GAIA: Understanding the Galaxy

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Abstract.

The GAIA Observatory, ESA’s Cornerstone 6 mission, addresses the origin and evolution of our Galaxy, and a host of other scientific challenges. GAIA 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 one per cent of the Galactic stellar population. Combined with astrophysical information for each star, provided by onboard 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 also 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.

There are many scientific tasks to optimise GAIA which demand immediate effort, providing an ideal opportunity to play a major role in the project, and in the future of astronomy. Those interested in being part of GAIA activities, or wanting to know more, should contact Michael Perryman (mperryma@astro.estec.esa.nl) or Gerry Gilmore (gil@ast.cam.ac.uk) and see http://astro.estec.esa.nl/GAIA.

You can make your own three-dimensional model of the GAIA satellite by downloading the instructions and model parts from the WWW page. To make the model all you need is paper, glue, scissors and a spent match stick.
1. Introduction

GAIA is the astrophysics mission selected as Cornerstone 6 in the ESA science programme. The acronym has many interpretations, with Galactic Astrophysics through Imaging and Astrometry being most apt.

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 per cent as far as the Galactic Centre, 30 000 light years away. Stellar motions will be measured even in the Andromeda galaxy.

2. GAIA: The Scientific Case

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

2.1. Structure and Evolution of the Milky Way Galaxy

Understanding the Galaxy in which we live is one of the great intellectual challenges facing modern science. The Milky Way contains a complex mix of stars, planets, interstellar gas and dust, radiation, and the ubiquitous dark matter. These components are widely distributed in age (reflecting their birth rate), in space (reflecting their birth places and subsequent motions), on orbits (determined by the gravitational force generated by their own mass), and with chemical element abundances (determined by the past history of star formation and gas accretion). Astrophysics has now developed the tools to measure
these distributions in space, kinematics, and chemical abundance, and to inter-
pret 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 Uni-
verse: 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 com-
plementary observational approaches: (i) a census of the contents of a large,
representative, part of the galaxy; (ii) quantification of the present spatial struc-
ture, from distances; (iii) knowledge of the three-dimensional space motions, to
determine the gravitational field and the stellar orbits. That is, one requires com-
plementary astrometry, photometry, and radial velocities. Astrometric measure-
ments 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 distrib-
ution 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 accu-
racy, but the full six-dimensional stellar distribution function throughout a large
part of the Galactic disk. This will allow not only a determination of the grav-
itational 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 compo-
nents, e.g., the past variations of pattern speed and strength of the central bar
and spiral arms.

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

2.2. 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 success-
sor or a precursor to the stellar halo? Is it a merger remnant? It is not clear
whether the formation of the bulge preceded that of the disk, as predicted by
‘inside-out’ scenarios; or whether it happened simultaneously with the formation
of the disk, by accretion of dwarf galaxies; or whether it followed the formation
of the disk, as a result of the dynamical evolution of a bar. Large-scale surveys
of proper motions and photometric data inside the bulge can cast light on the
orbital distribution function. Knowing the distance, the true space velocities
and orbits can be derived, thus providing constraints on current dynamical the-
ories of formation. GAIA data for bulge stars, providing intrinsic luminosities, metallicity, and numbers, can be inverted to deduce star formation histories.

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

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

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

2.3. 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 $[\text{Fe}/\text{H}] < -3.5$, represent a powerful tool to understand primordial abundances and the nature of the objects which produced the first heavy elements.

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

Those merging and accretion events leave signatures in the phase-space distribution of the stars that once formed those systems. Helmi et al have shown that, after 10 billion years, the spatial distribution of stars in the inner halo
should be fairly uniform, whereas strong clumping is expected in velocity space. This clumping appears in the form of a very large number of moving groups (several hundred in a 1 kpc³ volume centered on the Sun, if the whole stellar halo were built in this way) each having very small velocity dispersions and containing several hundred stars. The required velocity accuracies to detect individual streams are less than a few km s⁻¹, requiring measurement precision of order μas.

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

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

2.4. Large Scale Structure of the Galactic Disk

We note here just two of the many aspects of this science GAIA will explore.

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

The expected kinematic pattern (at least, in existing plausible models) is most strongly constrained by the straightness of the line of nodes: these should wind up in at most a few rotation times, typically less than 2 Gyr. A relevant shear pattern corresponds to systematic motions dependant on warp phase and galactocentric distance superimposed on Galactic rotation. A plausible velocity
amplitude associated with the warp at the optical disk edge is significantly less than $0.1\Omega$, with $\Omega$ 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 $\sim 90$ $\mu$as yr$^{-1}$ in latitude and $\sim 600$ $\mu$as yr$^{-1}$ in longitude. For such a signal to be detected the reference frame must be rigid to better than a few microarcsec on scales of $\sim 10^{\circ}$ (i.e. matching the high-frequency warp structure) and on scales of $2\pi$ radians, requirements well within the GAIA capabilities. The corresponding distance requirements are more demanding: at the warp a mean parallax is less than 100 $\mu$as, so that resolution of the warp within 10 per cent implies distance accuracies of 10 $\mu$as at $I \sim 15$ mag. Along lines of sight with typical reddening, the study of the Galactic warp will be within the limits of GAIA’s performance.

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

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

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

### 2.5. Stellar Astrophysics

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

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 per cent for $7 \times 10^5$ stars out to a few hundred pc, and to 1 per cent accuracy for a staggering $2.1 \times 10^7$ stars up to a few kpc. Distances to 10 per cent will reach beyond 10 kpc, and will cover a significant fraction of our Galaxy, including the Galactic centre, spiral arms, the halo, and the bulge, and—for the brightest stars—to the nearest satellites. The faint limiting magnitude allows investigation of white dwarfs as well as the bottom of the main sequence down to brown dwarfs. For the first time, this will provide an extensive network of accurate distance measurements for all stellar types.

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

Essentially all Jupiter-mass planets within 50 pc and with periods between 1.5–9 years will be discovered by GAIA.

### 2.6. Solar System

Solar system objects present a challenge to GAIA because of their significant proper motions, but they promise a rich scientific reward. The minor bodies
provide a record of the conditions in the proto-Solar nebula, and their properties therefore shed light on the formation of planetary systems. Discovery and orbital determination of near-Earth objects is a subject of high public interest.

In addition to known asteroids, GAIA will discover a very large number, of the order of $10^5$ or $10^6$ (depending on the uncertainties on the extrapolations of the known population) new objects. It should be possible to derive precise orbits for all the newly discovered objects, since each of them will be necessarily observed many times during the mission lifetime. These will include a large number of near-Earth objects. GAIA is ideal to look for these objects because of the enormous area of sky that must be searched.

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

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

2.7. The Local Group, distant Galaxies, Quasars, and the Reference Frame

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

Orbits in the Local Group: Gravitational Instability in the Early Universe

The orbits of galaxies are a result of mildly non-linear gravitational interactions, which link the present positions and velocities to the cosmological initial conditions. Non-gravitational (hydrodynamic) or strongly non-linear gravitational interactions (collisions, mergers) are sometimes significant. It is uniquely possible in the Local Group to determine reliable three-dimensional orbits for a significant sample of galaxies, in a region large and massive enough to provide a fair probe of the mass density in the Universe. Such orbital information provides direct constraints on the initial spectrum of perturbations in the early Universe, on the global cosmological density parameter $\Omega$, 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 $\sim 100$ kpc from another large galaxy. Improved distances will be derived from the GAIA-calibrated standard distance indicators, such as
Cepheids and RR Lyraes. 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 $\sim 0.3$ arcsec spatial resolution for all sufficiently high-surface brightness galaxies. This provides a valuable and unique data set at two levels: for statistical analysis of the photometric structure of the central regions of many tens of thousands of galaxies; and for study of the large-scale structure of the local Universe. The scientific value of this huge and homogeneous database will impact all fields of galaxy research, naturally complementing the several redshift surveys, and the deeper pencil-beam studies with very large telescopes. Among the most important unique GAIA science products will be determination of the colour and photometric structure in the central regions of a complete, magnitude-limited sample of relatively bright galaxies.

Supernovae: GAIA will detect all compact objects brighter than $V = 20$ mag, so that in principle supernovae can be detected to a modulus of $m - M \sim 39$ mag, i.e., to a distance of 500 Mpc or $z \sim 0.1$. 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, $\pm 5$ per cent. Rapid detection of such transient sources will allow detailed ground-based determination of light curves and redshifts.

Quasars: The astrometric programme to $V = 20$ mag will provide a census of $\sim 500,000$ quasars. The mean surface density of $\sim 25$ deg$^{-2}$ at intermediate to high Galactic latitudes will provide the direct link between the GAIA astrometric reference system and an inertial frame. They are also of direct astrophysical interest. Existing ground-based studies of gravitational (macro) lensing among the quasar population are restricted to resolutions of $\sim 1$ arcsec. GAIA will provide sensitivity to multiply-imaged systems with separations as small as $\sim 0.2$ arcsec. For the brighter quasars, $V < 18$ mag, with a surface density of $\sim 1$ deg$^{-2}$, where examples of lensing are most common, GAIA’s sample of $\sim 50,000$ 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. This homogeneous sample would provide decisive astrophysical information, including
constraints on the cosmological parameters $\Omega$ and $\lambda_0$. Photometric variability of multiply lensed quasars is of course 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 extragalactic radio-sources with an rms uncertainty in position between 100 and 500 $\mu$as. 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 ($\omega$) and $0.6$ mas in the components of the orientation vector ($\varepsilon$) 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 $60\mu$as in the orientation of the frame.

2.8. Fundamental Physics: The Space-Time metric

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

Detailed analyses indicate that the GAIA measurements will provide a precision of about $5 \times 10^{-7}$ for $\gamma$. 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.

3. GAIA: the mission

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

The telescopes are of moderate size, with no specific design or manufacturing complexity. The system fits within a dual-launch Ariane 5 configuration, without deployment of any payload elements. A ‘Lissajous’ orbit at the outer Lagrange point L2 has been identified as the preferred operational orbit, from where an average of 1 Mbit of data per second is returned to the single ground
station throughout the 5-year mission. The 10 microarcsec accuracy target has
been shown to be realistic through a comprehensive accuracy assessment pro-
gramme; 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 local-
isation accuracy: this challenge, while demanding, has been proven deliverable
by the Hipparcos experience.

3.1. GAIA: the observatory

GAIA will record more than just huge volumes of positional data on a vast num-
ber 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 avail-
able spatial resolution exceeds that available in ground-based surveys. Source
detection happens on-board at each focal-plane transit, so that variable and
transient sources are detected. All these complementary datasets, in addition
to the superb positional and kinematic accuracy which is derivable from their
sum, make GAIA an optimal observatory mission: every observable source will
be observed every time it crosses the focal plane.

These data allow studies from asteroids to distant supernovae, from planets
to galaxies, and naturally interest almost the entire astronomical community.
Because of this enormous interest, GAIA will be an open observatory mission,
directly making available its rich scientific resource to the sponsoring communi-
ties. 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 scien-
tific legacy, providing a wealth of quantitative data on which all of astrophysics
will build.

3.2. GAIA Mission Organisational Structure

GAIA is unusual for a space project, in that ESA will provide the payload
inside the mission budget. This results in vastly less pressure on national science
budgets, but presumes a slightly unusual project management structure.

Following selection of GAIA as Cornerstone 6, the work of the ESA Science
Advisory Group was complete. A new structure is currently being implemented,
to guide the project over the next few years towards final detailed definition, and
into construction. The ESA effort is supervised by a project scientist (Michael
Perryman, formerly HIPPARCOS project scientist) and a project manager (Oscar
Pace, the GAIA study manager). Two Industrial contracts are soon to be
placed to oversee system development, and the many technical studies under-
way in European industry. These studies will be overseen by a GAIA Science
and Technical Advisory Group, chaired by Michael Perryman. The members of
this act as coordinators for the (currently 20) groups of community scientists
who are active in defining GAIA. A Space Astrometry Forum (Chair: Francois
Mignard, Nice) brings together the various space astrometry missions for issues such as reference frames. General oversight of the GAIA studies is provided by the GAIA Consultative Committee (Chair: Gerry Gilmore).

3.3. GAIA: How can I be involved?

There are many scientific tasks to optimise GAIA which demand immediate effort. GAIA will be defined and designed beyond major change in 3 years time. We have that much time to get it right. This challenge provides an ideal opportunity for interested scientists, and for PhD projects, to play a major role in the project, and in the future of astronomy. Among these tasks are definition of the GAIA photometric system, development of data reduction algorithms and methods, modelling the sky as seen by GAIA, developing systems for real-time access to GAIA photometry, and so on. The GAIA data will underpin astronomy for decades to come. The techniques needed to analyse 100Tb of multi-dimensional data are those of relevance for all future research. The science content of 100Tb of GAIA data is vast. Work has started. Much needs to be done.

Scientists interested in being part of GAIA activities, or wanting to know more, should contact Michael Perryman (mperryma@astro.estec.esa.nl) or Gerry Gilmore (gil@ast.cam.ac.uk).

4. Conclusion

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

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

While challenging, the entire GAIA design is within the projected state-of-the-art, and the satellite can be developed in time for launch in 2010. 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.