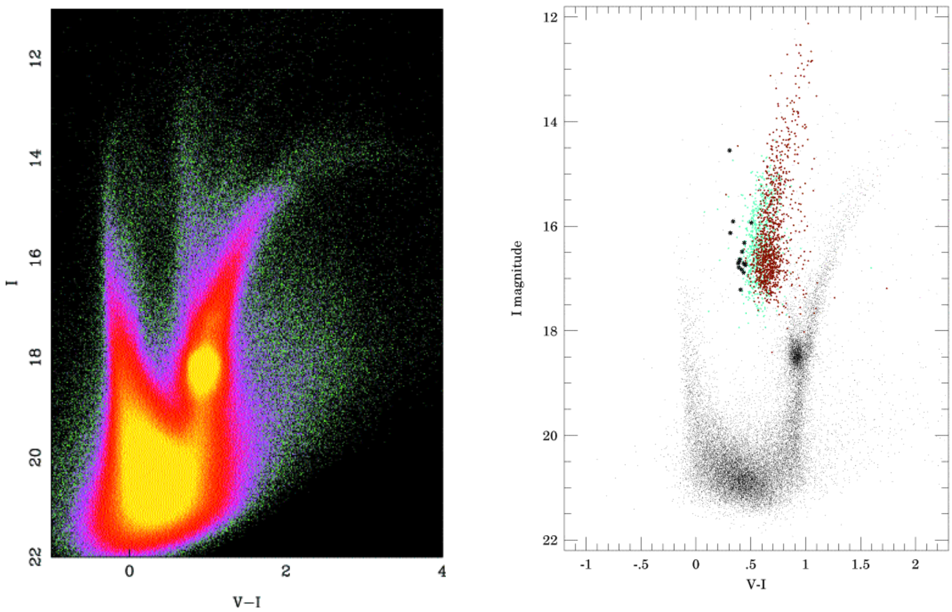


Figure 8: Left: A colour-magnitude diagram for the centre of the Large Magellanic Cloud. This is for a field of about 4 × 4 deg^2, centred 3^0 north of the bar. It contains 2.4 million stars brighter than I = 20 mag (data provided by the Magellanic Cloud Photometric Survey, courtesy of Dennis Zaritsky). Right: Colour-magnitude diagram for an area of 14 × 57 arcmin^2 in the Small Magellanic Cloud bar. There are 45 500 stars with I < 20 mag. Over-plotted are the Cepheids from OGLE, with fundamental, first overtone, and single-mode second overtone indicated separately by colour (from the OGLE consortium, courtesy of Andrzej Udalski).

allows unique cosmological studies, from the space motions of Local Group galaxies, to studies of huge numbers of supernovae, galactic nuclei, and quasars.

Local Group Orbits: 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 Section 2.2. The transverse motions will be derivable uniquely from the GAIA proper motion.

Galaxies, Quasars and Supernovae 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 ~0.2 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. 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 unique GAIA science products will be determination of the colour

B (mag)	P	N_{QSO}	$\sigma_{\mu,\,tot}$ (µas yr^{-1})	$\sigma(\omega_1)$	$\sigma(\omega_2)$ (µas yr^{-1})	$\sigma(\omega_3)$	$\sigma(a_1/c)$	$\sigma(a_2/c)$ (µas yr^{-1})	$\sigma(a_3/c)$
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	0.32
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

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 $|b| > 20^0$; $\sigma_{\mu,tot}$=mean standard errors in the proper motion per object and coordinate, including an assumed contribution of σ_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.

and photometric structure in the central regions of a complete, magnitude-limited sample of relatively bright galaxies.

GAIA will detect all compact objects brighter than V=20 mag, so that in principle supernovae can be detected to a modulus of m-M~39 mag, i.e. to a distance of 500 Mpc or z~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 percent. Rapid detection of such transient sources will allow detailed ground-based determination of light curves and redshifts.

The astrometric programme to V=20 mag will provide a census of ~500 000 quasars. The mean surface density of ~25 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 ~1 arcsec. GAIA will provide sensitivity to multiply-imaged systems with separations as small as ~0.2 arcsec. For the brighter quasars, V<18 mag, with a surface density of ~1 deg^{-2}, where examples of lensing are most common, GAIA's sample of ~50 000 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 also a proven method to determine H_0.

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 extra galactic radio-sources with an rms uncertainty in position between 100 and 500 µas.

Object	Monopole term					Quadrupole term		
	Grazing µas	χ_{min} µas	χ=45° µas	χ=90° µas	χ_{max} µas	J_2	Grazing µas	χ=1° µas
Sun	1 750 000	13 000	10 000	4100	2 100	$\leq 10^{-7}$	0.3	-
Earth	500	3	2.5	1.1	0	0.001	1	-
Jupiter	16 000	16 000	2.0	0.7	0	0.015	500	$7x10^{-5}$
Saturn	6 000	6 000	0.3	0.1	0	0.016	200	$3x10^{-6}$

Table 4: Light deflection by masses in the Solar System. The monopole effect dominates, and is summarized in the left columns for grazing incidence and for typical values of the angular separation. Columns χ_{min} and χ_{max} give results for the minimum and maximum angles accessible. J_2 is the quadrupole moment. The magnitude of the quadrupole effect is given for grazing incidence, and for an angle of 1°. For GAIA this applies only to Jupiter and Saturn, as it will be located at L2, with minimum Sun/Earth avoidance angle of 35°.

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 60 µas in the frame orientation.

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 also provide exciting astrophysics.

In order to quantify GAIA's determination of the reference frame, completed simulations have used realistic quasar counts. These show (Table 3) 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 (Table 4). Accurate measurement of the parameter γ of the Parameterized 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 length 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 general relativistic metric, can be tested for any discrepancies with the prescriptions of General Relativity. This provides a constraint on the Parameterized Post-Newtonian 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 One example of an application of GAIA to fundamental physics is the 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.

Gravitational Waves Other interesting applications of the GAIA mission 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 Ω_{gw}.

3 Spacecraft and Payload

3.1 Satellite Design

The GAIA satellite design has been developed to take advantage of the dual launch capability of Ariane-5. The operational orbit selected for GAIA is a Lissajous-type, eclipse free orbit around the L2 point of the Sun-Earth system (at 1.5 million kilometres from the Earth). This particular orbit offers many advantages: a very stable thermal environment, a very high observing efficiency (since the Sun, Earth and Moon are always out of the instrument fields of view), and a low radiation environment. An operational lifetime of five years is foreseen.

The satellite consists of the payload module and the service module, mechanically and thermally decoupled (Figure 9). The solar array/sunshield assembly, which is the only deployable element, has a span of 9.50 m when deployed. The optical covers are removed from the instrument entrance apertures in orbit.

The service module has a conical shape in order to avoid any turning shadows onto the solar array/sunshield assembly. It interfaces on one side with the standard adapter of the Ariane-5 launcher, and on the other side with the payload module. The service module structure is made of aluminium, with carbon-fibre-reinforced plastic shear walls. All units accommodated in the module are thermally coupled to the lateral panels of the module which are used as radiators and covered with optical solar reflectors. The temperature of the service module is at around 20^{0} C, while the payload module temperature is about 200 K, with a temperature stability of the order of tens of μK. The system therefore provides a very quiet and stable thermal environment for the payload optical bench.

The solar array/sunshield assembly includes six solar array wings that are stowed during launch against the six lateral panels of the service module. Each wing is made of two solar panels based on Ga-As cells on carbon-fibre reinforced plastic structure. The solar panels are insulated from the payload module with multi-layer insulation on their

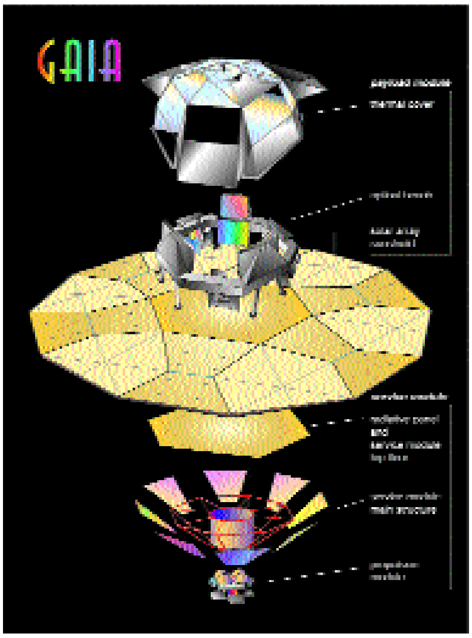


Figure 9: An exploded view of the GAIA satellite, with the primary payload and service module features identified. A more detailed view of the science payload, three telescopes mounted on a single silicon carbide optical bench, is shown in Figure 11.

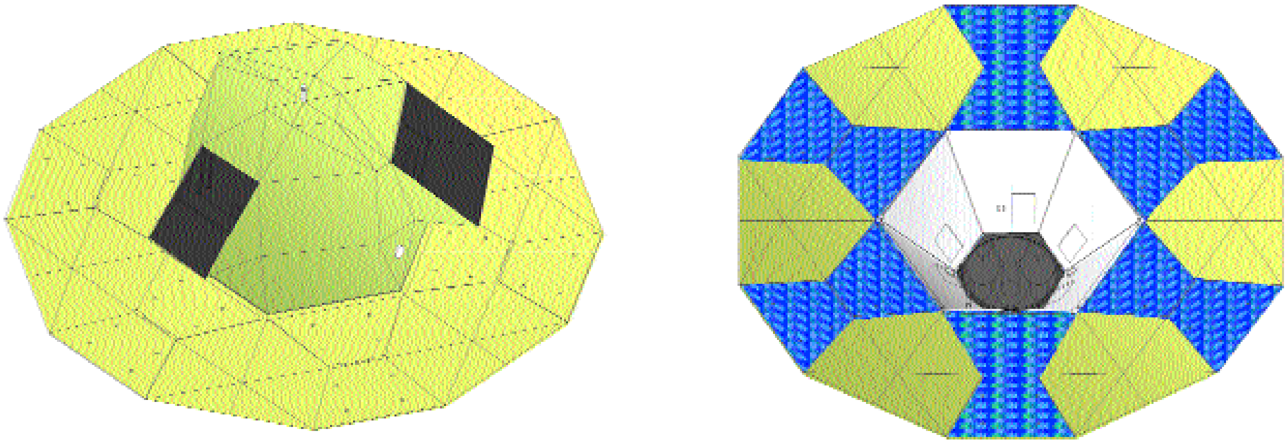


Figure 10: The GAIA satellite in orbit, with solar panels and sun shield deployed, viewed from above (left) and below (right). In the left figure, the entrance apertures of the telescopes can be seen, shielded from direct solar illumination by the solar array/sunshield assembly.

rear face. Additional insulation sheets, reinforced with kevlar cables, are spread between the solar array wings to complete the sunshield function. They are deployed together with the solar panels.

Communication to ground is provided by an X-band link, with 3 Mbps science data rate, RF on-board power of 17 W, and a high-gain, electronically-steered phased-array antenna. The Perth 32 m diameter ground station is foreseen to be used for GAIA, with around 8 hours visibility per day. The satellite telecommand (2 kbps) and housekeeping telemetry (2 kbps) is provided by a low-gain antenna system with omni-directional coverage.

The present design concept (Figure 10) includes an autonomous propulsion system, with a 400 N motor, to bring the satellite from geostationary transfer orbit to its final orbit around L2. This propulsion system could be suppressed, with simplification of the satellite design, if the restartable stage of the Ariane-5 launcher becomes available in time.

3.2 Payload 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 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. Details of the scanning law and pointing performance are given in Figure 12 and Table 5.

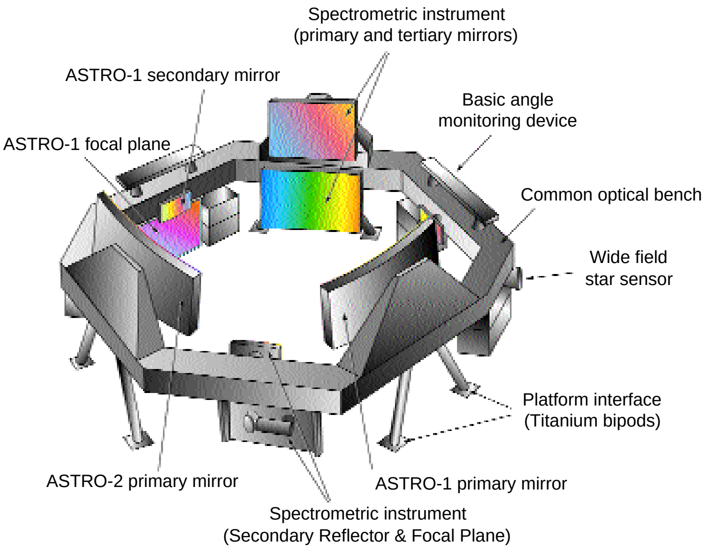
Parameter	Value
Satellite scan axis tilt angle	55 degree to the Sun
Scan rate	120 arcsec s^{-1}
Absolute scan rate error	1.2 arcsec s^{-1} (3σ)
Precession rate	0.17 arcsec s^{-1}
Absolute precession rate error	0.1 arcsec s^{-1} (3σ)
Absolute pointing error	5 arcmin (3σ)
Attitude absolute measurement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

Table 5: Scanning law and pointing requirements summary.

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.

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.

Figure 11: 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, the radial velocity, from spectroscopic Doppler shift measurements, as well as medium-band photometry.



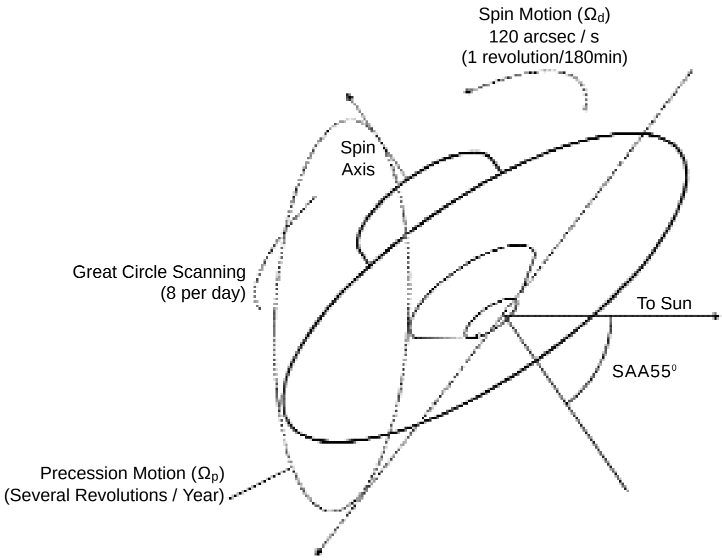


Figure 12: The observation strategy. The satellite rotates about its spin axis, which itself precesses at a fixed 55⁰ to the Sun.

The payload (Figure 11) comprises:

(a) two astrometric viewing directions. Each of these 'Astro' instruments comprises an all-reflective three-mirror telescope with an aperture of 1.7 x 0.7 m^2, the two fields separated by a basic angle of 106⁰. Each astrometric field comprises an astrometric sky mapper, the astrometric field proper, and a broad-band photometer. 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, time-delayed integration, 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 x 0.70 m^2. The field of view is separated into a dedicated sky mapper, the radial velocity spectrometer, and a medium-band photometer. Both instrument focal planes are also based on CCD technology operating in time-delayed integration 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 silicon carbide 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 in 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.

3.3 Focal Plane Design

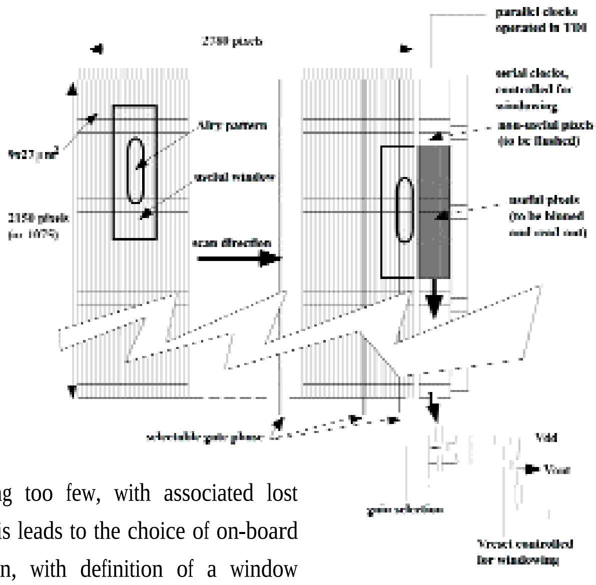
Design of the GAIA focal plane CCD arrays provides a good example of the interplay between the science case and technological constraints during system optimisation (Table 6, Figure 13).

Because of the very large number of CCDs and the relatively high image acquisition frequency (elementary integration time of approximately 0.9s), the data rate at focal plane output is enormous, corresponding to several gigapixels per second if all

Feature	Information
Array size	25 x 58 mm^2 active area
Pixels per CCD	2150 x 2780
Dead zones	0.25 mm; 0.6 mm;
Pixel size, image	9 x 27 μm^2
Phases, image	4
Pixels, serial register	27 x 27μm^2
Phases, serial register	4
Device thickness	10-12 µm
Si resistivity	20-100 Ω cm
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 $\mu V/e^-$
Additional gates	5-10
Power dissipation	<560 mW
Non-uniformity	<1% rms local
Mean dark current	$<0.5\ e^- s^{-1} pix^{-1}$ (200 K)
Non-linearity	<1 percent over 0-2 V; <20 percent over 2-3.5 V
CTI, image area	$<10^{-5}$ at beginning; 10^{-4} after major flare
CTI, serial register	$<10^{-5}$ at beginning; $\sim 5 \times 10^{-4}$ after major flare
Quantum efficiency	trade with MTF and read noise
Nyquist MTF	trade with QE and read noise
Read-out noise	trade with QE and MTF

Table 6: Properties of the GAIA CCD's.

Figure 13: 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.



pixels were read out 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 mag, 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 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.

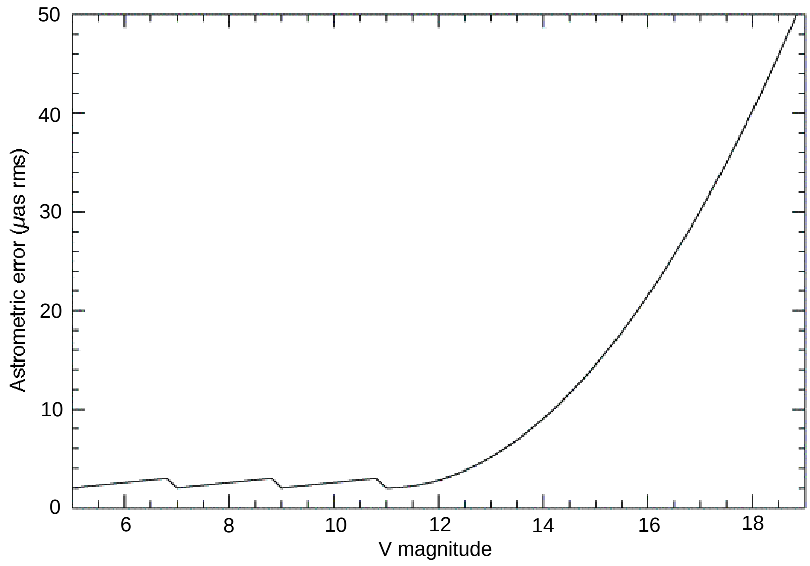


Figure 14: Nominal accuracy performance versus magnitude, for a G2V star. For V <15 mag the astrometric performance improves because the number of detected photons increases until the detector saturation level is reached (V ~ 11.6 mag for G2V star). Once saturation is reached, the performance is practically independent of magnitude.

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, modulation transfer function, 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 modulation transfer function; 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 total detection noise (including the effects of analogue video noise, quantization noise, and correct definition of the electrical bandwidth).

3.4 Accuracy Assessments

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 (Figure 14).

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 Figure 15. In summary, GAIA will observe of order one billion stars, the majority of which will have very well-determined properties. The dependence of these limits on Galactic coordinates is also illustrated in Figure 15.

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 2-3 m. This size limit is that set by the Ariane launcher shroud, and represents a practical upper limit for a spacecraft with non-deployed optics.

3.5 Data Reduction

The total amount of (compressed) science data generated in the course of the five-year mission is about 2 x 10^{13} bytes (20 TB). Most of this consists of CCD raw or binned pixel values with associated identification tags. 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 modelling 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;

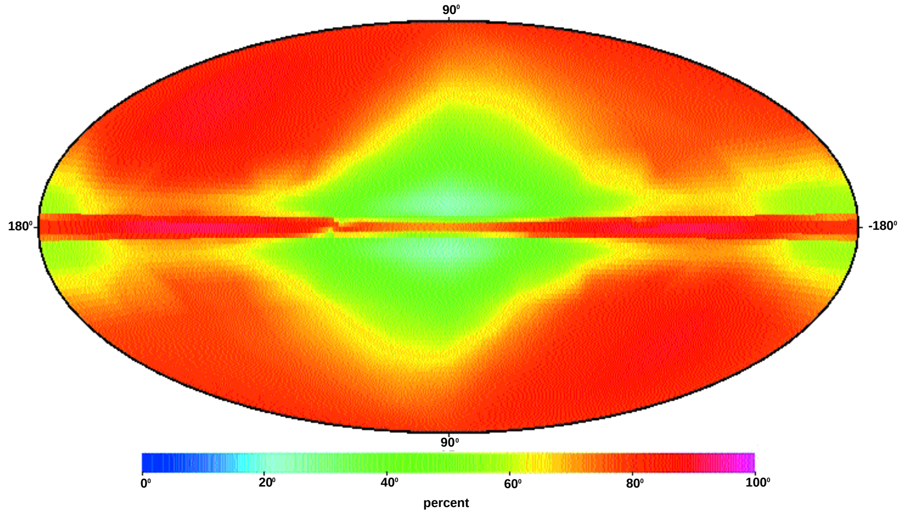


Figure 15: Density of stars with V < 15 mag and relative parallax error less than R = 0.02. The whole sky is shown as an Aitoff projection in Galactic coordinates, with the direction l=b=0° at the centre.

- 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 straightforward 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. Whichever consortia of scientific institutes in the various ESA countries eventually develop the GAIA databases, and the analysis methodologies, they will include and build upon such expertise, rather than acting in isolation.

4 Related Ground and Space Projects

Interest in the astrophysical capabilities of astrometry has led to a variety of recent proposals for space missions dedicated to astrometry. Two are approved, both by NASA (SIM, FAME), while one, a German national proposal (DIVA), is awaiting funding. SIM is designed to demonstrate and apply long-baseline interferometry; FAME and DIVA are both 'mini-GAIA' scanning instruments. These missions are summarised in Table 7.

SIM is an ideal mission for precise measurements of a small number of carefully pre-selected targets of specific scientific interest. DIVA and FAME will both provide an excellent reference frame, substantially improve calibration of the distance scale and the main phases of stellar evolutionary astrophysics, and map the Solar Neighbourhood to much improved precision.

GAIA is a survey mission, focused on galactic structure and evolution, and with broad applications to extra-solar planets, the Solar System, galaxies, large-scale structure, being also ideal for statistical analysis of the unknown.

The implications of GAIA's large sample, faint limiting sensitivity and high accuracy are substantial, and put GAIA in a different class from the other astrometric missions. Only GAIA can address the three key questions which underpin its science case:

- When did the stars in the Milky Way form?
- When and how was the Milky Way assembled?
- What is the distribution of dark matter in our Galaxy?

Table 7: Summary of the capabilities of Hipparcos and GAIA, along with those of other proposed astrometric space missions. Numbers of stars are indicative; in the case of SIM they are distributed amongst grid stars and more general scientific targets. Typical accuracies are given according to magnitude where appropriate.

Mission	Agency	Launch	No. of stars	Mag limit	Accuracy (mas)	(mag)
Hipparcos	ESA	1989	120 000	12	1	10
DIVA	Germany	2003	40 million	15	0.2 5	9 15
FAME	USNO/NASA	2004	40 million	15	0.050 0.300	9 15
SIM	NASA	2007	10 000	20	0.003	20
GAIA	ESA	2009	1 billion	20	0.003 0.010 0.200	12 15 20

5 Project Management

The GAIA mission, providing a complete survey to V ~ 20 mag, is the 'ultimate' observatory: every astronomical target which is accessible to GAIA will be observed with the full instrument complement on every possible occasion.

GAIA should be developed as a 'system', with consideration given to the end-to-end accuracies, involving contributions from the satellite, the payload instrumentation, and the data analysis. Management of the satellite development will follow well-established ESA precedents. After selection, a number of detailed studies will becarried out, to develop and prove necessary technology. An invitation to tender will then be issued for the detailed design and construction of the satellite. Procurement of the satellite and payload elements would be entrusted to a prime contractor, while Announcements of Opportunity would allow interested European scientific institutes to participate in the development, construction, and testing of well-identified payload elements and related activities.

Operational procedures should maintain as much flexibility as is feasible for scientists to acquire data from GAIA as rapidly as possible, whilst ensuring that the data are calibrated, verified, and properly documented. Most photometric results should be released rapidly, in close to real-time where feasible, to allow the follow-up of phenomena such as bursts, supernovae, gravitational lensing events, minor planets and near-Earth asteroids, and the photometric detection of extra-solar planetary transits.

Science operations pre-launch will be relatively simple and consequently inexpensive: no observing proposals need to be solicited in order to define the observing programme; indeed no specific scheduling is possible or desirable. Execution of the data analysis will be a major challenge for European scientists, involving both theoretical and observational astronomers, and computer scientists. Again, announcements of opportunity would be issued for participation in these activities, including the provision of algorithms for calibration and treatment of the data. Principles of participation would follow guidelines to be established or approved by the ESA advisory committtees.

Community access to the data might take a number of forms. Preliminary photometry should be available continually throughout the mission. An early release of the processed data based on the first 18 months, for rapid exploitation, is feasible. The final astrometric and photometric data may simply be released after the data analysis teams have completed the processing. Another option is to solicit proposals from scientists for priority access. The question of scientific reward for the instrument and data processing teams needs to be considered. Specific recomendations to the ESA SPC can be made when the instrument and data reduction consortia are finalised. A priority is to maximise community access to reliable data as soon and as widely as is feasible.

Studies of the data processing suggest that the final GAIA Catalogue should be completed, documented, and made available to the community within three years of the end of operations. Organisation and execution of the scientific activities would be supervised by a GAIA Science Team.

6 Public Relations, Education, and Outreach

Space science missions, and in particular astronomical studies of the visible Universe, have an extraordinary interest for the public at all levels. In addition to the primary ESA goals of basic research and applied technological developments, this means that related goals, such as helping to ensure that a continuing supply of scientists, engineers, and technologists will be available to meet the needs of the twenty-first century, can build on GAIA. The images, scientific discoveries and new appreciation of the scale and diversity of nature provided by astronomy captivate imagination, inform teachers, and excite students and the public about science and exploration. GAIA is exceptionally well-suited for this educational, awareness and technical training requirement. GAIA will provide opportunities and challenges at all levels, from the evolution of the Galaxy and the search for extra-solar planets, through applied gravitation, to the technical challenges in accessing large data sets remotely. Every one of these is of direct and topical interest, and produces knowledge of very wide and continuing general applicability.

7 The GAIA Study

This summary of the GAIA mission is based on the GAIA Study Report, which is the result of a large collaboration between ESA, the European scientific community and European industry. The scientific aspects of the study were supervised by the Science Advisory Group Members, chaired by M.A.C. Perryman (ESA), comprising: K.S. de Boer (Sternwarte Universitat Bonn); G. Gilmore (University of Cambridge); E. Høg (Copenhagen University Observatory); M.G. Lattanzi (Osservatorio Astronomico di Torino); L. Lindegren (Lund Observatory); X. Luri (Universitat de Barcelona); F. Mignard (Observatoire de la Côte d'Azur); and P.T. de Zeeuw (Sterrewacht Leiden). The work of the Science Advisory Group has been supported by a Science Working Group, chaired by P.T. de Zeeuw and G. Gilmore (18 members) and responsible for quantifying the science case; a Photometry Working Group, chaired by F. Favata (18 members); an Instrument Working Group, chaired by L. Lindegren (16 members); and 52 other European scientists directly supporting the GAIA study. Technological activities have been led by the ESA Study Manager, O. Pace (SCI-PF), supported by M. Hechler (ESOC Study Manager), and eleven D-TOS engineers. ESA scientific involvement includes contributions from S. Volonté (ESA Paris) and from scientists within the ESA Astrophysics Division. The satellite design study has been under contract to Matra Marconi Space (F), under the Study Manager P. Mérat, and involving EEV Ltd (UK), and Alcatel Space (F). An Alenia Study Team, under Study Manager S. Cesare, evaluated an interferometric design, with involvement of the Istituto di Metrologia 'G. Colonnetti', EICAS Automazione, the Osservatorio Astronomico di Torino, Matra Marconi Space (F), and Alcatel Space. Other industrial studies have been carried out by SIRA(UK; CCD CTE), and TNO-TPD (Delft; basic angle monitoring).

8 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.

The GAIA project offers a wide and highly attractive range of possibilities for European collaboration, ranging from the satellite design, development and operation, instruments and payload elements and related activities that can be undertaken according to the interests of national institutes, advanced computational and database aspects, and a diverse range of scientific activities related to the data reductions, scientific analysis, and astrophysical interpretation of the final data.

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. GAIA will provide a quantitative, stereoscopic movie of the Milky Way, and so unlock its origins.