GAIA: ORIGIN AND EVOLUTION OF THE MILKY WAY

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ABSTRACT

GAIA is a short-listed candidate for the ESA Cornerstone mission C5, meeting the ESA Survey Committee require-
ment for an observatory mission, dedicated to astrometry, providing 10 micro-arcsecond accuracy at 15th magnitude.
The GAIA mission concept follows the dramatic success of the ESA HIPPARCOS mission, utilising a continuously
scanning spacecraft, accurately measuring 1-D coordinates along great circles, in (at least) two simultaneous fields
of view, separated by a known angle. These 1-D relative coordinates are later converted to the five astrometric
parameters of position and motions in a global analysis. GAIA will provide precise astrometry and multi-colour
photometry for all the one billion stars, quasars, and compact galaxies to I=20 on the sky. GAIA will additionally
provide the sixth phase-space parameter, radial velocity, from a slitless spectroscopic survey of most stars brighter
than about magnitude 17. The technical challenges are considerable, but achievable. The scientific returns are
spectacular, with greatest impact in the study of stellar populations and dynamical structure of the galaxies of our
Local Group, and in providing the first complete census of the stars and massive planets in the Solar neighbourhood.
GAIA will revolutionise our knowledge of the origin and evolution of our Milky Way Galaxy, and of the distribution
of planetary systems around other stars.

Keywords: GAIA, HIPPARCOS, Galactic Astrophysics, Milky Way Galaxy, Stellar Populations, Planetary Sys-
tems, Space Astrometry

1. GAIA: THE ESA CONTEXT

The European Space Agency supports a series of major missions, known as `cornerstones`*, complemented by a larger
number of smaller projects. The special feature of cornerstone missions is that they serve a large community in a
discipline of long-term importance. Forthcoming cornerstone missions include XMM (C2, launch 1999), Rosetta (C3,
launch 2003), and FIRST (C4, launch 2006). The provisional timetable for Cornerstone C5 involves final selection
in the next two years, for scheduled launch in 2009.

In 1992 a Survey Commitee was assembled at the request of the ESA Council to establish scientific priorities for
its long-term scientific programme, in the post-Horizon 2000 era. Following on from the success of the first space
based dedicated astrometric project, HIPPARCOS, the committee recommended "that ESA initiate a Cornerstone-
level programme in interferometry for use as an observatory open to the wide community. The first aim [of which]
is to perform astrometric observations at the 10 microarcsec level."

Absolute astrometry at this level of accuracy for large samples of stars constitutes a very powerful scientific
tool, allowing investigation of the structure, contents, and dynamics of the Milky Way, through determination of
the distances and motions, and detection of possible planetary or brown dwarf companions, of very large samples of
stars, as well as study of the dynamics of nearby external galaxies. To this end the GAIA mission is under study to
address the scientific requirements and technological challenges implied by such a mission. Two industrial studies

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FIGURE 1: An illustrative summary of the primary GAIA scientific goals, superimposed on the Lund map of the Milky Way and Local Group galaxies.

are underway, by Alenia (It) and Matra Marconi Space (Fr), to define complementary approaches to the payload design. The Alenia study considers a Fizeau interferometer design, with precision metrology and mechanical control; the Matra Marconi study has concentrated on a payload in which the requisite extreme stability is provided by a stable passive monolithic structure.

It is useful to note that the only currently approved space astrometric mission is the NASA project SIM. GAIA and SIM are remarkably complementary in both design and scientific goals, though should deliver rather similar limiting astrometric accuracy. SIM is primarily a technology precursor mission for the Origins programme, and so is necessarily based on long-baseline Michelson interferometers. Any such instrument must operate in pointed mode, on a pre-selected target list. SIM will provide superbly accurate astrometry for of order 10^4 stars over a five-year mission life. It is thus ideal for rare but intrinsically interesting classes of stars. GAIA is a scanning satellite, following the proven HIPPARCOS model of operation, with fewer constraints on its mode of implementation. Thus, GAIA may adopt a design which reduces technological complexity. GAIA is optimised for very large samples, up to 10^9 stars. It is thus ideal for providing an accurate global picture of the Milky Way based on reliable statistical samples, for the discovery of new classes of rare object, and for searches for planetary systems.

2. THE ORIGIN AND EVOLUTION OF GALAXIES: AN OBSERVATIONAL CHALLENGE

Understanding the origin, past evolution, present-day structure, stellar and planetary contents, and long-term future, of the part of the Universe in which we live ranks among the great intellectual challenges facing modern science. The current astrophysical paradigm is that galaxies like the Milky Way grew, primarily under the influence of gravity, from small-amplitude fluctuations in the very early Universe. The growth of these fluctuations, and all later structures, is dominated by the nature and amount of the apparently ubiquitous but as yet unidentified dark matter. As the early fluctuations in the dark matter and primordial hydrogen and helium grow into collapsing and cooling clouds, stars will form, the most massive of which rapidly evolve, create new chemical elements, and disperse them through supernovae. The lower mass stars, and their planetary systems, survive to the present day. The star-forming gas clouds and their dark matter halos themselves aggregate into larger and larger structures, containing more and more

of the chemical elements, eventually forming the dramatic diversity of types of Galaxy which exist today, including the Milky Way Galaxy and its several dwarf satellite companions, and the several other neighbour galaxies which comprise our Local Group.

This broad-brush summary, while plausible, remains to be tested in detail, and depends sensitively on several key processes – the behaviour of dark matter, the nature of star formation, the incidence of planetary systems – which remain entirely unknown. Is progress possible? Perhaps surprisingly, understanding the complex origin of the Milky Way is readily amenable to progress by direct observation. This process of Galacto-archaeology is in principle feasible as a direct observation because typical low-mass stars live for longer than the present age of the Universe, and preserve in their atmospheres an (almost) unmodified record of the chemical elements from which they were formed. Thus, the numbers and chemical element abundances of long-lived stars provide a direct fossil record of the creation history of the chemical elements, and of the rate at which stars have formed since the Big Bang. In addition, their orbits encode the crucial complementary information needed to understand galaxy formation and evolution: analysis of the spatial distributions of stars and their orbital energies traces the otherwise unobservable spatial distribution of dark matter; departures from smoothness in the distribution of stars in velocity and coordinate (phase) space retain a memory of the rate and time at which large galaxies have grown by devouring their smaller companions. For stars near the Sun, planetary companions induce observable wobbles on the orbit through the Milky Way of their parent sun, allowing their detection from precise position and kinematic data.

Are such observations possible in practice? Yes indeed. The required observational products are three spatial coordinates, two providing a direction, the third a distance down the line of sight, and three orthogonal velocity coordinates, two in the plane of the sky and the third radial component. Ideally, for at least a large subset of the targets, one additionally desires a measure of the abundance of the chemical elements – obtainable from analysis of the stellar spectrum – and a measure of the age – derivable in special cases from analysis of photometry if the distance is known. While in principle one might obtain such information for all 10^{11} stars in a galaxy like the Milky Way, in practice, fortunately, only a representative sub-set need be observed. A critical requirement of course, without which the value of any data set is substantially degraded, is very accurate knowledge of the selection function which defines the sub-set of about 10^9 stars that will be observed. This implies accurate photometry to faint limiting magnitudes, and high spatial resolution imaging, since much of the sky is crowded, or occupied by compact background galaxies or interstellar emission.

Thus the requirements for a direct observational determination of the origin, content, structure and evolution of the Milky Way Galaxy become well defined: photometry, spectra and astrometry.

i) A photometric survey, to provide accurate definition of the subset of all stars which are to be studied further, and some complementary age information;

ii) A radial velocity survey, to provide one of the three components of the velocity vector, and complementary chemical abundance information from the requisite spectra;

iii) Three position coordinates, two of which are angles, the third requiring a parallax distance;

iv) The two components of the transverse velocity vector, which appear as proper motions on the plane of the sky.

One may immediately define the required performance to meet these science goals. In order to probe the whole Milky Way and its satellites using reasonably understood albeit intrinsically luminous stellar tracers, the proper motion survey must reach fainter than about I=18, while the radial velocity survey must reach an accuracy of a few km/s to apparent magnitudes of about I=17 (*cf* Gilmore & Hoeg 1995; Gilmore & Perryman 1997 for details). A representative space velocity for an outer disk star, or a star in a representative stellar cluster, is of order 100μas/yr, implying a required precision of order 10μas. Detection of solar system-like planetary systems, if they exist, around the nearest 100,000 stars requires similar astrometric precision, of about 10μas.

Provision of precise astrometric information for bright stars has been proven possible by the success of the ESA HIPPARCOS satellite mission. GAIA is being developed to build upon the HIPPARCOS success, extending performance by some two orders of magnitude in precision, some four orders of magnitude in sensitivity at the sample

FIGURE 2: The three panels illustrate a slice of sky, centred on the Sun, $90° \times 10°$ on a side, containing the Hyades open star cluster. Each point represents one star, with the uncertainty in its line of sight distance illustrated where it exceeds the size of the point. The left hand panel shows the current state of the art of ground-based measurements; the centre panel the HIPPARCOS state of the art; the right hand panel a few percent of the sources in the sky as it will be mapped by GAIA.

completeness limit, and four orders of magnitude in sample size. With these gains Galactic archaeology will become a real observational science, and we will have our first accurate census of the stars – and planetary systems – in our local neighbourhood.

Figure 2 illustrates the limitations in our present knowledge of even our immediate Galactic neighbourhood, and the gains which await from GAIA.

3. ASTROPHYSICS WITH GAIA

A detailed photometric and kinematic survey of a billion stars is a major undertaking. Would not a million do? One should therefore start by asking just why large samples are needed. The table below lists the most obvious subset of the GAIA scientific case, while further details and examples may be found in Gilmore & Hoeg (1995); Gilmore & Perryman (1997); and Perryman, Lindgren & Turon (1997). The general goals of the GAIA science program are summarised in Figure 1 above. To further illustrate the need for large sample statistical astrophysics we present three brief outlines of primary GAIA science: the origin of the Milky Way Galaxy, the distribution of dark matter, and the number of planetary systems near the Sun.

3.1. GALACTIC ASTROPHYSICS WITH GAIA

The kinematic and metallicity distribution functions of complete samples of long-lived stars have long been recognised as providing unique constraints on the early stages of evolution of the chemical elements in the Galaxy. The main sequence lifetime of low-mass dwarf stars is greater than the age of the Galaxy; the chemical-abundance distribution function of such stars provides an integrated record of the chemical-enrichment history without the need for model-dependent corrections for dead stars. Pioneering studies focussed on the only reasonably-complete sample available, which is that for solar-like stars in the immediate solar neighborhood; in effect the brightest stars within about 30pc of the Sun. These samples have been sufficiently small that reliable study of those stellar populations which are not

Table 1. A brief summary of the GAIA scientific case

THE HISTORY OF OUR GALAXY	test hierarchical formation theories
	inner bulge/bar dynamics
	disk-halo dynamical interactions
	continuing dynamical evolution
	what is the warp
	star cluster disruption
	weigh spiral structure
	star formation history
	chemical evolution
	link to high redshifts
STELLAR EVOLUTION	large sample to detect rapid evolutionary phases
	quantify pre-main sequence evolution
	complete census of the local neighbourhood
STELLAR FORMATION	dynamics of star forming regions
	luminosity function for pre-Main Sequence stars
BROWN DWARFS	census of brown dwarfs in binaries
PLANETARY SYSTEMS	complete census around $\sim 3.10^5$ stars
THE LOCAL GROUP	rotational parallaxes for Local Group galaxies
	kinematic separation of stellar populations
	galaxy orbits to give cosmological history
BEYOND THE LOCAL GROUP	parallax calibration of distance scale
	zero proper motion QSO survey
	photometry of 10^8 galaxies
THE NATURE OF MATTER	Galactic rotation curve
	disk mass profile from $\sigma_z(R)$
	internal dynamics of Local Group dwarfs
FUNDAMENTAL PHYSICS	Determine the space-curvature parameter γ to 10^{-6}.
REFERENCE FRAMES	Define the local metric
SERENDIPITY	the first all-sky phase-space map.....

common in the solar neighborhood has necessarily been difficult. This is a serious restriction, as such stars might in principle be a major contributor to the stellar population in a valid, representative volume of the Galaxy. For example, stars of the Galactic inner disk and bulge, and outer halo, are barely represented, if at all. In addition, intrinsically-rare stellar populations and short-lived phases of stellar evolution are missed entirely, even though they may be crucial for understanding important physics, or significant events in Galactic history.

The observational situation has been improved recently in three ways: by collection and analysis of spectroscopic data for all-sky samples of stars extending to somewhat greater, but still essentially local, distances; by deeper pencil-beam surveys, to isolate *in situ* samples of old disk, thick disk and halo stars; and most dramatically, by the HIPPARCOS mission which has quantified local kinematics. The combination of the large ($\sim 10^5$ stars) but local samples with the smaller but distant samples ($\sim 10^4$ stars) has allowed the deconvolution, to first order, of the abundance distribution functions, and the mean velocity dispersions, of the dominant Galactic populations. While our understanding of Galactic structure and evolution has advanced considerably of late, extension of these analyses

has become limited by the intrinsic breadth and overlap of the population distribution functions and by the small size of the available *in situ* samples.

The theoretical situation has also become more specific. Though the many dynamical, structural and chemical evolution questions one poses concerning galactic evolution may seem well-defined and relatively distinct, it is now clear that the answers are intimately interrelated. For instance, galaxies probably accrete their neighbours, so that the place of origin of a star may be far from its present location; dynamical instabilities in disks result in the mixing through phase space of stellar populations, blurring the relation between a star's present location and its birthplace. Bar instabilities are also likely to cause significant gas transport, and may drive star bursts and possibly nuclear non-thermal phenomena. Major mergers may thicken disks. Bulges may be accreted, or created during mergers.

Modern models of Galaxy formation make fairly specific predictions concerning each of these possibilities. For example, fashionable Cold Dark Matter models, which contain aspects of both the monolithic ('ELS') and the multi-fragment ('Searle-Zinn') pictures often discussed in chemical evolution models, 'predict' growth of the Galaxy about many small cores, which should contain the oldest stars. After several of these merge, defining what is to become the eventual Milky Way Galaxy, the new central regions will retain the oldest stars. Subsequent accretion of small 'galaxies' forms the outer halo and the disks, while late accretion will continue to affect the kinematic structure of both the outer halo and the thin disk. The normal star formation in the disk produces clusters and associations. The latter are unbound at birth, and the former lose stars due to internal dynamical evolution and the Galactic tidal field, resulting in a multitude of moving groups o fstars with a common origin. Considerable phase-space substructure should thus be detectable almost anywhere in the Galaxy.

Dissipational models for thick-disk formation predict observable spatial gradients in the distribution of the chemical elements, and similar scale lengths for the thick and thin Galactic disks. Specific column-integral element abundance distributions can be calculated (numerically) for some of these models and compared to observations. Satellite merger models for thick disk formation require the stars from the satellite to be detectable, as a tail in the thick disk distribution functions below [Fe/H]$=-1$. 'Continuum' models of thick disk formation from the thin disk require that an accurately defined joint distribution function over chemical abundance and kinematics for the oldest stars be smooth and continuous. Alternative models, such as the discrete merger model, can then be distinguished by their prediction that the distibutions overlap in abundance, and perhaps velocity dispersion, but not in angular momentum (Gilmore, Wyse & Kuijken 1989). Most detailed models make specific predictions concerning the abundance distribution function in a cylinder, through the Galactic disk - the 'G-dwarf problem' – which remains widely studied, and a valuable diagnostic of early accretion and gas flows in the disk. Extension to a more representative volume is necessary for Galactic-scale analyses. Some further details are presented in Gilmore & Wyse (1986).

That is, quantitative study of the essential physics of galaxy evolution requires that one must study the distributions over chemistry, kinematics and spatial structure of a large and representative sample of stars. Such a sample can be provided only by accurate measurement covering a substantial fraction of all of the phase space potentially available to stellar populations. In coordinate terms, one must measure the stars where they are, across most of the volume of the Galaxy. In number terms, one must measure large enough samples in each place that the local properties, and their gradients, can be known reliably. Since one does not know, prior to measurement, where a star is, one must measure very large numbers of stars in each direction to be confident of one's conclusions. The ambitious goal of understanding the Milky Way requires an ambitious experiment.

3.2. DARK MATTER STUDIES WITH GAIA

The nature of the dark matter which apparently dominates the evolution of structure in the Universe, and the dynamics of every galaxy, is one of the biggest questions in contemporary physics. Extensive analyses suggest that the smallest length scale on which dark matter is gravitationally dominant is that of the dwarf satellite galaxies of the Milky Way. Thus these galaxies provide the best possible testbed to determine the density, velocity dispersion, and 3-D distribution of the dark matter. Such studies are complemented, and linked, to those on cosmological scales by measurements on larger length scales, which are attainable by mapping the dynamics of the Milky Way and the Local Group.

The technique to achieve this requires two approaches: detailed dynamical mapping of the dwarf satellites of the Milky Way, especially Sagittarius, the nearest, and the Large Magellanic Cloud, the largest; complemented by detailed determinations of the rotation curve and disk mass of the Galaxy as a function of radius. It has been shown that extant data, with at most a few hundred accurate radial velocities and little or no useful proper motion

data, is inherently unable to achieve this dynamical mapping. The problem is degeneracy between anisotropic stellar orbits, supporting the galaxy by stress, and gravitational potential gradients, supporting the galaxy by pressure. Extant data cannot distinguish robustly between dark matter distributions which are very centrally concentrated, are moderately extended isothermal, or are very extended. An ability to distinguish between these different allowed dark matter distributions is clearly a key step for progress.

This degeneracy can be broken with sufficiently accurate and sufficiently extensive proper motion and radial velocity data. Current simulations suggest the need for some thousands of stars per satellite galaxy, and some millions throughout the Galactic disk, for this experiment.

3.3. DETECTION OF PLANETARY SYSTEMS

In order to understand the numbers of planetary systems in the Milky Way we need to know at minimum how they are distributed with different parent star properties, and what range of orbital sizes they have. Any such understanding requires careful analysis of a large and complete sample of stars to see if they are parents of planetary systems, or are isolated. Astrometry provides the ideal tool for this experiment.

The reflex motion of the Sun induced by Jupiter's orbital motion is equivalent to 500μas at 10pc; that of the 3-year period planet on its primary 47UMa is 362μas. These values illustrate the utility of accurate astrometry with a time base of several years for planetary detection. Careful simulations show that GAIA has a detection efficiency for a Sun-Jupiter system which exceeds 50% at 150pc, covering $\sim 3.10^5$ stellar systems, and is still useful at 200pc (Lattanzi, Spagna, Sozzetti & Casertano, 1997).

This sensitivity is complemented by the other special feature of the GAIA mission: its unique capability to identify the complete sample of stars within the few hundred parsecs centred on the Sun. Thus GAIA will be able to survey the nearest 300,000 stars for planets, because it will identify those 300,000 stars. This will allow accurate determination of the frequency of planetary systems as a function of the type of parent star, as well as of planetary mass and separation. Such a data set will of course provide, at the same time, a superb determination of the number of brown dwarfs – objects between planetary and stellar mass – which are invisible binary companions to luminous stars. This distribution is a key parameter in understanding accretion rates and angular momentum transport in star formation, but is at present unknown.

3.4. FUNDAMENTAL PHYSICS and REFERENCE FRAMES

Very precise determination of the spatial reference frame is a critical requirement in many fields: in astrophysics from inter-planetary navigation to relative location of observations at different wavelengths. GAIA is both precise in individual measurements, and dense in numbers of observations. Thus it will enhance both the local density and the global integrity of the reference frame. GAIA will observe an all-sky grid of cosmologically distant point sources which are observable at (almost) all wavelengths from radio to X-ray – the quasars – and use these to improve both the zero-point global determination of the astronomical reference and its local implementation in any specific line of sight.

Any astrometric measurement at micro-arcsec scales is dominated by the systematic distortions of the local metric generated by local masses, especially the Sun and major planets. Light bending by the Sun is 4000μas even at the ecliptic pole, 90° from the Sun; by the Earth is 40μas at its limb, 17000μas at Jupiter's limb. Precise determination of these systematic effects allows determination of both the time-space and space-space components of the metric tensor, at a level which is of interest for some viable scalar-tensor theories of gravitation. The combined effects are related to the well-known geodetic precession and gravito-magnetic (Lense-Thirring) effects, often quantified through the parameterised post-Newtonian (PPN) parameter γ. Light deflection uniquely is sensitive to only the space-space part of the metric, allowing sensitive determination of its amplitude (cf de Felice, Lattanzi, Vecchiato & Bernaca 198). γ is currently known to be equal to the General Relativistic prediction to one part in 10^{-3}. GAIA will determine γ to one part in 10^{-6}.

4. THE GAIA SPACECRAFT

Achievement of the ambitious scientific goals noted above imposes demanding technical performance specifications on a spacecraft. The most obvious requirement is stability during the time it takes to collect the large number of photons needed for an accurate location of an image. To appreciate this it is helpful to recall the principles of global astrometry, as implemented by the HIPPARCOS mission.

FIGURE 3: An exploded view of the GAIA spacecraft, superimposed on an HST image of part of the Large Magellanic Cloud, one of GAIA's prime scientific targets. The spacecraft support module is at the left hand side, separated by a large sunshield from the payload module. The possibly unnecessary 400N motor is at the extreme left, at the Sun and Earth pointing end. Next is shown the ring of phased-array antennae, supporting the high telemetry requirement. Solar power arrays and the sunshield are shown, followed by the science payload. This is a set of three telescopes on a single support structure, which also supports the focal planes and electronics. The whole spacecraft spins as a single structure about the horizontal axis in this view. This arrangement provides the essential thermal and mechanical stability for GAIA.

4.1. GLOBAL ASTROMETRY

The fundamental measurement in any astronomical astrometric system is of the angle between two or more stars. Global astrometry extends this concept by determining all the angles between all the stars in a large sample covering the whole celestial sphere. It is then possible to use this multiply redundant measurement set to solve for a reference grid with rigidly orthogonal coordinates over the whole sky. One additionally requires a set of zero-point reference objects, to determine the origin and rotation of this global rigid grid. The crucial requirement is to have a spinning spacecraft whose orbit precesses its lines of sight over the whole celestial sphere.

To obtain their sets of relative positions, HIPPARCOS used, and GAIA will use, two lines of sight at a rigidly fixed angle (basic angle) perpendicular to the spacecraft spin axis. This allows an instantaneous measurement of the differential positions between all the sources (stars, galaxies, quasars, asteroids, planets...) in the two fields. A little later the spacecraft has rotated slightly, leaving some sources behind, and adding new sources for additional relative position measurements. As the spacecraft spins (GAIA will have a spin period of about 3 hours) the scanning path on the sky of the two lines of sight will allow measurement over one complete spin period of relative positions for all objects around the great circle. An observation proceeds by clocking the focal plane CCD detector in TDI mode at the spacecraft spin rate, integrating charge during the transit time of an image across the focal plane. As a star falls off the trailing edge of the focal plane, the area containing its integrated image is readout, the time noted, and both transmitted to ground for later centroiding and analysis.

Precession moves the scanned circle around the sky, allowing whole sky coverage. Repeating this some 100 times over five years gives one sufficient information to derive not only the positions of everything observed relative to everything else observed, but also a sufficiently long time baseline that one may additionally determine the transverse

(proper) motions of everything relative to everything else, as well as the apparent motion of relatively nearby sources due to the annual motion of the Earth around the Sun, or parallax, which directly provides the stellar distances. Solving this very large data set for all these parameters is a well-defined though not straightforward task. It is then necessary to set zero points relative to non-moving objects: in the case of a satellite with high accuracy, the only known objects which define a suitable (Machian) reference frame are those at cosmological distances, among which quasars are the ideal. GAIA will use more than 10^5 quasars to define its reference system.

4.2. OPTICAL DESIGN and FOCAL PLANE

The primary design constraint for GAIA is that it be able to be launched in an Ariane5 shroud. This provides an upper limit on the optical baseline of any monolithic payload of about 2.5m. Given launch costs, restriction to a shared launch with a second independant payload is highly desirable, which provides a size and mass limit.

Both Fizeau and monolithic payloads are under evaluation for GAIA. At the time of writing consideration of the monolithic payload is more advanced, so it is that option which is summarised here. Analysis of the Fizeau interferometer system made clear that precise (nm) mechanical control is most easily provided by combining the separate apertures onto a single monolithic mirror, and freeing that mirror from mechanical and thermal disturbances. It is a relatively small step from there to use of the full, albeit very rectangular, primary mirror. An extra advantage of such a strategy is to minimise the number of independently controlled sub-systems, regardless of their required accuracy, significantly assisting system simplicity and reliability.

The current GAIA design, illustrated in the exploded view above, has three telescopes, each a three-mirror system, mounted around a carrying strut. Two telescopes are identical, and provide the two optical systems necessary to allow global astrometry. The third is fitted with a slitless spectrograph, and provides the spectra for radial velocity and chemical element abundance determination.

The two astrometric telescopes have a primary mirror of 1.7 by 0.7m, with the spectroscopic telescope being somewhat smaller. The entire structure is SiC, to maximise rigidity and thermal uniformity while minimising weight.

The astrometric telescopes are currently assumed to have a focal length near 50m, allowing use of high efficiency currently available CCDs as detectors. The focal planes cover somewhat more than 0.5sq deg with acceptable image quality, requiring some 250 independent CCDs for each astrometric telescope. The outer parts of the focal plane provide sufficient image quality for on-board image detection. This is a particularly important advantage over HIPPARCOS, where pre-launch selection of targets was necessary. As emphasisied in the scientific case above, pre-selection of targets significantly restricts the scientific potential of the mission. In fact, on present performance expectations, the single factor limiting the number of sources which can be measured by GAIA is the telemetry rate in providing useful data to ground.

The radial velocity telescope is similarly a three-mirror system, differing from the primary astrometric systems only in shorter focal length, and in addition of a slitless spectroscopy capability. Spectra are integrated during a focal-plane transit, readout, and transmitted down for radial velocity and chemical element abundance analysis.

4.3. ORBIT and OPERATIONS

An obvious advantage for any precise system is location in a benign environment, though such environments invariably possess some disadvantages. For GAIA the benign environment involves location at the outer Lagrangian point L2, some 1.5million km from Earth, in a maximally stable thermal environment. The cost is reduced telecommunications capability, and possibly increased on-board motor requirements. This latter requirement, for an on-board 400N capability to reach L2 after launch into geostationary orbit and release, may become unnecessary, if the expected restart mode of Ariane 5 is implemented. Direct injection of GAIA into L2 by the Ariane5 launch system would then be feasible. The telecommunications restriction remains the most significant negative however, given that only one ground station is likely to be affordable for the mission.

Nonetheless, the current orbit is expected to be a halo orbit, of fairly high amplitude, around L2. This orbit avoids any eclipses during the whole mission, and maximises the uniformity of illumination of the spacecraft shielding by the Sun, Earth and Moon, thereby minimising variable thermal gradients on the payload. The orbit also retains maximum efficiency for illumination of the solar arrays, and naturally provides an efficient scanning pattern around the sky. Since this requires the spacecraft to be spinning around its line of sight towards the ground station, efficient communications requires a set of phased-array antennae distributed around the service module.

Even the most benign location will still mean that the spacecraft requires occasional orbital correction, due to such factors as solar wind variations. Since sudden accelerations are very disadvantageous for astrometry, the expected means of spacecraft control will involve Field Emission Electric Propulsion, FEEP. This system delivers thrust (a few mN) through acceleration of cesium atoms. It provides very smooth accelerations over a mission lifetime with extremely low-mass requirements. FEEP thrusters are being space qualified late in 1998, and are expected to be available, and suitable, for GAIA.

5. CONCLUSION

GAIA is a proposed global astrometric mission which builds on the success of space astrometry demonstrated by HIPPARCOS. The substantial gains in accuracy, sensitivity, and sample size now available, relative to HIPPARCOS, allow extension of our scientific horizons to one of the great intellectual challenges: understanding the origin and evolution of our own galaxy, the Milky Way. In addition GAIA will determine the distribution function of planetary systems, by identifying and surveying the complete sample of the 300,000 nearest stars, and significantly improve tests of standard general relativity. The technological challenges in implementing the GAIA promise are considerable, but achievable.

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