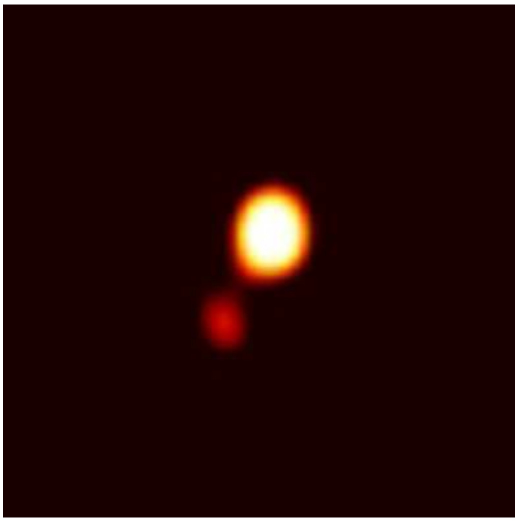


A brown dwarf orbiting its stellar companion, a faint main-sequence star. The image was obtained by adaptive-optics imaging on the Gemini North Telescope. The separation between the two components is of the order of 3 AU, which is a typical distance for this kind of system. Image courtesy Gemini Observatory/Melanie Freed, Laird Close, Nick Siegler University of Arizona/ Hokupa'a-QUIRC image, University of Hawaii, IfA.

Gaia: Brown-Dwarf Binaries

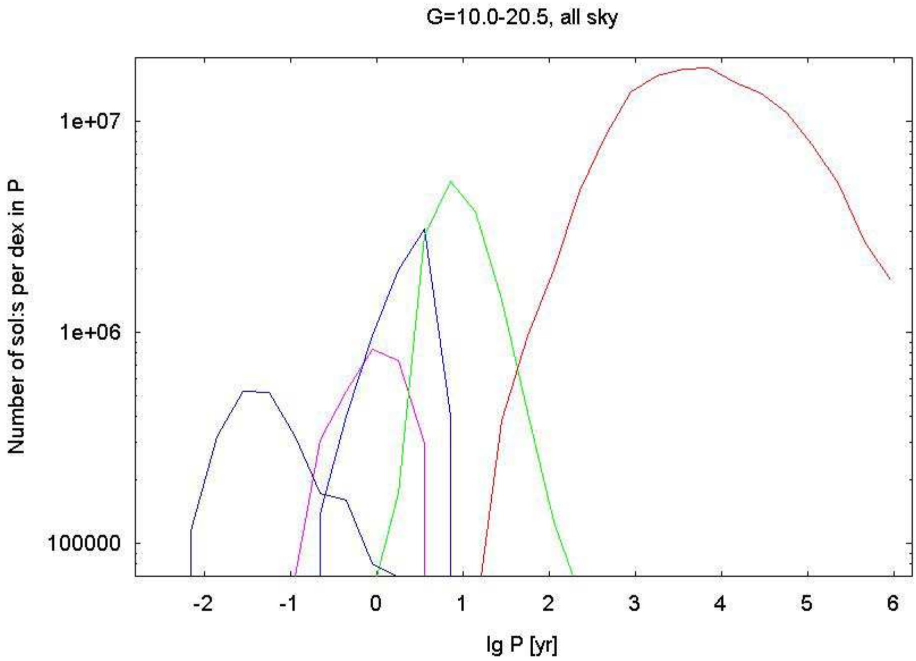
Although brown dwarfs are at least as numerous as stars, our knowledge of their intrinsic physical properties, of their formation processes, and of the characteristics of the brown-dwarf population as a whole is comparatively poor. This situation is mainly due to the fact that brown-dwarf astronomy is a relatively new branch of science: the first brown dwarf ever was observed as recently as 1995 and the first dynamical brown-dwarf mass was only measured in the year 2000.

The main reason that so little is known about these objects is their low luminosity, which renders even nearby specimens faint. Another reason is the degeneracy between the effects of age and mass on observed brown-dwarf colours and magnitudes. In this respect, brown dwarfs in binaries provide critical information, because of the possibility of measuring dynamical masses. However, brown dwarfs in binaries can also help to answer more general questions such as *What is the origin of free-floating brown dwarfs? Is the formation process of brown dwarfs in binaries related to the formation of binary brown dwarfs? How do the binary-distribution characteristics (mass ratio, separation, etc.) of brown dwarfs differ from their stellar counterparts?*

A puzzling discovery is that, while planets are now routinely observed orbiting F-, G-, and K-dwarfs, few of these types of stars have brown-dwarf companions. Most of the brown dwarfs in binaries are found orbiting late-M-type stars, but while the distribution of separations peaks around 30 AU in FGK-type binaries, few brown dwarfs are detected at separations larger than 15 AU in low-mass systems. The origin of these differences is not known.

From present-day knowledge, it is estimated that about $\sim$15% of low-mass stars in the solar neighbourhood have brown-dwarf companions. There also seem to be numerous systems in which both components are brown dwarfs. With estimates of the M-star population representing about 50 million stars in the Gaia Catalogue, the present-day knowledge suggests that Gaia will observe several million systems in which one component is a *bona fide* brown dwarf. Among these, Gaia will detect a sizeable fraction of separated components. At distances less than 50 pc, and assuming the presently known distribution of separations, $\sim$6000 systems could be detected as separated components.

Although the long periods and faint magnitudes of brown dwarfs will not permit Gaia to measure viable orbits for many systems, the Gaia data will represent an unprecedented pool of measurements for follow-up observations and accurate mass determinations. Together with accurate parallaxes (better than 1% relative accuracy at distances $<$50 pc), Gaia will allow the above-mentioned questions to be addressed in detail.



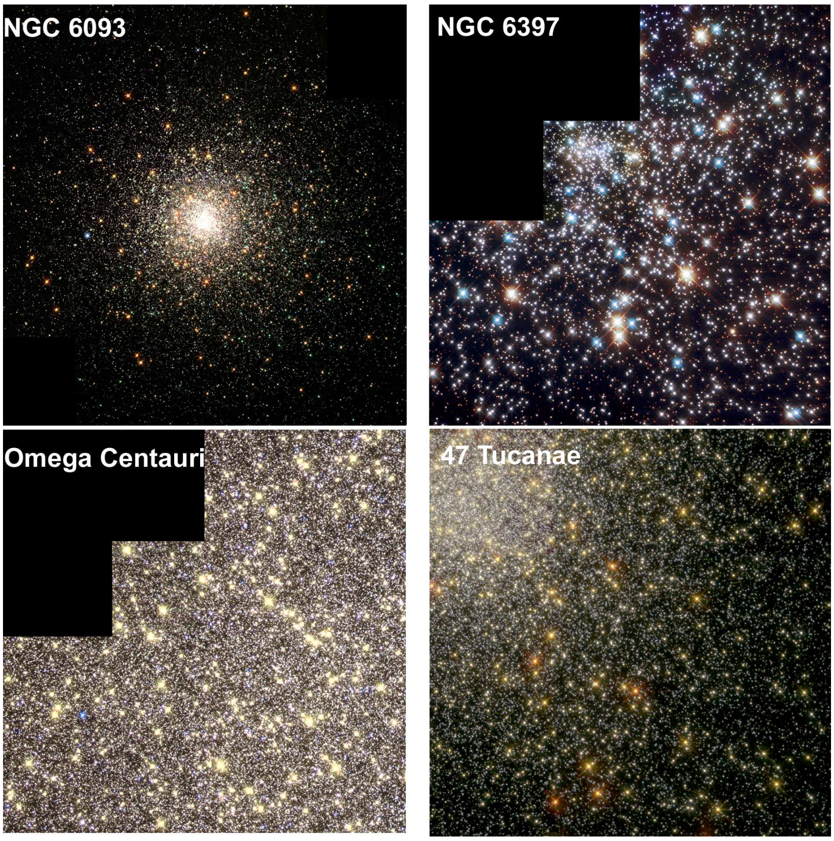
Estimated numbers of binary solutions from Gaia as a function of period. From left to right: $\sim 7{\times}10^5$ radial-velocity orbits, $8{\times}10^5$ radial-velocity-plus-astrometry orbits, $2{\times}10^6$ astrometry orbits, $4{\times}10^6$ non-linear proper-motion systems, and $4{\times}10^7$ resolved binaries. Gaia will also provide solutions for millions of eclipsing binaries with periods below 10^{-2} yr.

One of Gaia's unique features is the well-defined sampling and subsequent observations of tens of millions of binaries over the entire sky. Even though by the time Gaia will be operational, large ground-based telescopes and interferometers may have resolutions and light-collecting areas exceeding those of Gaia, thus enabling detailed studies of individual binaries and multiples, relatively few objects will have been observed with such instruments. Moreover, the observed targets will have been selected basically at random and thus do not form a complete sample in any sense.

As a result of its aperture size, Gaia will resolve all binaries with separations above some 20 mas which have moderate magnitude differences between the components. Many such systems exist and these will form the bulk of the 'Gaia Binary Catalogue'. Since distances of Gaia binaries will tipically exceed a kilo-parsec, orbital periods of most of them will be too long for orbit determination. Nevertheless, direct observational data in the form of the distributions of separations and magnitude differences will already provide a unique handle on the basic $f(a)$ (semi-major axes) and $f(q)$ (mass ratio) distributions.

One of Gaia's strengths is its extreme sensitivity to non-linear (proper) motions. Large fractions of the astrometric binaries with periods in the range 0.03 – 30 yr will be recognised immediately, If the period of such systems is below 7 – 8 yr, it will be possible to determine a photocentre orbit. At the bright end (up to 15-th magnitude), radial-velocity observations will define large numbers of shorter-period binaries. At the shortest periods, Gaia will (photometrically) observe millions of eclipsing binaries, mostly too faint for radial-velocity observations. In summary, Gaia will observe binaries with periods between hours and millions of years, but the actual 'detection-efficiency' will be a complex function of period, distance, and absolute magnitude.

The figure above shows results from detailed simulations. The five curves give the expected total number of binary-star solutions from five solution methods. From left to right: the radial-velocity observations that give short-period orbits are only available for the brightest stars. The next two curves refer to combined radial-velocity-plus-astrometry and the astrometry-only orbits. The 'non-linear proper motion' detections peak at a period of 10 yr since these systems are resolved at longer periods. To these five solution types should be added a large number of eclipsing binaries with periods below 10^{-2} yr. The 'all-sky/all magnitude' curves shown above are a combination of results from all distances. Looking at a nearby sample ($<$ 500 pc), many resolved binaries have periods short enough for orbit determination, i.e. there is good overlap between the solution methods, and hence binaries of all periods may be observed. For more distant samples, there are no resolved orbits, and as shown by the dip in the figure, binaries with a period of about 100 yr will be hard to detect with Gaia.



Globular clusters will be extensively observed by Gaia, giving precise distances and ages for these objects which are among the oldest objects in the Milky Way. Their distances provide a clue to Population-II distance scales and their ages give a lower limit for the age of the Universe. Images NGC 6093 and Omega Centauri, copyright NASA & The Hubble Heritage Team (STScI/AURA); NGC 6397, copyright ESA & Francesco Ferraro; 47 Tucanae, copyright NASA & Ron Gillard (STScI).

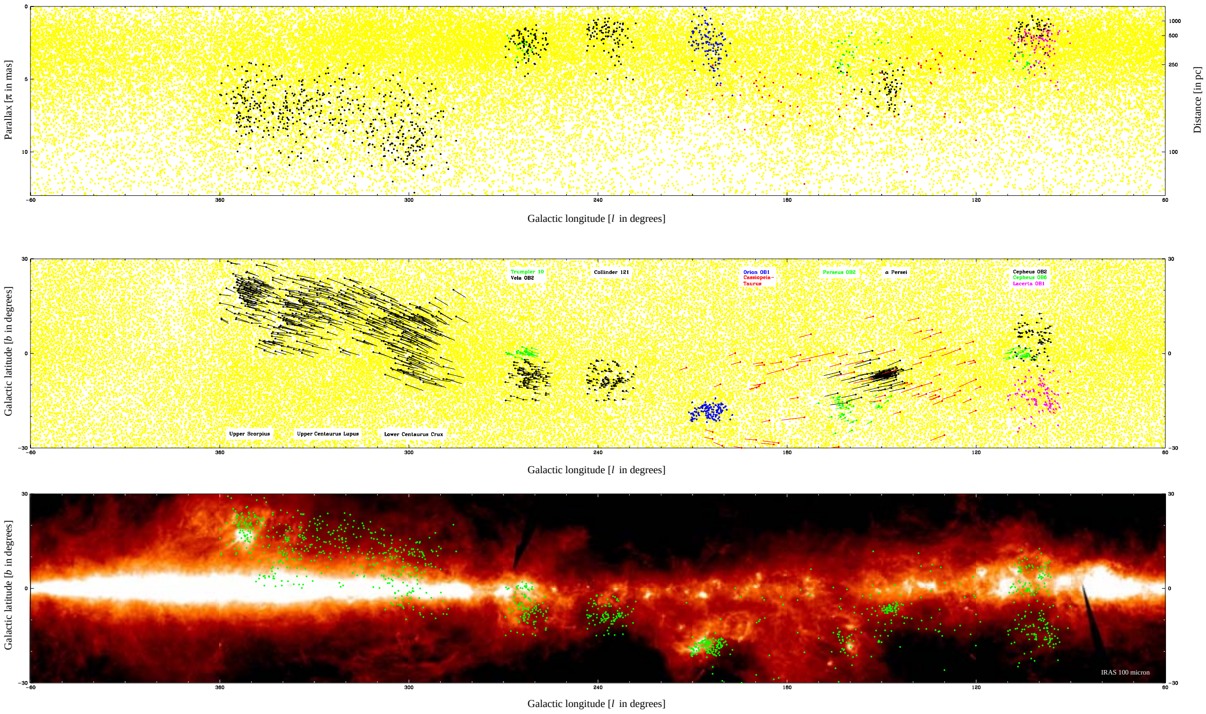
Gaia will have a major impact upon our knowledge of the distance scale in the Universe by providing accurate distances and physical parameters for all types of observable primary distance indicators in the Milky Way and in the closest galaxies of the Local Group. It will generate a complete sampling of these indicators versus the corrections due to metal, oxygen, or helium contents, colour, population, age, etc. In particular, Gaia will extensively observe many Galactic open and globular clusters and countless Cepheids and RR Lyraes, thus providing solid calibrations for cluster-sequence fitting and period-luminosity relations.

Major efforts have been made during the past decade to observe distance indicators in external galaxies (for example, the Hubble Space Telescope key project). Nowadays, the dominant contribution to the uncertainty on these distances, and hence on the most important cosmological parameter describing the Universe – the Hubble constant – is the uncertainty in the distance to the Large Magellanic Cloud (LMC).

Gaia will provide a firm foundation to the sequence of steps leading to the determination of distances of far-away galaxies and, as a consequence, to the determination of the Hubble constant by measuring individual trigonometric distances to the Cepheids and brightest stars of the LMC. Moreover, Gaia will establish a first check of the universality of the period-luminosity relationship for pulsating variables, with direct distances of all Galactic and LMC Cepheids and with mean Gaia distances for Cepheids in the closest galaxies of the Local Group.

Gaia will also provide an extensive picture of the whole Hertzsprung–Russell diagram, undoubtedly leading to new or renewed insight (Mirae period-luminosity relation, eclipsing binaries, white-dwarf luminosity function, etc.).

Moreover, Gaia will touch a second crucial parameter for the description and understanding of the Universe: its age. The accurate determination of the distances of the oldest objects in the Galaxy, namely subdwarf stars and globular clusters, combined with a fit to theoretical models of stellar evolution, will lead to a precise estimation of their ages. These age estimates naturally provide a lower limit to the age of the Universe, since these objects formed some time after the Big Bang.

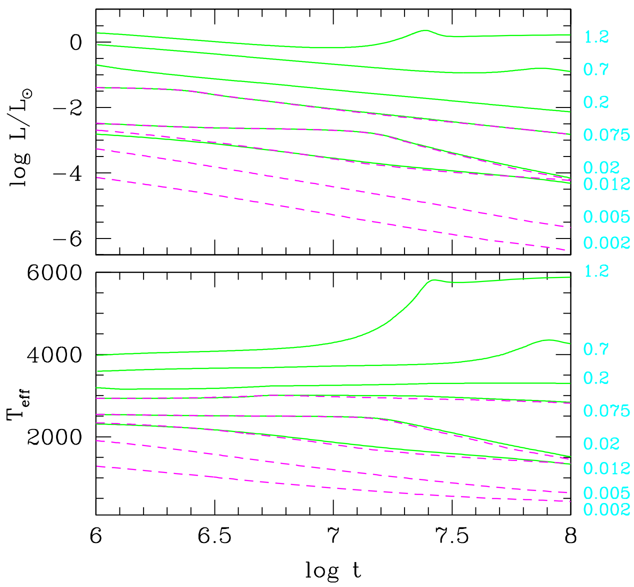


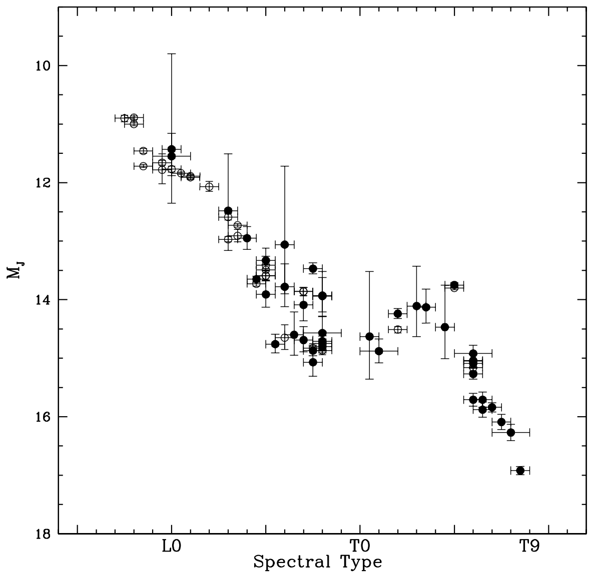
Kinematic selection of nearby OB associations using Hipparcos positions, parallaxes, and proper motions (de Zeeuw et al., 1999, AJ, 117, 354): (upper panel) parallaxes of the OB-association members, superimposed on all stars observed by Hipparcos in the range $-30^\circ < b < 30^\circ$; (middle panel) positions and proper motions of the members in Galactic coordinates; (lower panel) positions of the members superimposed on the IRAS 100-μm background.

The most conspicuous component of the Milky-Way galaxy is its flat disc which contains nearly 10^{11} stars of all spectral types and ages orbiting the Galactic centre. The Sun is located at about 8.5 kpc from the Galactic centre. The disc displays spiral structure, and also contains interstellar material, predominantly atomic and molecular hydrogen, and a significant amount of dust. The disc of the Milky Way contains, besides numerous open clusters and associated super-clusters/moving groups, various manifestations of recent star formation events, including OB associations and the large-scale Gould Belt (see figure above). The inner kilo-parsec of the disc also contains the bulge, which is less flattened, may contain a bar, and consists mostly of moderately-aged stars. At its centre lies a supermassive black hole of $\sim 4 \times 10^6$ $M_\odot$. The disc and bulge are surrounded by a halo of about 10^9 old and metal-poor stars, as well as ∼160 globular clusters and a small number of satellite dwarf galaxies. This entire system is embedded in a massive halo of dark material of unknown composition and poorly known spatial distribution.

The distributions of stars in the Galaxy over position and velocities are linked through gravitational forces, and through the star formation rate as a function of position and time. The initial distributions are modified, perhaps substantially, by small- and large-scale dynamical processes. These processes include instabilities which transport angular momentum (for instance bars and warps) and mergers with other galaxies.

Understanding our Galaxy requires measurement of distances and space motions for large and unbiased samples of stars of different mass, age, metallicity, and evolutionary stage. Gaia's global survey of the entire sky down to 20-th magnitude is the ideal – and only – approach to define and measure such samples. The huge number of stars, the impressive astrometric accuracy, and the faint limiting magnitude of Gaia will quantify our understanding of the structure and motions of stars within the bulge, the spiral arms, the disc, and the outer halo, and will revolutionise dynamical studies of our Galaxy.





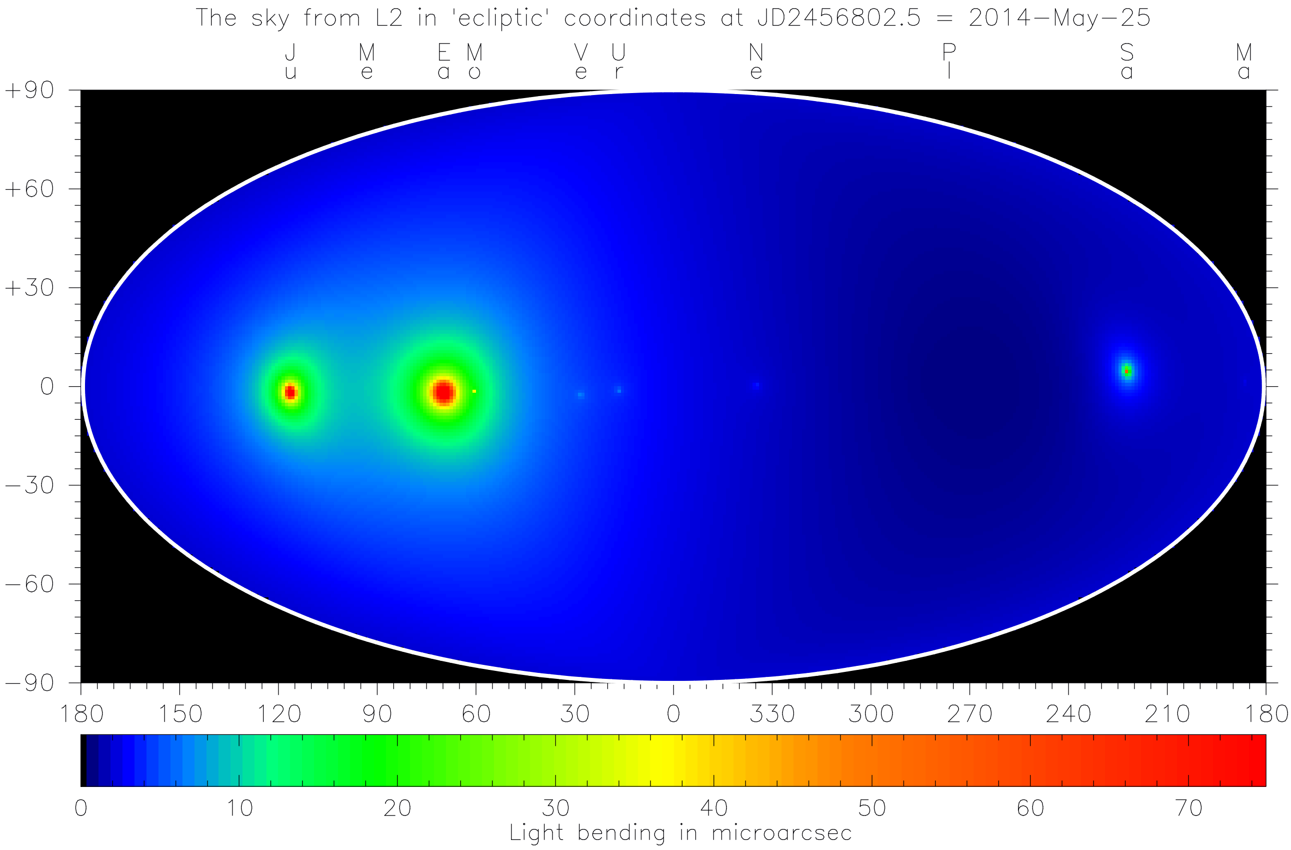
Left: the evolution of the luminosity (top) and effective temperature (bottom) as function of time (in yr) of brown dwarfs for different masses (shown on the right of this figure, in blue, in units of the solar mass). The solid green lines assume no dust formation; the dashed pink lines permit dust formation and retain it in the atmosphere. Gaia will measure accurate properties for young brown dwarfs in numerous clusters and star-forming regions (Baraffe et al. 2002, A&A, 382, 563). Right: absolute J-band magnitudes of field brown dwarfs obtained from ground-based astrometry and photometry. Late-L and T dwarfs are very faint in the optical, so Gaia will only be able to detect a limited sample of old field brown dwarfs out to several parsec. Yet even for these, Gaia will measure distances to better than 1% (Vrba et al. 2004, AJ, 127, 2948).

In observing the entire sky down to 20-th magnitude, Gaia will observe large numbers of isolated brown dwarfs in the solar neighbourhood. Structural models show that brown dwarfs cool and fade rapidly after formation, so that the distance out to which Gaia can detect them is a function of their mass and age. Gaia should see Pleiades-age (∼100 Myr) brown dwarfs out to around 400 pc and younger brown dwarfs, such as those in the Orion Nebula Cluster (1–3 Myr), out to about 1 kpc. This volume encompasses numerous young clusters and star-forming regions such as Chamaeleon, where brown dwarfs are known to exist. For an I = 20 mag brown dwarf at 200 pc, Gaia will obtain a distance accuracy of about 4% and transverse velocities to around 0.2 km s^{-1}.

One of the main contributions of Gaia to substellar astrophysics will be a detailed spatial and kinematic map of brown dwarfs in clusters of known age and metallicity (determined from Gaia parallaxes of higher-mass stars), permitting a comprehensive study of mass segregation and ejection of brown dwarfs. These are key ingredients to understanding the formation mechanism of substellar mass objects, whether it be via cloud fragmentation and gravitational collapse, premature ejection from an accreting envelope, or some other mechanism.

Brown dwarfs will be identified primarily from their absolute luminosities obtained from the precise Gaia parallaxes as well as from the on-board multi-band photometry. The latter will provide physical parameters of brown dwarfs, in particular the effective temperature, but perhaps also metallicity and the nature of cloud coverage. As brown dwarfs will be found in clusters of a range of ages, a significant contribution of Gaia will be an accurate observational determination of their cooling curves. The photometry and absolute magnitudes will furthermore help in the detection of spatially and astrometrically unresolved brown-dwarf binaries. From this information, we will be able to determine the substellar mass function and the three-dimensional spatial and age distribution of brown dwarfs, thus establishing their formation history in the context of the Galaxy.

Predictions of the number of brown dwarfs which Gaia will detect depend sensitively on their cooling function and their distribution. Rough estimates based on current knowledge are of the order of 50,000 over a wide range of masses and ages. The absolute luminosities, colours, and kinematics obtained from Gaia will provide us with detailed insight into the physical properties, formation, and evolution of this substellar population.

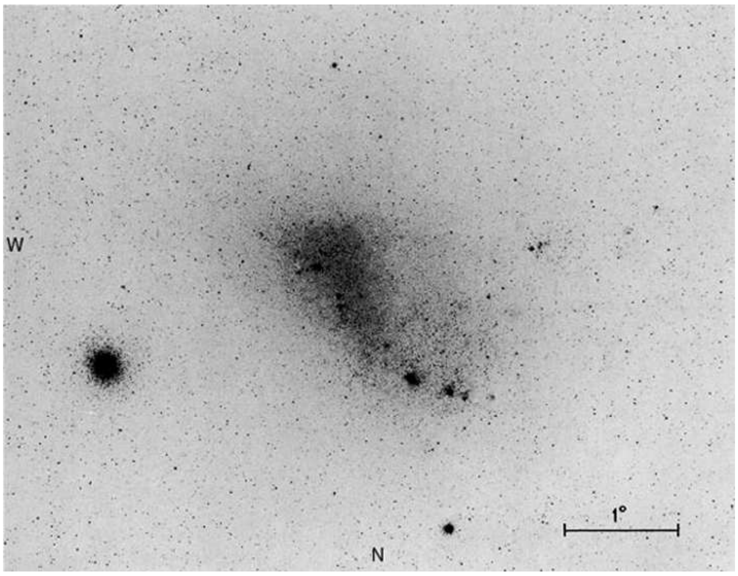


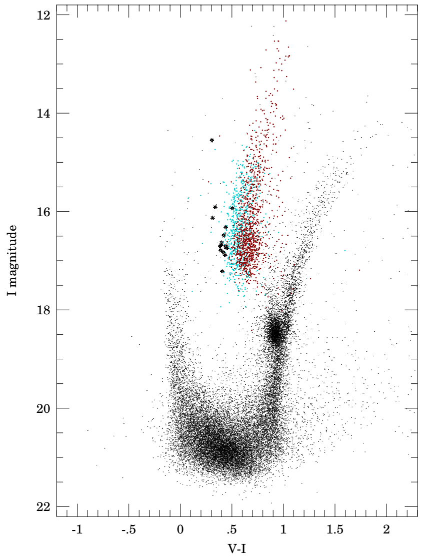
All-sky map (in ecliptic coordinates, for an L2-based observer) displaying the total amount of post-Newtonian light deflection due to all planets, and the Moon, at 25 May 2014 (two-letter object-name abbreviations appear above the top axis). The Sun has been suppressed because of its immense contribution, extending all over the sky, compared to the other bodies. The colour coding has been chosen such that significant light bending is predicted in all regions of the sky coloured different from blue.

Gaia will determine the positions, parallaxes, and proper motions for the brightest 1 billion objects in the sky. Expected astrometric accuracies are 20–25 μas at 15-th magnitude and a few μas for the brightest stars (up to 12-th magnitude). At these accuracy levels, it is vital to treat the Gaia data in a general-relativistic context. For example, photons detected by Gaia are bent during the last hours of their long journey, while traversing the solar system, under the influence of the gravitational fields of the Sun, planets, moons, asteroids, etc. The amount of this post-Newtonian light deflection depends on the mass of the perturbing object, its distance to the observer (Gaia), and the angular separation at which the photon passes the object. A well-known example is a light ray grazing the limb of the Sun: an observer on Earth will notice a deflection of 1.75 arcsec.

In the context of Gaia, correcting for solar-system light bending is critical: for a spherical perturbing body with a mean mass density ρ (in g cm^{-3}), the light deflection for a limb-grazing light ray is larger than δ (in μas) if its radius $r > \rho^{-1/2} \cdot \delta^{1/2} \cdot$ 624 km. Typically, $\rho \sim 1$ g cm^{-3} for objects in the solar system, so that Gaia's astrometric measurements will be 'affected' to a significant extent ($\delta \sim$ 1–10 μas) by all bodies with radii larger than $\sim$ 624 km. (For Jupiter and Saturn, the quadrupole contributions of their gravitational fields should also be taken into account.)

In principle, this translates for Gaia, observing from L2, to the Sun and all planets (including the Earth and Moon) and to a number of the larger moons (notably Io, Europa, Ganymede, Callisto, and Titan; light deflection in these cases, however, is only significant at angular separations smaller than a few arcseconds). In practice, however, due to the geometry of the scanning law which effectively creates a 45°-radius zone of avoidance on the sky centered on the Sun, the contributions from Mercury and the Moon, for example, can always be neglected. Minor bodies (e.g. main-belt asteroids and Kuiper-Belt objects) and smaller moons are unimportant. The Sun, on the other hand, contributes significantly to light bending even 180° away from its center.





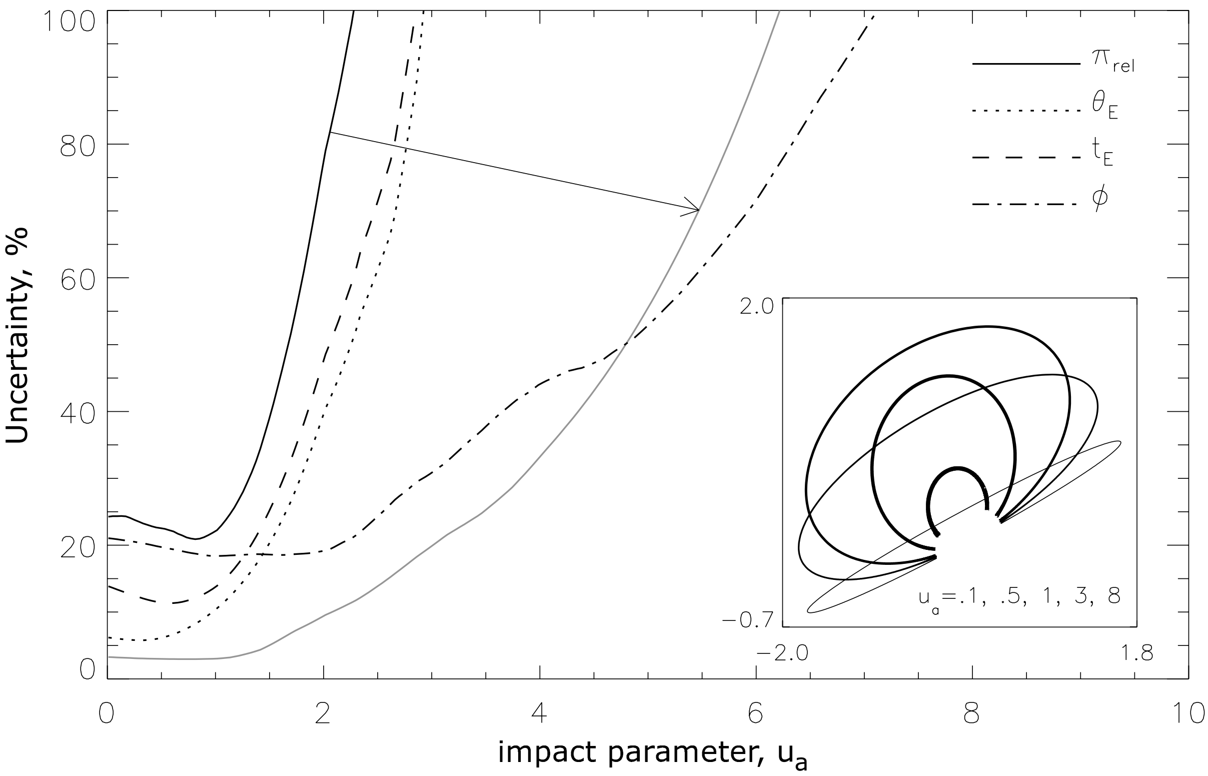
Left: the Small Magellanic Cloud as it appears on the sky. The big globular cluster (to the left) belongs to our own Galaxy. Image by Henize using the Mt. Wilson 10-inch refractor. Right: colour-magnitude diagram for an area of 14 × 57 arcmin^2 in the SMC bar. There are 45,500 stars with I < 20 mag. Overplotted are the Cepheids from OGLE, with fundamental, first overtone, and single-mode second overtone indicated separately by colour. Image from the OGLE consortium, courtesy of Andrzej Udalski. Gaia will observe millions of stars in the Large and Small Magellanic Clouds and will give even more detailed information.

The Magellanic Clouds are substantial galaxies in their own right, which provide the nearest examples of young intermediate-to-low chemical-abundance stellar populations for study. The Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) will provide millions of stars for Gaia analyses. The key scientific questions for Gaia involve the dynamics of the LMC–Galaxy and the LMC–SMC interactions, the luminosity calibration of stellar populations, the dynamics of star-forming regions, and the dynamical structure of the LMC 'bar'. At the LMC and SMC distance of roughly 50 kpc (parallax 20 μas), individual bright stars, with I = 12–16 mag, will have transverse velocities determined to approximately 1–2 km s^{-1} ($\sim$20 μas yr^{-1}). Gaia will allow kinematic mapping and membership analyses of young star-forming regions in the LMC and SMC with comparable precision to that presently available in the Milky Way. In other words, it will be possible to compare directly the kinematics and structure of star-forming regions in a large spiral disc with those in a mid-sized irregular galaxy.

The dynamical evolution of the solar neighbourhood is dominated by diffusion of stars in velocity space, crudely described as an age-velocity dispersion relation. This process is not well understood, but presumably involves energy input from spiral arms and molecular clouds. The Gaia kinematics in the LMC and SMC will quantify the age-kinematics relation in a very different environment, constraining the key dynamical processes.

One of the major puzzles in the structure of the LMC and the SMC is their asymmetric luminosity distribution. While the large-scale, radially-averaged luminosity profiles of both galaxies follow fairly smooth exponentials, both show significant bar-like asymmetries. This is most obvious in the LMC, and in stars of ages less than a few Gyr old. However, the LMC 'bar' is substantially offset from the dynamical centre, and seems unrelated to the stellar-dynamical m=2 modes of cold discs. It appears to be sufficiently long-lived to have survived differential rotation for several rotation periods. It is presently unknown what the dynamical status of the bar is, or even if it is in the same plane as the main LMC disc. Gaia will provide three-dimensional dynamics across the whole bar and disc region, quantifying the dynamical relationship between these features. While an individual parallax to an LMC star will be imprecise (20 per cent error), the very large number of targets will map the spatial structure of the LMC/SMC system with high spatial resolution directly.

The masses of the LMC and SMC are poorly known. Current analyses involve approximate solutions fitting the poorly known transverse velocity, and assuming simple disc structure, for a small number of test particles. Gaia proper motions will map the membership of the clouds as far as they extend, including the 'inter-cloud' regions of young metal-poor star formation, the complex SMC 'wing', and stars associated with the HI Magellanic Stream. This will map the dark-halo structures of both the intact LMC and the apparently distorted SMC, determining the extent of their halos, the density of the Milky Way at 50 kpc, and the effects of the LMC–SMC interaction.



The percentage error in estimation of the microlensing parameters as a function of impact parameter. Accurate recovery of the relative parallax (π_{rel}) is hard, whereas recovery of the angular Einstein radius (θ_E) and the Einstein crossing time (t_E) is easier. (The lens distance is 150 pc, the source distance is 4 kpc, the transverse velocity is 20 km s^{-1}, while the accuracy is 150 μas.) The arrow shows improvement in the relative parallax estimate when photometric follow-up information is available. The inset shows the centroid shift evolution with increasing impact parameter (source parallactic and proper motion removed).

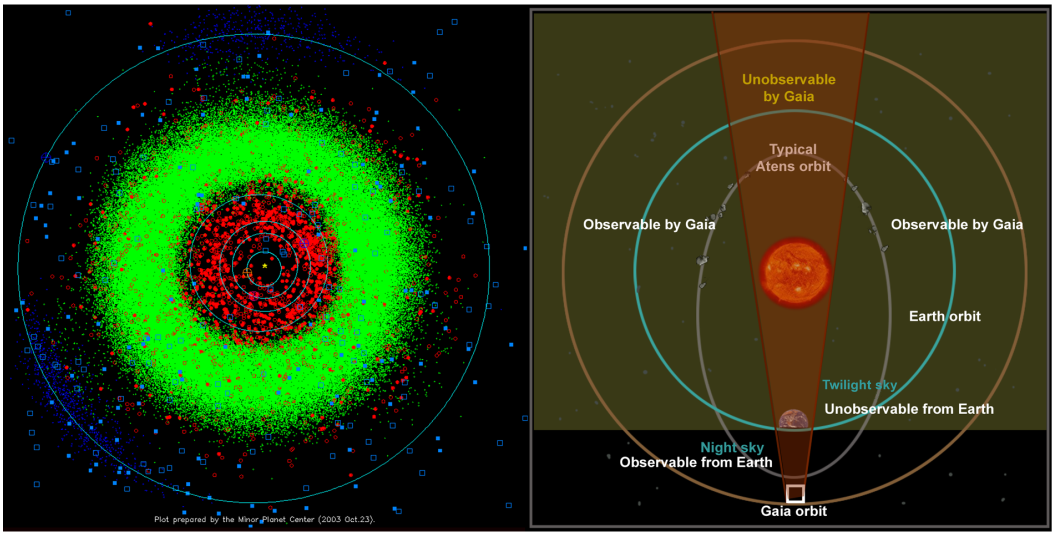
Gaia can observe gravitational microlensing by measuring the photometric amplification of a background source star at epochs when it is coincidentally aligned with a foreground lens. The all-sky averaged photometric optical depth associated with such an alignment is $\sim 5 \times 10^{-7}$, hence there will be ~7500 photometric microlensing events during Gaia's 5-year mission lifetime, most of which will have only a few data points because of the poor sampling.

If photometry is combined with the measurements of the centroid of the two images of a microlensed source, then complete information about the distance and the mass of the lens can be obtained. The all-sky averaged astrometric microlensing optical depth is ~ 1.5–2.0×10^{-5}. This means that between about 15,000 and 20,000 sources will have the variation of centroid shift at least $5\sqrt{2}$ times larger than the typical astrometric accuracy together with a closest approach (source to the lens) during the lifetime of the Gaia mission.

The most valuable events are those for which the Einstein crossing time (t_E), the angular Einstein radius (θ_E), and the relative parallax of the source with respect to the lens (π_{rel}) can all be inferred from Gaia's data stream. The mass of the lens then follows directly. Gaia measurements alone will provide a sample of at least 500 stars with accurately determined masses. However, the numbers can be improved still further if Gaia observations are supplemented with ground-based photometry. A total of 1000 masses will be measured with the help of dedicated telescopes on the ground.

Astrometry can provide direct estimates of the angular Einstein radius (θ_E) and the lens proper motion angle. However, the values of impact parameter (u_a) and Einstein crossing time (t_E) are more difficult to obtain with astrometry alone. On the other hand, just a few data points on the light curve of a microlensed star will allow the time scale and the maximum amplification (and hence impact parameter) to be determined. A further increase in the number of mass measurements is possible if ground-based photometry is supplied.

One of the major scientific contributions of microlensing studies with Gaia will be the determination of the mass function in the solar neighbourhood. Microlensing is the only known technique which can measure the masses of objects irrespective of whether they happen to be components of a binary system or emit electromagnetic radiation.



Left: minor planets (indicated by green circles) in the inner solar system. Objects with perihelia within 1.3 AU are plotted as red circles. Orbits of major planets are shown in light blue. Image courtesy Minor Planet Center. Right: Gaia is ideally situated to probe the asteroid blind spot between the Sun and Earth. As this schematic diagram shows, some regions of the sky that are unobservable from Earth can be observed by Gaia.

While tracking stars with its telescopes, Gaia will also observe solar system objects by the thousands, primarily asteroids of the main belt circling the Sun between the orbits of Mars and Jupiter. With its ability to detect faint and fast-moving objects, it is expected that Gaia will also detect several thousand Near-Earth Objects (NEOs), which are thought to be comets and asteroids that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's neighbourhood. Much further away, beyond the orbit of Neptune, bigger objects are clustered in the Kuiper belt. The largest of these will also be detected with Gaia.

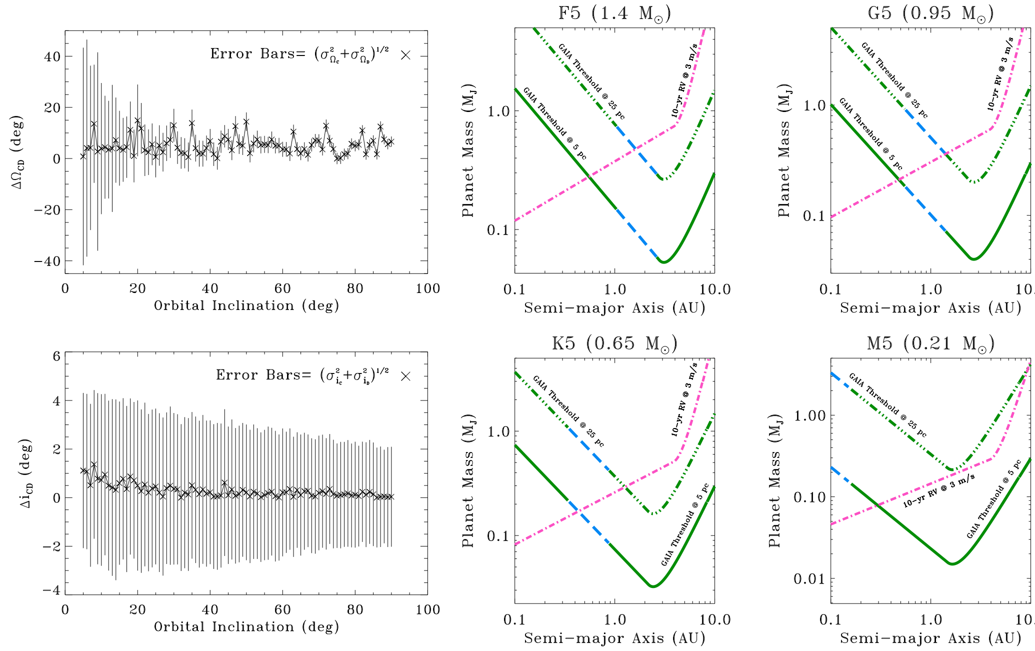
The scientific interest in asteroids is due largely to their status as the remnant debris left over from the process that formed the inner planets, including Earth. Asteroids are also the source of most meteorites that have struck the Earth's surface and many of these objects have already been subjected to chemical and physical analyses.

Due to its vantage point of observation at the Lagrange point L2 and its ability to observe down to an angular distance of 45 degrees from the Sun, Gaia will be ideally situated to probe the asteroid blind spot between the Sun and Earth and to discover small bodies orbiting the Sun inside the Earth's orbit, a region virtually unreachable from the Earth. In the course of its all-sky survey, Gaia will also observe the sky far from the ecliptic, where ground-based surveys of minor planets are predominantly active, an instance very favorable to the discovery of objects roaming the solar system on exotic orbits.

Gaia will accurately measure the positions and velocities of asteroids over the five years of the mission leading to a determination of their orbits with an unprecedented precision. Orbital parameters are essential to compute well in advance when and where a stellar occultation by a small body will be observable. Such events yield a wealth of information on the sizes and shapes, and when the masses are known, on the densities of these objects. Orbits are also a key element in identifying members of 'orbital families' sharing a common origin.

The tiny gravitational pull experienced by asteroids during close approaches between two bodies – thousands of such encounters are predicted to take place during Gaia's operational life – pushes them away from their path. This small deviation will be recorded in the Gaia astrometric measurements, leading to the mass of the perturber. About 150 asteroid masses will thus be determined to better than 50% by Gaia, as compared to the approximately 20 known today.

Beyond astrometry, Gaia's multi-epoch photometric data will reveal the surface properties of minor planets by telling us how much light is reflected in a particular colour. A refined classification of the population of minor bodies will emerge from this giant database, revealing the kinship between asteroids, NEOs, and meteorites. In addition, the variation of the physical parameters with the distance to the Sun will also be studied.



Left: coplanarity analysis for the υ And system. Right: Gaia planet discovery space as a function of orbital radius, stellar spectral type and distance from the observer (green solid line: 5 pc; green dashed-dotted line: 25 pc). The blue dashed line represents the habitable zone of the star. The pink dashed line indicates the planet discovery space for 3 m s^{-1}-precision radial-velocity measurements.

The size of the stellar sample out to 150−200 pc to be investigated for planets - comprising hundreds of thousands of objects - constitutes the most significant contribution Gaia will provide to the science of extra-solar planets. Indeed, the results derived from Gaia's microarcsecond-precision astrometric measurements will help decisively improve our understanding of orbital parameters and actual mass distributions. Gaia will thus provide important data to constrain theoretical models of formation, migration, and dynamical evolution of planetary systems.

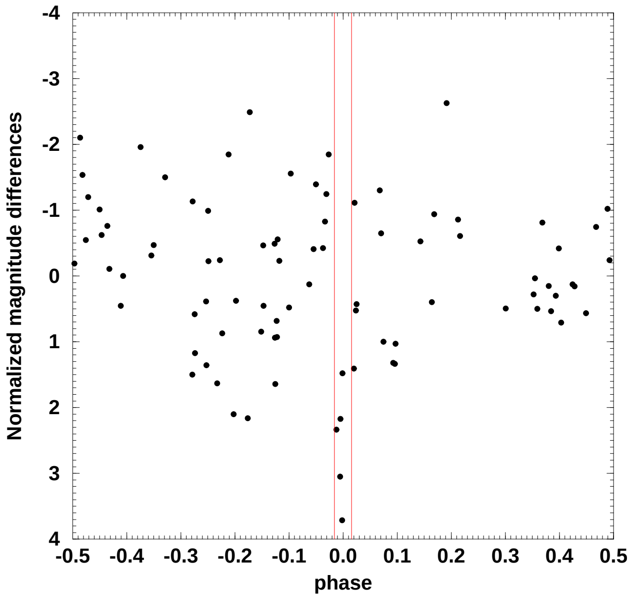
Within 200 pc of the Sun, and limiting counts to bright solar-type main-sequence stars, i.e. objects brighter than 13-th magnitude and with spectral types earlier than K5, about $N_\star \sim 3 \times 10^5$ iobjects are predicted to exist. The table below shows how, given reasonable assumptions on the planetary frequency as a function of orbital radius, on the detection threshold, and on the accuracy of orbit determination, Gaia will be capable of discovering thousands of planets around these stars. Gaia will accurately measure the orbital characteristics and actual masses for a significant fraction of the detected systems.

Δd (pc)	$N_\star$	Δa (AU)	N_d (1)	N_m (2)
0-100	~61 000	1.3 - 5.3	≥ 1600	≥ 640
100-150	~114 000	1.8 - 3.9	≥ 1600	≥ 750
150-200	~295 000	2.5 - 3.3	≥ 1500	≥ 750

(1) Number of giant planets (N_d) that could be detected by Gaia around solar-type stars, as a function of increasing distance from the Sun. (2) Number of detected planets (N_m) for which orbital elements and masses can be measured to better than 20%. A uniform frequency distribution of 1.3% planets per 1-AU bin is assumed.

The frequency of multiple-planet systems, and their preferred orbital spacing and geometry, is not currently known. Star counts predict $\sim$ 13 000 stars to 60 pc. Gaia, with its high–precision astrometric survey of the solar neighbourhood, will observe each of these, searching for planetary systems composed of massive planets in a wide range of possible orbits, making precise measurements of their orbital elements, and establishing quasi-coplanarity (or non-coplanarity) for detected systems with favorable configurations.

Gaia observations of nearby stars, out to 25 pc, will also contribute to populating the database of stars to be observed by the future ESA/NASA Darwin/TPF mission. Gaia astrometry will confirm the existence of Jupiter signposts from radial-velocity measurements, and will extend spectroscopic surveys to the large database of nearby M dwarfs, complementing ground-based observations. The Gaia measurements will provide estimates of the actual planet masses, thus contributing to models establishing whether or not dynamical interactions would permit an Earth-like planet to form and survive in the habitable zone of any given star. Finally, Gaia will measure the inclinations of the orbital planes, complementing ground-based studies of exo-zodiacal cloud emission for the extra-solar system.



Transits of the star HD 209458 = HIP 108859 as seen in Hipparcos photometric observations, with the transit duration indicated by two vertical lines. The transits were predicted from ground-based observations after the Hipparcos mission.

In the search for extra-solar planets, three complementary techniques can be employed: *Radial-velocity* measurements can find planets in close orbits around their stars, but give no information about the inclination angle of the orbit, and therefore only the minimum mass of the planet can be established. *Astrometry* is suitable for detecting long-period planets, but requires precise measurements and long time spans. *Planetary transits* only occur in those systems with proper alignment of the orbit relative to Earth, but a transit reveals the planet's radius, if the exact inclination angle of the orbit can be determined. Detection or measurement both by astrometric and transit methods are feasible with Gaia; the astrometric method is described elsewhere.

The transit of an extra-solar planet across its parental stellar disc will often occur in Gaia observations and is of interest for detection or measurement for stars brighter than about 16-th mag. The photometric effect of a transit will be most significant in the measurements made in the 9 astrometric CCD strips (AF1–9). A precision of about 1 milli-magnitude per field crossing of Gaia's focal plane is expected for stars brighter than 14-th mag, much more accurate than from Hipparcos. This corresponds to a signal-to-noise ratio of 10 for a Jupiter-size planet around a Sun-like star. For 'known planets' around bright stars, Gaia photometry may yield significant additional information.

A photometric measurement for only one transit of the field in principle suffices to determine the radius of the planet when the stellar radius is known. However, the secure identification of a photometric dimming as being due to a planetary transit requires additional information, e.g. from astrometry or radial velocities or from other transits. Stars with surface spots may be recognised as such and may not be suited for detection of transits.

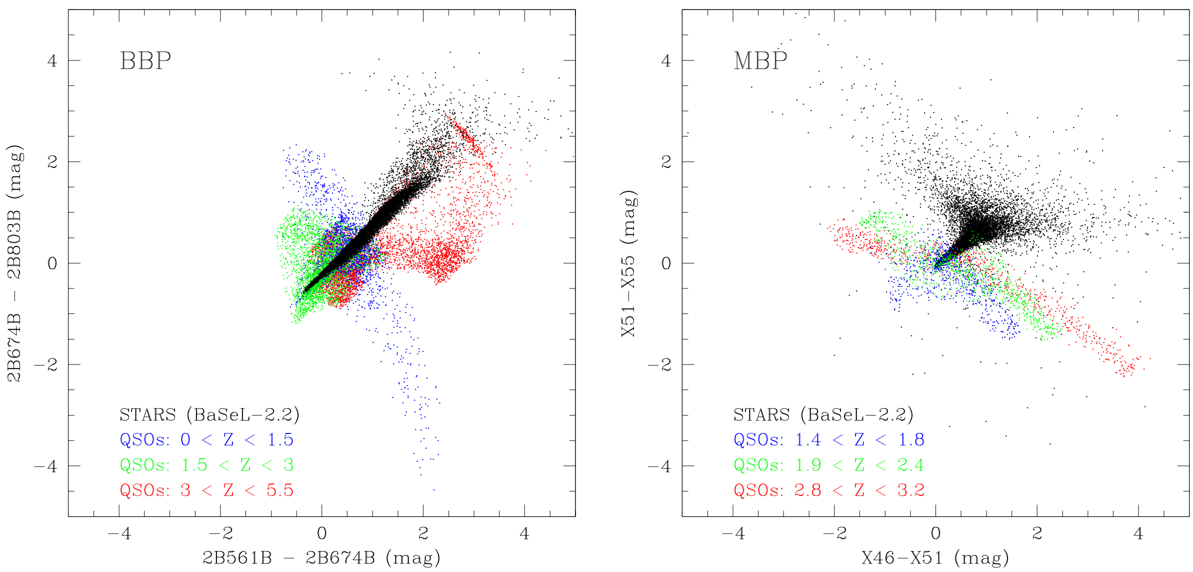
	F	G	K	M	Sum
$0 < a < 2$AU:	3000	2000	1500	15	6500
$a > 2$AU:	50	30	20	0	100

The predicted number of planetary transits with Gaia for the four spectral types F, G, K, and M, for small and large orbital radii. A signal-to-noise ratio of at least 10 has been assumed.

The number of detected planets (see table) is highly sensitive to the assumed distribution of planetary orbit sizes. From the distribution of currently detected extra-solar planets, it is possible to give a qualified estimate of the distribution for planets in small orbits. For larger orbits, the assumed distribution is an estimate based on our knowledge of the solar system and considering theories of planetary formation.

The advantage of Gaia observations over other surveys, either from space or from the ground, is that all sufficiently bright stars will be observed many times during the mission, thus providing a complete all-sky survey with a well-known selection function.

Gaia: Planetary Transits



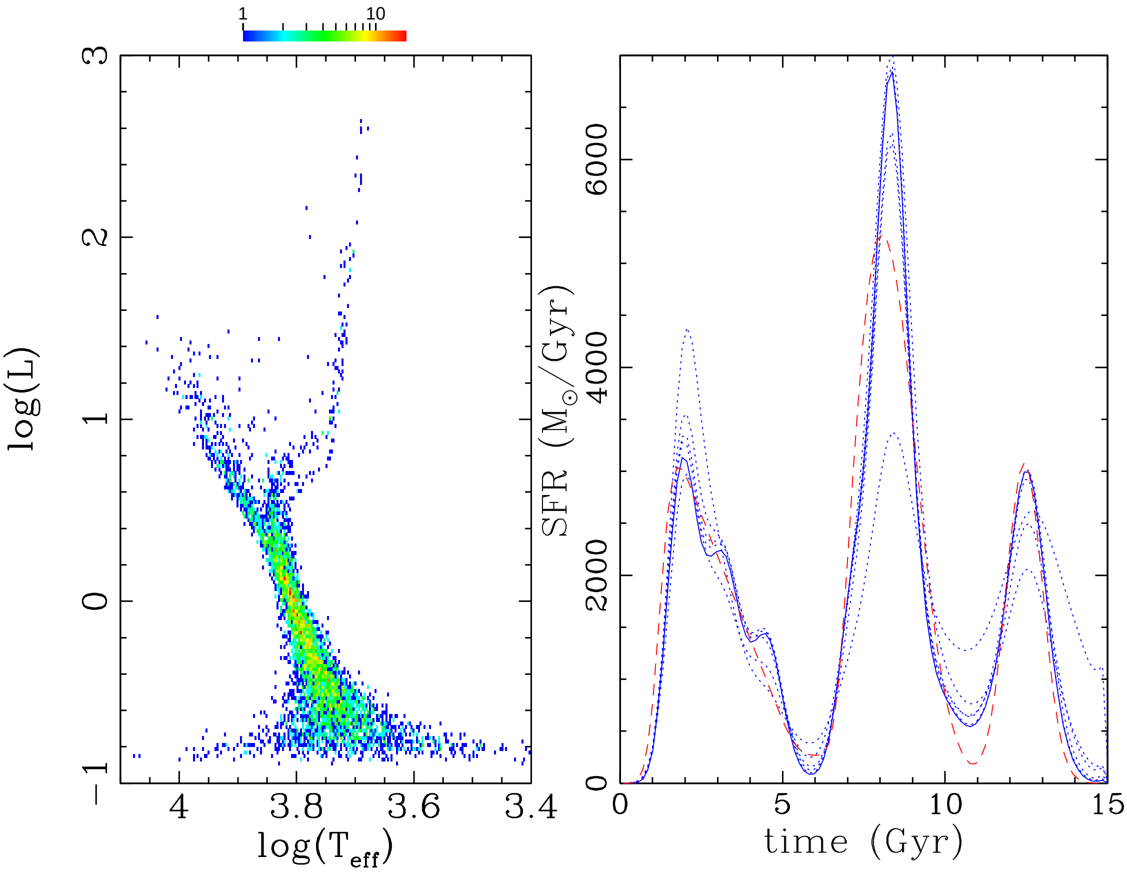
Examples of colour-colour diagrams showing star and QSO loci in simulated broad-band photometry (left) and medium-band photometry (right). In medium-band filters, QSO emission lines make strong signatures at specific redshifts (see right plot, where the signatures of the CIII], CIV and Ly-alpha emission lines are visible in the distribution of the blue, green, and red objects respectively). The figures refer to an obsolete photometric-filter system studied for Gaia during the assessment phase. The flight-model payload design features two low-dispersion photometers (BP and RP) returning spectra covering the entire wavelength range supported by the telescope plus CCD.

Gaia will provide astrometric and photometric observations for about 500,000 quasars (QSOs) down to 20-th magnitude over the whole sky, 5 times more than the number expected from the Sloan Digital Sky Survey. The Gaia data set will constitute the first all-sky survey of optically-selected active galactic nuclei (AGN) and QSOs.

AGN and QSOs are of prime importance in establishing the relativistic reference frame, one of the scientific objectives of the Gaia mission. Gaia's QSO sample will have a profound impact on studies of the large-scale structure of the Universe. Their spectroscopy will allow the gas content in distant galactic haloes and in intervening intergalactic clouds to be probed. In addition, about 2000 QSOs in the final sample are expected to be lensed by a foreground galaxy, and 50 per cent of these should directly be identified as multiply-imaged objects thanks to Gaia's reconstructed sky-mapper images. This number is an order of magnitude larger than the number of known lensed QSOs. The number and properties of lensed QSOs in a statistical sample contain information on the nature of distant lensing galaxies and on the geometry of the Universe. Thus, Gaia also offers the prospect of constraining the values of cosmological parameters.

Since QSOs only represent 0.05 per cent of the objects detected by Gaia, it is crucial to be able to discriminate them from the much more numerous stars. In principle, Gaia's data will offer three methods to reach this objective, based on three properties of QSOs: (i) their colours occupy a different locus from the one formed by stars in the multi-dimensional colour space built from Gaia's photometric data (see the figure above); (ii) their variability can be detected by photometric measurements collected during the 5-year mission lifetime; (iii) their lack of proper motion and parallax can be determined by the astrometric instruments. Which (combination of) method(s) will be used for QSO selection remain to be decided.

After having built sets of representative simulated QSO spectra, either characterised by their redshift, continuum slope, total equivalent width of emission lines, and reddening, or by weights for a set of spectral principal components, on-going studies aim at determining: (i) the parameter space over which QSOs can be discriminated against stars by photometric means alone; (ii) the rate of contamination of stars by QSOs if only photometry is used; (iii) the accuracy with which the redshift and other spectral parameters can be determined; (iv) the QSO limiting magnitude required to recover their spectra with good accuracy.

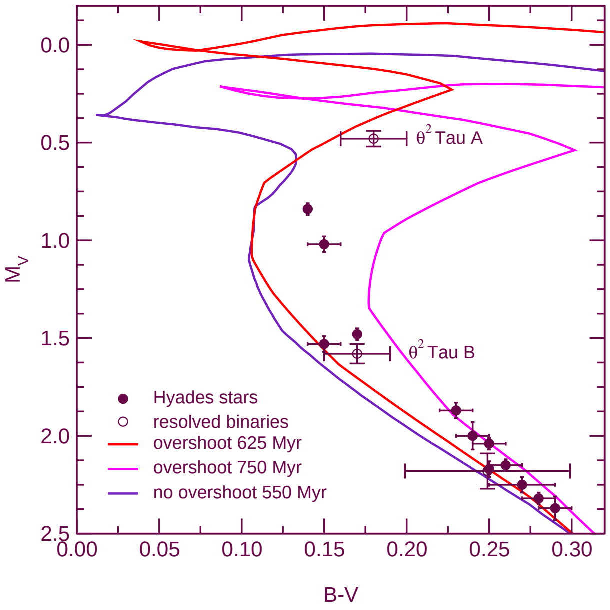


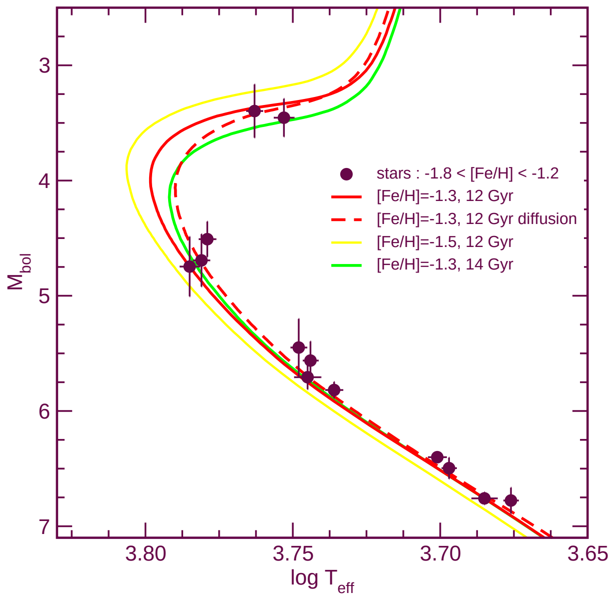
Left: synthetic Hertzsprung–Russell diagram appropriate for good-quality Gaia data. Right: derived star-formation history following inversion of the data in the left panel. Long-dashed red curve: true input star-formation history; dotted curves: successive intermediate iterations; solid curve: final iteration.

A primary scientific goal of Gaia is the determination of the star-formation histories, as described by the temporal evolution of the star-formation rate and the cumulative numbers of stars formed, in the bulge, inner disc, solar neighbourhood, outer disc, and halo of the Milky Way. In general, stellar age-metallicity-extinction degeneracies, convolved with current observational errors and uncertain stellar distances, have made determination of the star-formation history of a mixture of stellar populations unreliable and non-unique. The best available analyses involve comparison of an observed colour-magnitude diagram with a model population. While powerful, such analyses can never be proven unique. The Gaia astrometric, photometric, and spectroscopic data, combined with specifically-developed, direct-inversion tools, will resolve this ambiguity and will make the full evolutionary history of the Galaxy accessible.

The star-formation history defines the luminosity evolution of the Galaxy directly. In combination with the relevant chemical abundance distributions, the accretion history of gas may be derived. Together with kinematics, the merger history of smaller stellar systems can be defined. The sum of these three processes forms what is loosely known as 'galaxy formation'. Analysis of the Gaia results will provide the first quantitative determination of the formation history of our Galaxy.

The determination of the relative rates of formation and/or accumulation of the stellar populations in a large spiral, typical of those galaxies which dominate the luminosity in the Universe, will provide, for the first time, an ability to test galaxy-formation models in a quantitative manner. Do large galaxies form from accumulation of many smaller systems which have already initiated star formation? Does star formation begin in a gravitational potential well in which much of the gas is already accumulated? Does the bulge pre-date, post-date, or is it contemporaneous with the halo and inner disc? Is the thick disc a mix of the early disc and a later major merger? Is there a radial age gradient in the older stars? Is the history of star formation relatively smooth or highly episodic? In addition to their immediate and direct importance, answers to such questions will provide uniquely a template for analysis of data on unresolved stellar systems, where Gaia-type and -quality data can never be obtained.





Left: estimation of the age of the Hyades at turn-off. Gaia will obtain clean sequences in the Hertzsprung–Russell diagram for many open clusters, allowing stellar-age determinations in the Galactic disc. Right: estimation of the age of 13 halo stars for which high-quality Hipparcos data exists. With Gaia, the number of subgiants with accurate parameters will increase, yielding improved age determinations of the oldest stars.

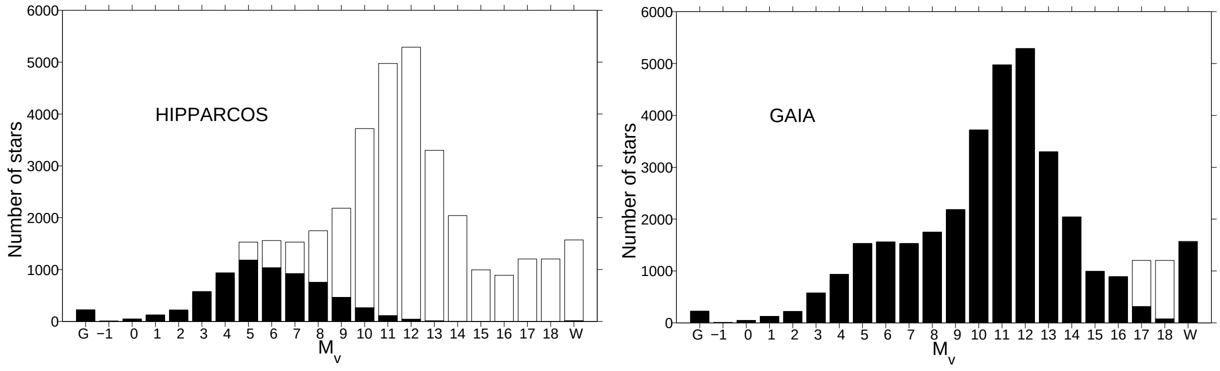
Precise stellar-age determinations are required for various Galactic structure and evolution studies and for cosmological studies. The primary age-determination method relies on comparisons of stellar models or isochrones with the best available data, in particular luminosity, effective temperature, and abundances, for individual stars or stellar groups. The principle of the method is general, but its application to different types of stars requires specific considerations.

A–F stars, open clusters and Galactic evolution: Galactic-evolution studies require the determination of the ages of relatively young objects in the Galactic disc, mainly open clusters and main-sequence A–F stars with ages ranging from several million to a few billion years. By providing accurate data for a large number of A–F stars, Gaia will reduce drastically the impact of the distance uncertainty on the age estimates for single stars. Gaia will also provide clean sequences in the Hertzsprung–Russell diagram for many open clusters containing hundreds to thousands of members. Cluster stars with masses spanning a large interval, and assumed to share the same age and chemical composition, constitute a unique tool for age determinations.

Helium abundance and chemical evolution of the Galaxy: The position of the zero-age main-sequence in the Hertzsprung–Russell diagram depends critically on the chemical composition of stars. The large sample of non-evolved low-mass stars with determined metallicities and accurate positions in the Hertzsprung–Russell diagram, that will be constituted from Gaia observations of K–M dwarfs, will be a key tool for interpreting the stellar helium abundances and the possible relation between helium and metallicity.

The oldest stars and the age of the Universe: The determination of the age of the oldest objects in the Galaxy (Population II) provides a lower limit to the age of the Universe. This can be used to constrain cosmological models and parameters. Currently, the best estimate for the age of the oldest stars is based on the absolute magnitude of the main-sequence turn-off in globular clusters, and is affected by the uncertainty on the cluster distances.

Gaia will improve the age estimate of the oldest stars. The number of subdwarfs with accurate distances will considerably increase in each metallicity interval allowing us to derive the distance of an increased number of globular clusters of various chemical compositions by main-sequence fitting. Furthermore, distances of a substantial number of field subgiants will be measured, improving the age determination of the field halo stars.

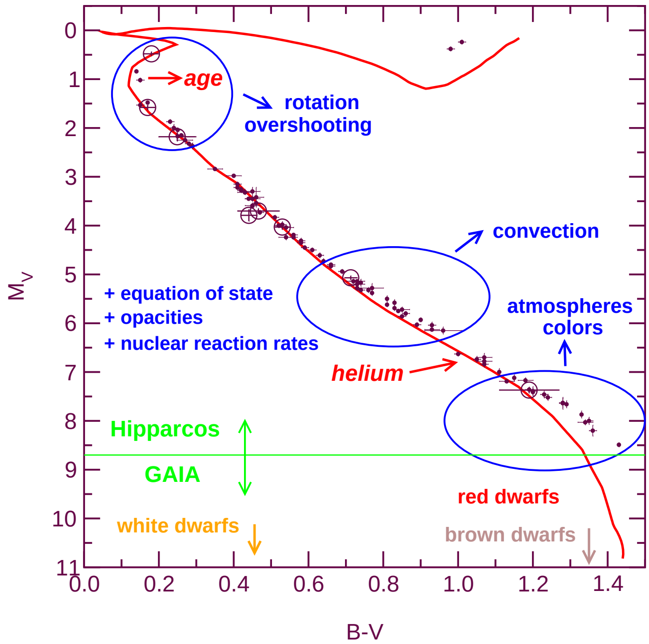


Comparison of the completeness from Hipparcos (left) with the expected completeness from Gaia (right). The plots show the number of star systems (individual stars or binary/multiple systems) within 50 pc of the Sun, as a function of absolute magnitude M_V, predicted by a systemic luminosity function based on data from the literature. The bar with the letter 'G' (at left) denotes giant stars, and with the letter 'W' (at right) denotes white dwarfs. The black parts of the bars give the number of star systems detected by Hipparcos or by Gaia. Figure courtesy Joan García-Sánchez.

Close or even penetrating passages of stars through the Oort Cloud can in principle deflect large numbers of comets into the inner planetary region, initiating Earth-crossing cometary showers and possible Earth impacts. Although the distribution of long-period cometary aphelia is largely isotropic, some non-random clusters of orbits do exist, and it has been suggested that these groupings record the tracks of recent stellar passages, with dynamical models suggesting typical decay times of around 2–3 Myr. Gaia's complete and accurate census of the distribution and space motions of the stars in the solar neighbourhood will allow a determination of the frequency of such close encounters, and will provide, for the first time, sufficiently accurate astrometric data for a large number of stars to carry out a reliable study of the link between comet showers and past impact events and mass extinctions on Earth.

García-Sánchez et al. (1999) used Hipparcos data to investigate close stellar encounters with the solar system, the consequences for cometary-cloud dynamics, and the evolution of the comet population over the history of the solar system. Effects of individual star passages on comet orbits were studied through dynamical simulations. Algol was the largest perturber in the recent past (although other stars have passed even closer), passing at a distance of about 2.5 pc about 7 Myr ago. Gliese 710 is the most significant known future perturber. At 19 pc from the Sun, and approaching at about 14 km s^{-1}, it will pass through the Oort Cloud, at about 69,000 AU from the Sun, in about 1 Myr. But the authors concluded that none of the predicted passages could have caused a significant disruption of the Oort Cloud, which supports the hypothesis that the currently observed flux of long-period comets corresponds to a steady-state value.

The figure above shows the number of star systems (individual stars or binary/multiple systems) within 50 pc of the Sun, as a function of the absolute magnitude. The black parts of the bars give the number of star systems detected by Hipparcos (left) or expected for Gaia (right). 'G' denotes giant stars and 'W' indicates white dwarfs. Hipparcos detected about 20 per cent of the nearby star systems, whereas Gaia will detect nearly all of them. Two explanations for an increased rate of impact events on Earth have been suggested: (i) a collisional breakup of a large asteroid in the asteroid belt that can deliver collision fragments to orbital resonances, resulting in large fragments ejected from the asteroid belt to Earth-crossing orbits; (ii) a comet shower caused by a close stellar passage, increasing significantly the number of comets with Earth-crossing orbits. The reliable determination of a close stellar encounter with the solar system during the time of the impact events would provide strong support to the cometary origin of such impacts, as opposed to the asteroid hypothesis. In particular, an extinction at the end of the Eocene period, 36 Myr ago, is identified with several large impact craters, multiple iridium layers, and other evidence of a prolonged period of increased cometary flux in the inner-planets region. Hipparcos data allowed the study of passages within a few million years. Gaia will enhance this time interval to a geologically interesting range. The encounters predicted by using Gaia data are expected to establish whether the currently observed comet flux corresponds to an enhanced or a steady-state flux, with implications for the size of the Oort-Cloud population. The prediction of future close or penetrating passages through the Oort Cloud may be used to estimate resulting enhancements in the inner-solar-system cometary flux.



Gaia will address a broad range of physical and astrophysical topics related to stellar structure and evolution. Pictured here: the Hipparcos Hertzsprung–Russell diagram of the Hyades compared to a model isochrone. Uncertainties in the stellar parameters and in the calculation of model atmospheres and interiors affect the determination of the cluster age and helium content.

The study of stellar structure and evolution provides fundamental information on the properties of matter under extreme physical conditions as well as on the evolution of galaxies and cosmology. The accurate and homogeneous astrometric and photometric data provided by Hipparcos has resulted in precise characteristics of individual stars and open clusters and the confirmation of certain aspects of internal-structure theory.

Further progress on stellar modelling is required, for example, on atmospheric modelling, transport processes of matter, angular momentum and magnetic fields, microscopic physics, etc. On the observational side, more numerous samples of rare objects, including distant stars and stars undergoing rapid evolutionary phases, an increased number of common objects with high-quality data, and a census over all stellar populations are required.

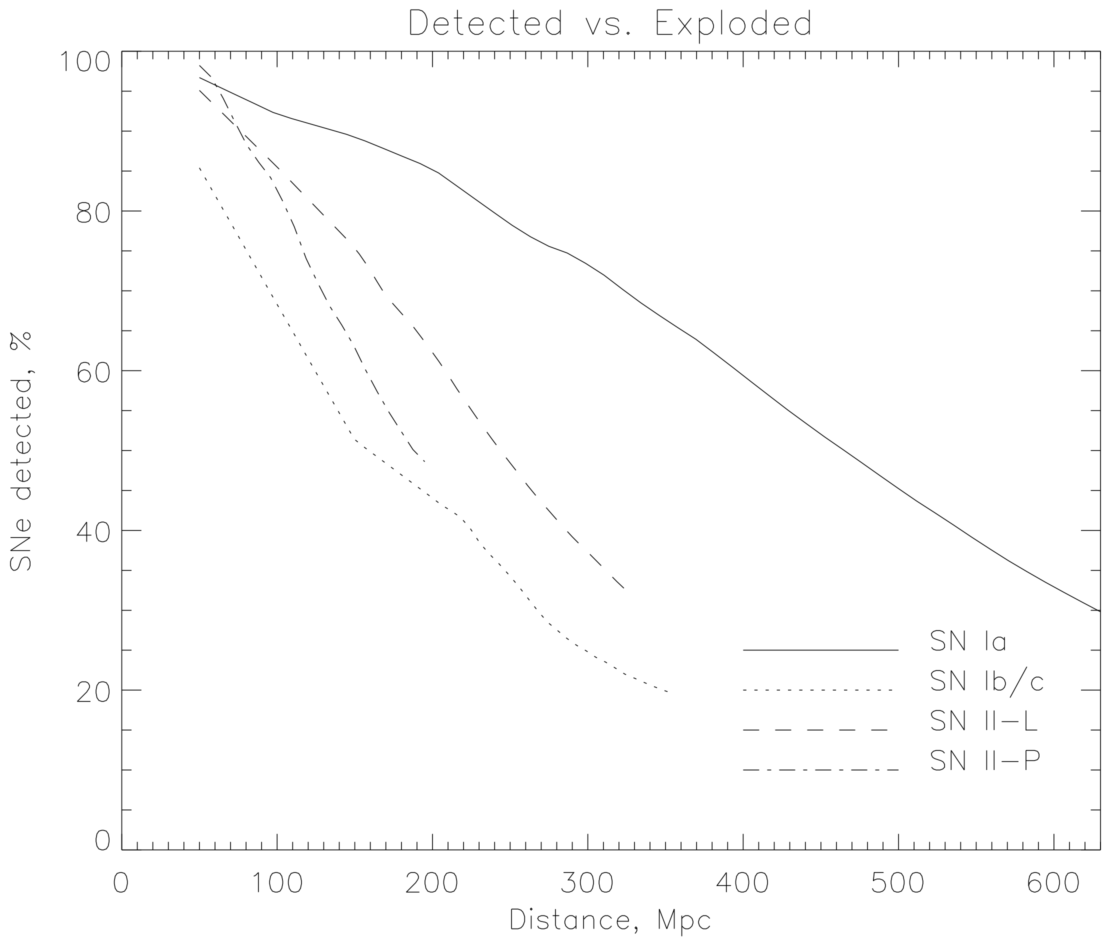
Gaia will return luminosities, surface temperatures, abundances, masses, and determinations of the interstellar extinction for all types of stars. The following are some of the effects that will be probed with the Gaia data:

The size of convective cores: Asteroseismic data – obtained from the ground or from the space mission COROT – combined with accurate estimates of global parameters from Gaia can probe the size of stellar convective cores. These define the amount of nuclear material available to sustain the luminosity, playing a crucial role in the evolution of intermediate- and high-mass stars.

Internal diffusion of chemical elements: Microscopic and turbulent diffusion of chemical elements in stellar radiative zones may have important consequences for stellar evolution, in particular for stellar ages when fresh helium is brought to the stellar cores. Diffusion may also modify the composition at the surface of stars during their life implying difficulties in linking abundances of elements presently observed to the initial abundances of the protostellar cloud.

The high-precision positions in the Hertzsprung–Russell diagram of stars of known surface abundances, provided by Hipparcos and by high-resolution spectroscopy, have revealed discrepancies between the observations and the predictions of standard stellar models. The large sample of stars with accurate parameters provided by Gaia will help in addressing these discrepancies.

Outer convective zones: Most stellar models are still built by treating convection according to the classical parametric mixing-length theory. Asteroseismic analysis of stars combined with the careful calibration of the Hertzsprung–Russell diagram allowed by Gaia for samples of different chemistries, ages, etc., will greatly enhance our capabilities of dealing with non-local convective models for stellar interiors.



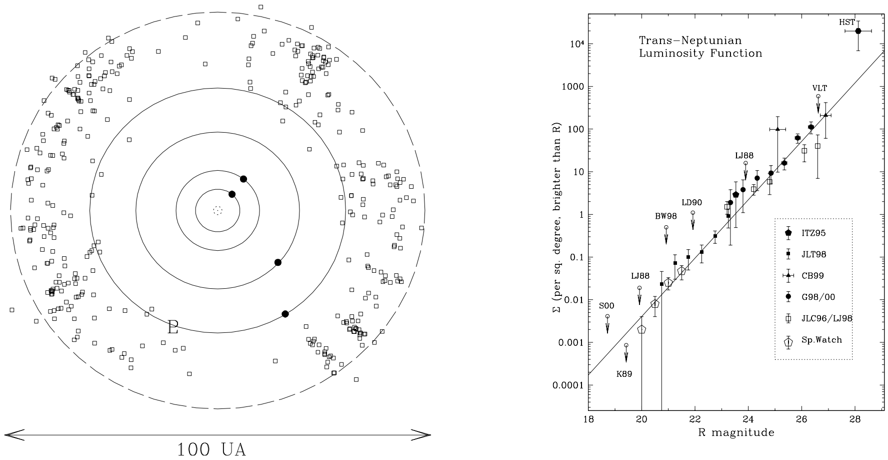
The total number of supernovae detected within distance D as a fraction of the total number exploded. Within 630 Mpc, Gaia detects ∼30% of all type Ia supernovae. Within 355 Mpc, Gaia detects ∼20% of all type Ib/c. For type II-L, Gaia detects ∼31% within 335 Mpc. Finally, for type II-P supernovae, Gaia detects ∼48% within 195 Mpc. Detection is defined as Gaia recording at least one data point on the standard supernova template.

Gaia is an ideal instrument to study nearby supernovae (i.e. within a few hundred Mpc). Gaia will provide a huge dataset of high-quality local type-Ia supernovae in which any deviations from 'standard candles' can be analysed. As the dataset is so large, there will likely also be a good number of relatively rare phenomena, such as sub-luminous supernovae and type Ib/c supernovae.

Gaia will record data on at least 21,400 supernovae during the five-year mission lifetime. This breaks down into ∼14,300 type Ia, ∼1400 type Ib/c, and ∼5700 type II. These supernovae span a redshift range up to z ∼ 0.14.

In the most favourable case, Gaia will alert on all supernovae detected before maximum. These numbers are ∼6300 type Ia, ∼500 type Ib/c, and ∼1700 type II during the whole mission. In other words, Gaia may issue ∼1700 supernovae alerts a year or ∼5 alerts a day. Roughly 75% of all alerts will be for type Ia supernovae, while the remainder will be for type Ib/c and II. All these numbers are lower limits since they may be increased by a factor of ∼2, depending on the supernova contribution from low-luminosity galaxies.

Supernova rates will be found as a function of galaxy type, as well as extinction and position in the host galaxy. Amongst other applications, there may be about 26 supernovae each year for which detection of gravitational waves is possible and about 180 supernovae each year for which detection of gamma-rays is possible. Gaia's astrometry will provide the supernova position to better than milli-arcseconds, offering opportunities for the identification of progenitors in nearby galaxies and for studying the spatial distribution of supernovae of different types in galaxies.



Left: the Kuiper Belt, as seen looking from the North Pole of our solar system. The 4 solid circles mark the orbits of Jupiter through Neptune, with their position in mid-1999 marked. The 'P' symbol marks the location of Pluto. The squares mark the positions of a sample of Kuiper Belt comets. Right: cumulative luminosity function of the Kuiper Belt. Symbols show several published surveys. The upper limits are 3-σ representations at the 50%-limit of the survey.

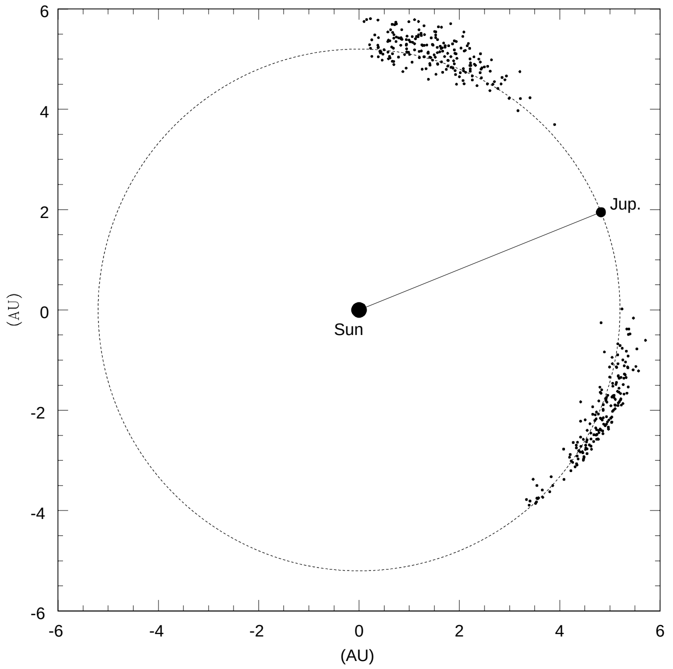
Edgeworth and Kuiper independently suggested the existence of a belt of material in orbits with semi-major axes between 30 and 50 AU, based on the observed distribution of short-period cometary orbits. Dynamical studies showed that after the giant planets reached their current masses the regions between them would be emptied of planetesimals on times scales much smaller than the age of the solar system. However, these studies also showed that outside of Neptune the hypothesised Edgeworth–Kuiper Belt (EKB) was stable, supporting modelling that the short-period comets come from this source via long-term gravitational instability. Today, more than 800 small bodies have been detected in the outer solar system, confirming that there is indeed an EKB. This belt has been found to be dynamically excited (random speeds much larger than would have allowed the accretion of these objects) and heavily depleted (much less material than would have allowed them to accrete).

Due to their large distance to the Sun and Earth, trans-Neptunian objects (TNOs) and Centaurs (objects with perihelia between the orbits of Jupiter and Neptune) are faint objects. Very few of them will be visible by Gaia: currently, only 65 objects are known to be brighter than magnitude 20 (the limit of completeness of Gaia) and 138 are brighter than magnitude 21 (10%-level of detection efficiency). Currently, we estimate to be about 75% complete for objects brighter than $m_R = 20$, and at least half complete for objects brighter than $m_R = 21$. So Gaia should detect a few tens of objects at most. Most of these should be Centaurs or Scattered Disk Objects (semi-major axis >50 AU and pericentre distance within gravitational reach of Neptune) on their way to the Centaurs region. Only a handful of Classical Kuiper Belt Objects (semi-major axis in the 30–50-AU range, low eccentricity, and low inclination) should be brighter than $m_R = 21$, and none should be brighter than $m_R = 20$.

Despite this small number, Gaia will provide a valuable contribution to the study of the outer solar system. First of all, it will be the first and only instrument that will survey the whole sky down to magnitude 20, allowing detection of any bright object of the solar system that is currently in front of the Milky Way, or at very high inclination. All ground-based observations have limited detection efficiency in the direction of the Milky Way because of stellar confusion. Starting or foreseen surveys should cover around 90% of the remaining sky. Existence or not of these bright objects will give fundamental clues on the formation mechanism of the EKB and the outer solar system.

For the largest Centaurs which will be cruising at 10 to 30 AU from Gaia, it should be possible to resolve them, providing the only direct measurement of the size of these objects, and hence of their albedo, besides Pluto. All other estimates of size and albedo rely on radio-photometry and thermal modelling.

Among the ~50 objects detected by Gaia, a handfull should be binaries. With the astrometric accuracy of Gaia, it will be possible to detect this binarity, and even to determine the orbit of the binary, providing a direct measurement of the mass of these objects. This sample will be a noticeable fraction of masses known at that time, allowing a decently accurate estimate of the volume bulk density.



Schematic view of the locations of the two clouds of a large sample of known Jupiter Trojans around the Lagrangian L4 and L5 points at an arbitrary epoch. The locations of the Trojans have been computed according to their known orbital elements. The orbit of Jupiter, for simplicity approximated by a circle of radius 5.2 AU, is also shown, as are the locations of the planet and the Sun.

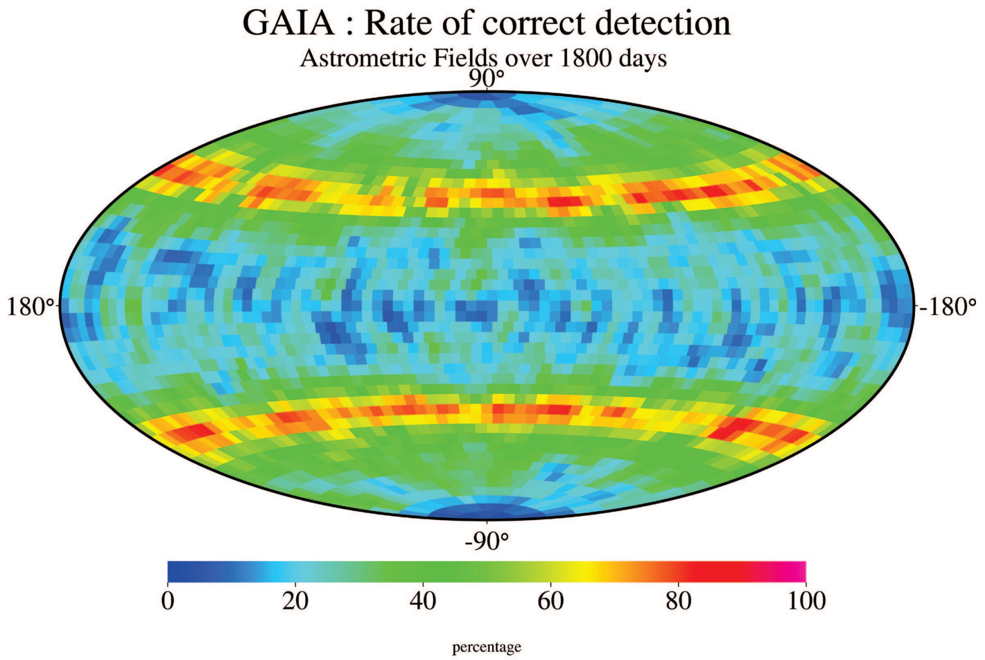
Uniquely among the minor planets, the so-called Jupiter Trojans are made up of small bodies librating around the stable L4 and L5 Lagrangian points of the Sun–Jupiter system on orbits thought to be stable over the age of the solar system. A few Mars and Neptune Trojans are also known to exist, whereas no results have been obtained from searches for Trojans of other planets.

There are many unanswered key questions related to the peculiar locations and orbital properties of Trojans, on which Gaia may cast some light: (i) Did they accrete from planetary grains in the same region where they are found today or were they trapped there in the early stages of the formation of ther solar system; (ii) Can Trojans be simply considered as a sub-class of the objects that we collectively call 'asteroids', or should we consider them as a separate category of bodies, somehow intermediate between main-belt asteroids and trans-Neptunian objects with distinctive physical properties?

The composition of Trojans constitutes a serious constraint for any study of the original gradient in composition of the planetesimals in the early phase of the solar system. A comparison of their spectral-reflectance properties with those of other classes of minor bodies, including main-belt asteroids, Hildas, Centaurs, trans-Neptunian objects, and comets, is an important task and clearly this is an area where Gaia will contribute significantly.

Another classically-debated problem is the possible systematic difference between the leading (L4) and trailing (L5) clouds. This could reflect a difference in their origin or be the result of a different dynamical and collisional subsequent history. In principle, there should be no difference in the dynamics of the two groups, but it happens that the L4 objects discovered so far are about 1.5 times as numerous as those at L5 (the census as of late July 2009 includes 1850 L4 objects compared with 1404 L5 objects). There are also claims that the distribution of orbital inclinations could be not identical between the two clouds.

Gaia observations of Trojans should help disentangle pieces of the puzzle. Precise astrometric measurements will produce significant improvements in the accuracy of the derived orbits of these objects, leading to the refinement of the statistics of the distribution of orbital elements. The systematic and homogeneous survey of the spectrophotometric properties of Trojans will make it possible to investigate the spectral diversity among Trojans, and to detect possible systematic differences in surface reflectance between the two clouds, as suggested by recent ground-based observations. Moreover, Gaia's photometric data is expected to produce reliable estimates of rotation periods, spin axis orientations, and overall shapes for a statistically significant sample of the whole population. Regarding object sizes, the large heliocentric distance will restrict that determination to the largest members of the population, such as 624 Hektor and 911 Agamemnon, which have diameters exceeding 100 km.



Probability of recovery, in the end-of-mission data, of a sinusoidal G-band-magnitude variation of period 4h50m and signal-to-noise ratio of 0.75 as function of position on the sky in ecliptic coordinates. The recovery probability varies between nearly 0 per cent and 100 per cent. Gaia's scanning law causes the end-of-mission number of observations to vary with position on the sky, explaining the positional dependency.

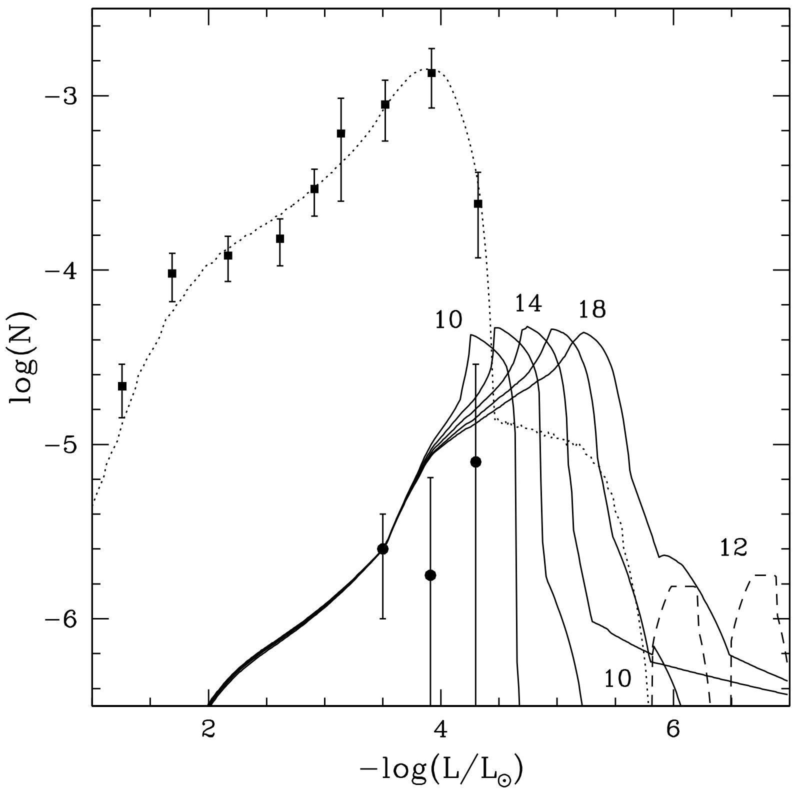
Gaia will provide multi-epoch, multi-colour photometry for all sources brighter than 20-th magnitude. In addition, high-quality broad-band photometric measurements will be made in the astrometric field. The combined photometric data will have the precision necessary to detect diverse variable phenomena and to describe nearly all types of variability. The photometric data will allow a global description of stellar stability and variability across the Hertzsprung–Russell diagram and will permit the identification of the physical processes causing variability.

For a 5-year mission, a sky-averaged number of 70 photometric measurements is expected from the astrometric field and from the Blue and Red Photometers. Expected numbers of variable objects are difficult to predict, but invariably large, with conservative estimates given by Eyer & Cuypers (2000): about 18 million variable stars in total, including 5 million 'classic' periodic variables, about 3 million eclipsing binaries, 300,000 with rotation-induced variability, 2,000–8,000 Cepheids, 60,000–240,000 Scuti variables, 70,000 RR Lyrae stars, a significant fraction of these in the bulge, and about 250,000 Miras and SR variables.

Precise physical and orbital parameters of eclipsing binaries will be derived for about 10,000 systems (Zwitter 2003). The pulsating stars include key distance calibrators such as Cepheids, RR Lyrae stars, and long-period variables, for which present samples are incomplete already at magnitudes as bright as 10. A complete sample of objects will allow determination of the frequency of peculiar objects, and will accurately calibrate period-luminosity relationships across a wide range of stellar parameters (i.e. mass, age, and metallicity). Variability on short (seconds) to long (of order 5 years) time scales can be detected.

Several dedicated asteroseismologic space missions (e.g., MOST, COROT, and Kepler) have been launched. Asteroseismological predictions have been achieved from the ground in the case of roAp stars from photometric observations (Matthews et al. 1999) and, for solar-like stars, from radial-velocity measurements (Bouchy & Carrier 2002). Parallax determination is a stringent constraint for testing stellar models when used in asteroseismology; on the other hand, absolute luminosities or masses derived from parallaxes can be used as the starting point for seismological models (Baglin 1997, Favata 1999).

In addition to stellar variability, other 'time phenomena' will also be present in the Gaia data: supernovae (estimated at $\sim$ 20,000; Belokurov & Evans 2003), microlensing events (though astrometry will be able to detect $\sim$ 100 events, about 1000 stars will have perturbed photometry; Belokurov & Evans 2002), planetary transits ($\sim$ 5,000 detectable transits are expected; Robichon 2003). Finally, non-stellar variable objects will be observed, including gamma-ray bursts, quasars, active galactic nuclei, and small bodies in the solar system.



Luminosity functions of disc (dotted line) and halo (solid lines) white dwarfs as a function of luminosity. This figure assumes bursts of star formation at 10, 12, 14, 16, and 18 Gyr that lasted for 0.1 Gyr. The luminosity function of disc white dwarfs was computed assuming a disc age of 9.3 Gyr. The observational data were obtained from Liebert et al. (1988, 1989).

White dwarfs are well-studied objects and the physical processes that control their evolution are reasonably well understood. In fact, most phases of white-dwarf evolution can be successfully characterised as a cooling process. In other words, white dwarfs slowly radiate at the expense of the residual gravothermal energy. The release of this energy occurs over long time scales (of the order of the age of the galactic disc, 10 Gyr).

The mechanical structure of white dwarfs is supported by the pressure of the gas of degenerate electrons, whereas the partially degenerate outer layers control the flow of energy. Precise spectrophotometric data – like those that Gaia will provide – will introduce tight constraints on the models. Specifically, Gaia will allow the mass-radius relationship to be tested. Even today, this relationship is not particularly well constrained. By comparing theoretical models with the observed properties of white dwarfs in binary systems, Gaia will be able to constrain the relation between the mass of the star on the main sequence and the mass of the resulting white dwarf.

Gaia will also provide precise information on the physical mechanisms (crystallisation, phase separation, . . .) operating during the cooling process. Given their long cooling time scales, white dwarfs have been used as a tool for extracting information about the past history of our Galaxy. The large number of white dwarfs that Gaia will observe will allow us to determine, with unprecedented accuracy, the age of the local neighbourhood and the star-formation history of the Galaxy. Furthermore, Gaia will be able to distinguish among the thin- and the thick-disc white-dwarf populations, and, in this way, it will be able to provide fundamental insight into the Galactic history. Gaia will also probe the structure and dynamics of the Galaxy and provide new clues about the halo white-dwarf population and its contribution to the mass budget of our Galaxy.

Finally, new constraints on the (hypothetical) rate of change of the gravitational constant (G) will be derived by comparing the measured average cooling rates of white dwarfs. More specifically, Gaia will largely reduce the observational errors in the determination of the disc white-dwarf luminosity function. Since the white-dwarf luminosity function measures the average rate of cooling of white dwarfs, and since this rate depends crucially on the rate of change of G, the Gaia observations will strongly constrain its rate of change.