THE SCIENTIFIC GOALS OF THE GAIA MISSION

M.A.C. Perryman[1], **L. Lindegren**[2], **C. Turon**[3]
[1]Astrophysics Division, ESTEC, 2200AG Noordwijk, The Netherlands
[2]Lund Observatory, Box 43, S-22100 Lund, Sweden
[3]Observatoire de Paris-Meudon, 92195 Meudon Cedex, France

ABSTRACT

The ESA candidate cornerstone mission GAIA is presently estimated to lead to positions, proper motions, and parallaxes of at least 40–50 million objects, down to about $V = 15$ mag, with an accuracy of better than 10 microarcsec (and possibly some 350 million objects to 18 mag with degraded accuracy), along with multi-colour multi-epoch photometry of each object. Consequently, distances and kinematical motions for tens of millions of objects, throughout our Galaxy, would be obtained—the expected accuracy is such that direct (trigonometric) distance estimates would be accurate to 10 per cent at 10 kpc, with transverse motions accurate to about 1 km s^{-1} at 20 kpc. The mission would address directly questions such as the cosmic distance scale, and the formation and structure of the Galaxy (disk/halo/bulge populations and kinematics, and the dark matter content). By-products would be unprecedented information on the space-time metric (γ to a precision of about 1 part in 10^6 or better); angular diameters of hundreds of stars; a vast body of information on double and multiple systems; extensive variability information on each object; and the most powerful and systematic method of detecting possible planetary companions proposed to date.

Key words: GAIA; space astrometry.

1. INTRODUCTION

Astrometric measurements provide model independent estimates of basic geometrical and kinematical properties of astronomical sources. Traditionally the most important applications are the determination of stellar distances, motions and masses. GAIA will provide an immense quantity of extremely accurate astrometric and photometric data from which ultimately all branches of astrophysics will benefit. In the areas of the physics and evolution of individual stars and of the Galaxy as a whole the impact will be immediate and profound. On a much more modest scale this process will begin already with the availability of the Hipparcos results. However, while Hipparcos could probe less than 0.1 per cent of the volume of the Galaxy by direct distance measurements, GAIA will encompass a large fraction of the Milky Way system within its parallax horizon, including much of the halo, and even touching on the nearest companion galaxies such as the Magellanic Clouds (Figure 1).

Another goal of astrometry is the establishment of an accurate set of reference directions for dynamical interpretation of the motions of the Earth and other planets and of the Milky Way system, i.e., an optical reference system. The importance of having access to a dense and accurate inertial reference frame is easily overlooked in comparison with the more direct benefits of, say, parallaxes. However, the ability to establish small systematic deviations in the patterns of motions, whether it concerns the search for transneptunian planets or dark matter in our Galaxy, crucially depends on the accuracy of the reference system. Through its global survey nature, GAIA is ideally suited to provide an extremely dense and accurate reference system. The limiting magnitude is sufficiently faint to allow a direct link with the extragalactic system by observation of quasars.

A 5-year mission is baselined, not only because of its resulting improvement in the achievable astrometric accuracy, but also because of the importance of such a temporal baseline for the dynamical studies of asteroids, for the determination of the parameters (including orbital motion) of double and multiple stars, for the detection of possible planetary and brown dwarf companions, and for the photometric variability studies.

In the following scientific survey, emphasis is given to topics where the estimated astrometric accuracies lead to clearly identifiable applications. In addition to these, the multi-colour, multi-epoch, submillimagnitude photoelectric photometry will open up vast areas for studies related to stellar stability over the entire Hertzsprung-Russell diagram. We have concentrated on scientific applications requiring an accuracy of the order of 20 μas or 20 μas/yr and a limiting magnitude around $V = 15$–16 mag (see Table 1), although GAIA may actually achieve even higher accuracy for brighter stars, and is expected to reach fainter magnitudes at a reduced accuracy. The single factor which could preclude an astrometric census of the billions of stars to $V = 20 - 21$ mag may be simply the satellite telemetry rate.

Table 1. Comparison between the Hipparcos and GAIA scientific capabilities.

	HIPPARCOS	GAIA
Limiting mag (V)	~12	>15-16...20
Completeness (V)	7.3–9.0	>15-16...20
Number of objects	120 000	35 000 000 (V=15) 300 000 000 (V=18)
Accuracy	1–2 mas	5–20 μas

2. PHYSICS AND EVOLUTION OF STARS

Stellar luminosities and ages: Luminosity estimates are based exclusively on determinations of stellar distances, themselves determined directly only from measurements of trigonometric parallaxes. With Hipparcos, direct distance measurements are limited to 100 pc with, say, 10 per cent precision, a distance horizon insufficient to include rare but astrophysically important categories of stars such as O stars, Cepheids, and RR Lyrae variables. From ground-based observations, distance determinations and luminosity calibrations have been restricted to the main sequence, with indirect distance estimates, for example based on statistical calibrations, used to estimate stellar distances and luminosities for rarer spectral types. Parallaxes with a precision of 20 μas would reach to 5 kpc with 10 per cent accuracy, or to 10 kpc with 20 per cent accuracy. For the first time this would provide an extensive network of distance measurements throughout a significant fraction of our Galaxy, including the Galactic centre, spiral arms, the halo, and the bulge. More rigorous age estimates would follow from evolutionary models.

Massive stars: Although only a small fraction of stars in the Galaxy are more massive than $20M_\odot$, such stars, which spend most of their short lives as H-burning O-type stars, play an important role in Galactic structure and evolution. Thus, accurate knowledge of the luminosity of these stars is important for comparing masses derived from stellar evolutionary models with those derived from stellar atmosphere models, for determining initial mass functions, and for studying stellar evolution in the high luminosity/high mass region of the Hertzsprung-Russell diagram. The absolute magnitudes of O stars are presently poorly determined (no O star is sufficiently close to the Sun to have a trigonometric parallax accurately measured), the absolute visual magnitudes coming primarily from O stars in clusters and OB associations whose distances are themselves uncertain, but are typically around 1–2 kpc. Typical apparent magnitudes are $V = 4$–6 mag.

Novae and nova-like variables: Distance determinations to novae are required to interpret the energetics of the outburst, and to place these objects more securely within the context of evolutionary models. Distance estimates can be made through modelling of the shell expansion velocity, but such applications are restricted to particular periods after outburst, and also suffer from modelling uncertainties. Most Galactic novae are brighter than $V = 12$ mag at maximum, although measurements to $V = 16$ mag or fainter would also allow the determination of distances to Galactic novae observed over the last few decades. Related objects, such as dwarf novae, AM Her stars, symbiotic stars, and cataclysmic binaries could be studied, providing accurate luminosities needed to distinguish among alternate possible energy generation mechanisms. Many such nova-like variables would lie within the distance horizon and the magnitude limit (say, brighter than $V = 16$ mag) necessary to provide distances to better than 5 per cent.

Planetary nebulae: Planetary nebulae appear to present a very narrow mass range for the remnant star, and thus provide the possibility of being good distance indicators. However, because of their rarity, and therefore their typical distances, and their nebulosity, no satisfactory method yet exists for the their distance estimation. Parallax measurements of the central stars would lead to significant advance in the understanding of the formation and evolution of the shells, the status of the central stars, and the role of these objects as standard candles. Many tens of planetary nebulae would be measurable down to $V = 16$ mag.

Cepheids and RR Lyrae stars: In addition to the importance of these stars to models of stellar structure and evolution, Cepheids and RR Lyrae form the cornerstone of the extragalactic distance scale. Some 55 Cepheids and 26 RR Lyrae stars are known to lie within about 1000 pc, and are already contained with the Hipparcos observing programme, but most of these lie beyond about 300–400 pc. Parallaxes at the 20 μas level would yield distance estimates to better than 2 per cent for these objects. In turn, the details of the period-luminosity-colour relationship for these objects would be significantly improved.

Stars in Open Clusters: Only two open clusters (Hyades and Coma Ber) lie within the 100 pc distance horizon yielding distances from Hipparcos (from individual objects within the clusters) to better than 10 per cent accuracy. Cluster studies are important for numerous reasons, mostly related to the fact that they represent a co-eval population of stars with well-defined initial chemical compositions. They can thus be used to follow the development of the formation of our Galaxy, and as a testbed for theories of stellar evolution. For example, they are amenable to studies of their dynamical behaviour, for the calibration of stellar luminosities and distances via properties such as the Wilson-Bappu effect and the mass-luminosity relation for binary stars, and for the calibration of the main sequence as a function of age, helium content, and metallicity. Some 30 open clusters are considered to lie within about 500 pc, sufficient to provide individual distances to 1 per cent accuracy with parallaxes measured at the 20 μas level.

Globular clusters: Little or no information will be provided by Hipparcos on the internal dynamics, and luminosity calibration, of stars within globular clusters, due to the faint magnitude and high central density of stars in these clusters. However, Hipparcos will provide a reference system with respect to which proper motions of cluster stars can be derived from ground-based observations acquired over long periods of time. Ages of globular clusters have indicated a possible discrepancy with the age of the Universe derived from present estimates of H_0 and Ω. Many observational effects and theoretical complications make interpretation of globular clusters properties far from straightforward; but cluster age determinations essentially require absolute magnitude calibrations of the main-sequence and, in particular, the turn-off point as a function of chemical composition. For absolute ages to be accurate to a billion years, essential for a resolution of the age conflict, the distance of the cluster must be determined with an accuracy of better than 3 per cent. An observing programme reaching 15 mag and 20 μas accuracy on the parallaxes would include 20 or more globular clusters (such as 47 Tuc, ω Cen, M3, M5, and M15) lying between 5 and 10 kpc, and would yield *individual* distances accurate to better than 10–20 per cent. Some 10 or more of the brightest stars per cluster would be observable, resulting in mean cluster distances at least a factor of three better than these individual accuracies.

Metal-poor stars and primordial nucleosynthesis: Recent determinations of boron abundances in the metal-poor star HD 140283 have raised important questions about the origin of this element: whether it originates from a high cosmic ray flux at the birth of the Galaxy, or primordial nucleosynthesis. If the former possibility is ruled out, it would seem to indicate that the standard Big Bang model is wrong, and that newer inhomogeneous models would be required. Cosmic ray spallation, in contrast, makes a specific prediction of the B/Be ratio, although the Be abundances turn out to be very sensitive to whether the star is a subgiant or a dwarf! A clear parallax determination (ground-based parallaxes are generally quite inadequate) would clarify this question. While the specific instance of HD 140283 should be resolved by the Hipparcos measurements, this example illustrates the importance of individual parallax determinations for astrophysical studies.

3. DYNAMICS OF STELLAR SYSTEMS

Visual and astrometric binaries: GAIA will be able to resolve binaries with an apparent separation exceeding 1–2 mas and a moderate magnitude difference. The astrometric and photometric characteristics of the components can be measured. For numerous systems with periods of a few years the absolute orbits can be determined and hence the individual component masses. Closer binaries, and systems with a faint companion, can in many cases still be detected from the non-linear motion of the photocentre. At the sensitivity level of GAIA some 25 per cent of all stars may turn out to be non-single. This vast material on stellar duplicity will be essential for a correct interpretation of the astrometric and photometric parameters, as well as providing important constraints on theories of stellar formation.

Interacting binary systems: A rich variety of astrophysical problems related to interacting binary systems would become accessible with parallaxes in the 10–20 μas range. The evolutionary history of interacting binary systems, and the origin of Type I supernovae, millisecond pulsars, low mass X-ray binaries, and globular cluster X-ray sources is intimately bound up with the behavior of compact binaries with mass transfer and loss. Accurate knowledge of the stellar masses and orbital separation can be derived from astrometric measurements (yielding the orbital separation and the orbital inclination) combined with estimates of the mass function determined by radial velocity measurements. Many specific questions about accretion rates, precursors, mass distributions, and kinematic behaviour could be addressed with these data, including studies of the black hole candidates. Galactic black hole candidates have bright secondaries (9 mag in the case of Cyg X-1, and 12 mag or fainter in the case of V404 Cyg) and wide orbits (with orbital periods of about 6 days), which should yield definitive black hole masses by determining orbital separation and inclination.

Be Star X-ray Binaries: Be star X-ray binaries are believed to consist of a recently formed neutron star and a Be star companion. The orbit has not yet circularized, and the eccentric motion produces periodic eruptions at periastron as the compact star passes through the mass outflow from the Be star. Measurement of the orbital parameters would yield information on the anisotropy of the supernova mass ejection. It is important to relate this to the kinematics of isolated pulsars, and to the physics of the explosion.

Dynamics of open clusters: The insight into the structure and dynamics of the Hyades provided by the Hipparcos results (Perryman et al. 1997, Brown et al. 1997), demonstrates dramatically the effect that GAIA astrometry would have on our understanding of open clusters (Platais et al. 1995). The two clusters within 100 pc accessible to individually significant parallaxes with Hipparcos would swell to some 30 clusters within 500 pc for which individual parallax accuracies would reach 1 per cent or better, at least a factor of five better than that achieved on the Hyades with Hipparcos. Details of mass segregation, the occurrence of binaries and the match to n-body simulations, cluster evaporation, evidence for tidal distortion and signatures for encounters with giant molecular clouds, and measurements of their internal velocity dispersion (and any indications of missing mass) could all be studied for these objects.

Dynamics of globular clusters: Accurate proper motions of stars within globular clusters are required to yield information on the cluster's internal velocity dispersion, and thus constrain dynamical models of their formation and evolution. Within 47 Tuc, for example, proper motions of 20 μas/yr correspond to transverse velocities of 0.4 km/sec. In addition, spectroscopic binaries have been detected in globular clusters with amplitudes of tens of km/sec and periods of years, corresponding to separations of order 1 mas. Parallaxes and annual proper motions at the level of 50 μas or better would provide distances and orbital data necessary to clarify the formation and evolution of these binary systems, and their role in the formation of the milli-second pulsars now known to exist in the cores of globular clusters (Tucholke & Brosche 1995).

4. UNDERSTANDING OUR GALAXY

Galactic dynamics: The huge number, impressive accuracy, and faint limiting magnitude of the GAIA mission would totally revolutionise the dynamical studies of our Galaxy, which are now perceived as being capable of providing considerable advances in our

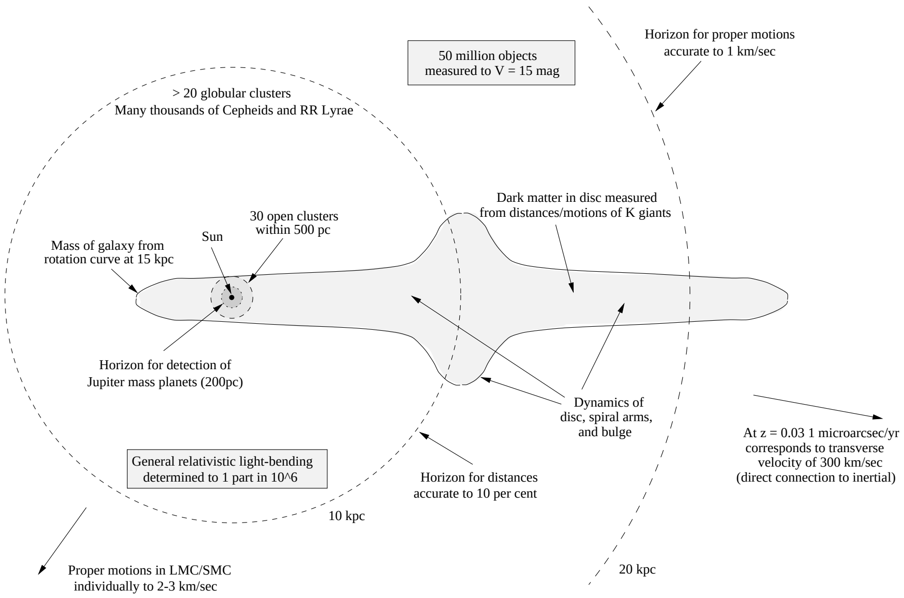

Figure 1. Schematic illustration of the scientific targets accessible to GAIA.

understanding of the structure and motions within the spiral arms, the disc and the outer halo. It is still unclear, for example, whether spiral arms are density wave enhancements in the background stellar distribution, or whether they are regions of enhanced star formation. If a density enhancement exists, it will affect the stellar motions in a characteristic way, and this could be tested on the relatively nearby Perseus arm (about 2 kpc distant). Stellar motions would be determined for stars near the arm, both foreground and background (distinguished by their parallaxes), with proper motion accuracy requirements of some 100 μas/yr, corresponding to about 1 km/sec in space velocity.

Formation of the Galaxy: The stellar distributions in the Galaxy, in terms of spatial and kinematic coordinates, are linked through gravitational potential gradients, and through the history of star formation as a function of position. The initial conditions are then later modified, perhaps substantially, by small and large scale dynamical processes: these include instabilities which can transport angular momentum (bars, warps...), and mergers. The questions related to understanding our Galaxy typically require access to very large data sets, and are thus ideally tackled by GAIA. Gilmore & Høg (1995) and Gilmore & Perryman (1997) have presented details of the following investigations in more detail, and have tabulated the requirements on accuracy and limiting magnitude for a variety of 'tracers' for the associated studies. Typically, they find that accuracies of tens of microarcsec, for large numbers of stars in the range $V = 15 - 18$ mag, are required.

The Galactic bulge: Is the bulge a remnant of a disk instability? Is it a successor or a precursor to the stellar halo? Is it a merger remnant? The bulge stars are predominantly at least 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? The analysis here is confused by the superposition of much foreground structure, by extreme reddening, by the presence of the central parts of the disk and the halo, by what may well be an unrelated dense central stellar cluster, and by the presence of continuing star formation, whose population provenance remains problematic. Given this complexity, clearly very considerable data sets, mapping as much of phase space as is possible, are required. One must determine distribution functions over age, metallicity, element ratios, location, angular momentum, and orbital characteristics. In fact, ideally, what is demanded is a large astrometric survey (including radial velocities), complemented by detailed chemical abundance studies of a suitable representative sub-sample.

The Galactic halo: At higher Galactic latitudes one may study particularly the disk gravitational potential, and hence the distribution of matter in the Galaxy, the kinematics of the old disk and thick disk, and of the halo. Photographic surveys have led the way here, although the data remain confusing and contradictory. It is not possible as yet to know robustly just what are the kinematic and spatial distribution functions of the various populations.

Galactic mergers: Big galaxies are believed to get that way by growing. But do they merge with gas, or with stellar systems? In what proportion? A stellar system merged late will leave a low-contrast stream in phase space, detectable from a suitably precise and suitably large volume map of phase space.

Dark matter within the disk: Two recent programs have attempted to determine the surface density of the Galactic disk in the solar neighborhood. One, led by Bahcall, finds evidence for dark matter in the disk, while the other (Gilmore & Kuijken) finds none. The issue is important because of the implications on the nature of dark matter—whether, if it exists, it admits matter in a baryonic or non-baryonic form. One source of uncertainty in the Bahcall result, based on the distribution of K giants perpendicular to the Galactic disk, is the error in the distances to individual stars. These are relatively bright objects (apparent magnitudes 10 and brighter); their distance scale could be recalibrated and substantially improved by direct parallax measurements of K giants with a range of metallicities. Parallaxes at the level of 50 μas would be required.

Dark matter within the halo: In the halo, however, the potential is purely dark-matter dominated. Is the dark matter flattened, or triaxial? These questions are direct tests of galaxy formation models, and the nature of the dark matter.

The mass of our Galaxy: The form of the rotation curve beyond the Sun is very sensitive to the existence and amount of dark matter near to it. No very reliable determination of the rotation curve has yet been derived. In an extension of the programmes being undertaken with the Hipparcos data, measurements of the distances and motions of disk stars are required at a range of Galactic longitudes, resulting in the rotation curve at distances out to 15 kpc determined from stars with $V < 12$ mag. Parallaxes at the level of 20 μas for an accuracy of 20 per cent in individual distances, and annual proper motions of about 200 μas/yr (or 10 km/sec), would be required.

5. DETECTION OF PLANETARY SYSTEMS AND BROWN DWARFS

The Hipparcos mission, due to its limited astrometric accuracy and mission duration, is unlikely to make any serious contribution to the possible detection of sub-solar mass planetary companions around nearby stars. The essential idea underlying the astrometric detection of low-mass companions is to detect the resulting non-linear photocentric motions in the paths of nearby stars.

The probable size of the effect can be judged by considering the path of the Sun as seen from a distance of (say) 10 pc. The perturbation caused by Jupiter has an amplitude of 500 μas and a period of 5 years, while the effect of the Earth is a one-year period with 0.3 μas amplitude. With a mission length of 5 years and a target mission accuracy of 20 μas, GAIA should be able to provide annual normal points with an accuracy of 50 μas. This is sufficient to detect Jupiter-mass planets (at the 3σ level) out to 30 pc.

This volume includes several thousand potential target stars, *all* of which can be monitored for possible companions. If the accuracy is instead 2 μas, which may be feasible for bright stars ($V < 10$ mag), then the detection horizon for Jupiter-mass planets is pushed beyond 100 pc and includes some 10^5 candidate stars. Screening all 50 million stars down to the survey limit of $V = 15$–16 mag for possible signatures of planetary and brown dwarf companions will provide a complete census of such bodies to well-defined detection limits. Further details are given by Lattanzi et al. (1997)

6. EXTRAGALACTIC ASTROPHYSICS AND GENERAL RELATIVITY

Distance and age scale of the Universe: these parameters are derived and constrained through the stellar distances described previously.

Proper motions of the Magellanic Clouds: Different explanations for the dynamical behaviour of the LMC/SMC, in particular whether these systems are gravitationally bound to our own Galaxy, implies systematic proper motions of below around 1 mas/yr, very much at the limit of the Hipparcos capabilities. Large numbers of stars measured in the LMC/SMC at the level of 50 μas or better, would clarify their dynamical relationship with our own Galaxy.

Galaxies and active galactic nuclei: Further out, the nuclei of active galaxies are sufficiently pointlike that their absolute proper motions may be measurable. At a redshift of 0.03, a transverse velocity of 1000 km/sec corresponds to a proper motion of 3 μas/yr. Thus, transverse velocities of nearby galactic nuclei due, e.g., to galaxy cluster potentials, might be detectable. For more nearby galaxies, studies will be needed to identify whether supernovae events, and gamma-ray burst events (cf. GRB 970228) might affect the astrometrically measured photocentre in a significant manner.

The role of quasars: Future astrometric missions, at levels of accuracy very much better than 1 μas, could determine the transverse motions of external galaxies and quasars routinely, and determine their kinematic properties independently of a dynamical model of the Universe. In the meantime, an astrometric programme reaching 15–16 mag would include a number of quasars, and this in turn would allow a direct tie between the resulting reference system and an inertial reference frame, something which has not been possible (directly) in the case of Hipparcos. The considerable importance of this possibility is that the resulting proper motions of all the stars within the global observing programme would not be subject to arbitrary offsets in their proper motions.

Light-bending by the Sun: The reduction of the Hipparcos data has necessitated the inclusion of stellar aberration up to terms in $(v/c)^2$, and the general relativistic treatment of light bending due to the gravitational field of the Sun (and Earth). Light bending by the Sun amounts to 4 mas even at 90° (i.e., for light arriving perpendicular to the ecliptic). The astrometric residuals may be tested for any discrepancies with the prescriptions of general relativity; in principle this provides a constraint on the post-Newtonian light-bending term, γ, equal to unity in general relativity. Figure 2 illustrates the determination of γ derived from final Hipparcos data in the context of previous determination by other means. The GAIA measurements would provide a precision of about 1 part in 10^6 or better in the determination of γ due to the Sun. Interestingly, this is close to the values predicted by those present theories which predict that the Universe started with a strong scalar component, and which is relaxing to the general relativistic value with time (e.g. Damour & Nordtvedt 1993). The importance of such theories is that they provide a possible route to the quantisation of gravity. For this reason, space experiments dedicated to

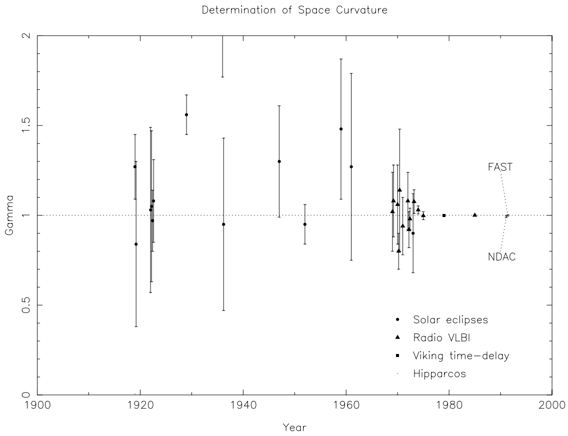

Figure 2. Determinations of the post-Newtonian parameter γ, representing the deviation of the gravitational light-bending from Newtonian theory. According to general relativity, $\gamma = 1$. The figure illustrates the values of γ derived by the NDAC and FAST consortia in the Hipparcos sphere solution process (ESA 1997). Other determinations (from Soffel, 1989) based on solar eclipse observations, VLBI observations and the Viking spacecraft (Shapiro) time-delay, are also illustrated. The Hipparcos results are derived from observations at large solar angles, while all other metric determinations have been based on observations within a few $R_\odot$ of the solar limb.

the measurement of γ with a precision of about 1 part in 10^6 have been proposed. GAIA would provide this precision as a by-product of its astrometric and photometric campaign.

Light-bending by the Earth, etc: Light deflection has also 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 (Dar 1992). Light-bending by the Earth is at the level of $\sim 40\mu$as, and GAIA could therefore extend the domain of observations by two orders of magnitude in length-scale, and six orders of magnitude in mass. (The Pound-Rebka experiment verified the general relativistic prediction of a gravitational redshift for photons, an effect probing the time-time component of the metric tensor, while light deflection depends on both the time-space and space-space components). Light bending at the Jovian limb is predicted to amount to 17 mas.

Higher-order gravitational effects: At the level of accuracy expected from GAIA, even more subtle effects will start to become apparent, such as the quadrupole components of the gravitational fields of the Sun and the planets, and the 'frame-dragging' effects of their motions and rotations (see, e.g., Soffel 1989).

Gravitational lensing and gravitational waves: Light modulation effects due to gravitational lensing by MACHOs (Alcock et al. 1993; Aubourg et al. 1993, Høg et al. 1995), and the possible metric perturbations due to gravitational waves (Fakir 1994, 1995), must also be considered.

ACKNOWLEDGMENTS

In compiling the survey of scientific capabilities of a microarcsec class astrometric mission we have drawn heavily from existing material describing the rich scientific capabilities of such an improvement in astrometric accuracy. In particular, we acknowledge the use of ideas and in some cases specific examples from Kovalevsky & Turon (1991), from the report of the ESA Interferometry Review Panel under the chairmanship of Dr. C. Dainty, and from the NASA report on the capabilities of an Astrometric Interferometry Mission, prepared by the Space Interferometry Science Working Group under the chairmanship of Dr. S. Ridgway. Many of these ideas were subsequently included in the original scientific case for GAIA (Lindegren & Perryman 1996, Perryman & Lindegren 1995), while the substantial contributions expected to be made with the availability of astrometric data of very large numbers of stars at $V = 15 - 18$ mag has drawn on the arguments presented by Gilmore & Høg (1995).

REFERENCES

Alcock, C. et al., 1993, Nature, 365, 621

Aubourg, E. et al., 1993, Nature, 365, 623

Brown, A.G.A. et al., 1997, ESA SP–402, this volume

Damour, T., Nordtvedt, K., 1993, Phys. Rev. Letters, 70(15), 2217

Dar, A., 1992, Nuc. Phys. B (suppl.), 28A, 321

ESA, 1997, The Hipparcos and Tycho Catalogues, SP–1200

Fakir, R., 1994, ApJ, 426, 74

Fakir, R., 1995, ESA SP–379, 113

Gilmore, G., Høg, E., 1995, ESA SP–379, 95

Gilmore, G., Perryman, M.A.C., 1997, PASP, Minnesota, in press

Høg, E., Novikov, I.D., Polnarev, A.G., 1995, A&A, 294, 287

Kovalevsky, J., Turon, C., 1991, Adv. Space Res., 11, (2)5

Lattanzi, M.G., Spagna, A., Sozzetti, A., 1997, ESA SP–402, this volume

Lindegren, L., Perryman, M.A.C., 1996, A&SS, 116, 579

Perryman, M.A.C., Lindegren, L., 1995, ESA SP–379, 35

Perryman, M.A.C., et al., 1997, A&A, in press

Platais, I., van Leeuwen, F., Mermilliod, J.-C., 1995, ESA SP–379, 71

Soffel, M., 1989, *Relativity in Astrometry*, Spinger-Verlag

Tucholke, H.-J., Brosche, P., 1995, ESA SP–379, 77