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Microarcsecond astrometry with Gaia: the solar system, the Galaxy and beyond

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Abstract. Gaia is an all sky, high precision astrometric and photometric satellite of the European Space Agency (ESA) due for launch in 2010. Its primary mission is to study the composition, formation and evolution of our Galaxy. Over the course of its five year mission, Gaia will measure parallaxes and proper motions of every object in the sky brighter than visual magnitude 20, amounting to a billion stars, galaxies, quasars and solar system objects. It will achieve an astrometric accuracy of 10 μas at V=15 – corresponding to a distance accuracy of 1% at 1 kpc – and 200 μas at V=20. With Gaia, tens of millions of stars will have their distances measured to a few percent or better. This is an improvement over Hipparcos by several orders of magnitude in the number of objects, accuracy and limiting magnitude. Gaia will also be equipped with a radial velocity spectrograph, thus providing six-dimensional phase space information for sources brighter than V $\sim$ 17. To characterize the objects (which are detected in real time, thus dispensing with the need for an input catalogue), each object is observed in 15 medium and broad photometric bands with an onboard CCD camera. With these capabilities, Gaia will make significant advances in a wide range of astrophysical topics. In addition to producing a detailed kinematical map of stellar populations across our Galaxy, Gaia will also study stellar structure and evolution, discover and characterise thousands of exoplanetary systems (extending down to about ten Earth masses for the nearest systems) and make accurate tests of General Relativity on large scales, to mention just some areas. I give an overview of the mission, its operating principles and its expected scientific contributions. For the latter I provide a quick look in five areas on increasing scale size in the universe: the solar system, exosolar planets, stellar clusters and associations, Galactic structure and extragalactic astronomy.

1. Introduction

Distance measurement has been historically one of the most fundamental challenges in astronomy. To measure cosmic distances from the Earth's surface we must generally rely on parallaxes, i.e. the apparent change in position of an object relative to some other object (or reference frame) brought about by a known displacement of the observer. Astronomical distance measurement is hard because these displacements (e.g. the motion of the Earth around the Sun) are small compared to the distances we want to measure (e.g. the distance to the Galactic centre), that is we need to measure very small angular changes in position.† The lack of accurate distances has been, and continues to be, one of the most significant limitations in studying the universe.

The topic of this conference – the transit of Venus across the Sun – is central to this issue, because the attempts to observe it were a milestone in observational astronomy and in our potential to measure distances. Following first Halley's and then Deslise's outline of a method to measure the solar parallax (and hence the Astronomical Unit,

† This problem has been captured more elegantly by Douglas Adams (1978): "Space is big. Really big. You won't believe how vastly hugely mindbogglingly big it is. I mean you may think it's a long way down the road to the chemist, but that's just peanuts compared to space."

Quantity	Hipparcos	Gaia
Magnitude limit	V=12.4	G=20
Completeness limit	V=7.3–9.0	G=20
No. of sources	120 000	26 million to G=15 250 million to G=18 1000 million to G=20
No. of quasars	none	0.5–1 million
No. of galaxies	none	1–10 million
Target selection	input catalogue	onboard; magnitude limited
Astrometric accuracy	$\sim$1000 μas	2–3 μas at G<10 5–15 μas at G=15 40–200 μas at G=20
Broad band photometry	2 (B_T,V_T)	4–5 bands
Medium band photometry	none	10–12 bands
Spectroscopy	none	R=11 500 (848–874 nm)
Radial velocities	none	σ=1–10 kms^{-1} to G=17–18

Table 1. Comparison of the capabilities of Gaia with its predecessor Hipparcos.

AU) from timing a Venus transit, numerous expeditions were mounted to observe the four transits occurring during the 18th and 19th centuries. While the degree of accuracy and consistency of these methods in determining the AU were not as high as hoped or expected (for reasons discussed elsewhere in this volume), they nonetheless made a vital contribution. The timing of transits, for example, was an ingenious addition to our otherwise limited way of measuring cosmic distances.

Now, some 370 years after the first transit observations of Mercury and Venus in the 1630s, distance measurement in the universe remains a fundamental issue in astronomy. It is vital for understanding the structure and evolution of stars, the formation and composition of our Galaxy and ultimately for tracing the origin of the universe. Almost all aspects of astrophysics rely to some degree on accurate distances, and this ultimately relies on astrometry: the measurement of positions over time and derivations of parallaxes and proper motions from them.

The Gaia mission will mark a significant step forward in astrometry. Following in the wake of the very successful Hipparcos mission (ESA 1997), Gaia will extend Hipparcos' capabilities by several orders of magnitudes and through this make significant breakthroughs in numerous astrophysical topics. Table 1 gives a brief comparison of the main capabilities of Gaia compared to Hipparcos.

In this contribution I summarise the main aspects of the satellite, its mission and its observational principles, and provide a sample of expected science contributions. For further information the reader is referred to the concept study report (ESA 2001) and its summary (Perryman 2001). I will say little about the radial velocity spectrograph on board Gaia: for this see the contribution in this volume by Mark Cropper.

2. Global astrometry

Astrometry is the practice of accurately measuring the positions of objects on the celestial sphere. At any instant the position of a celestial object is given by two coordinates, e.g. Right Ascension and Declination. By measuring positions repeatedly over time, we can measure parallax (due to the cyclic motion of the observing platform, e.g. the Earth about the Sun) and proper motions (linear motions through space in

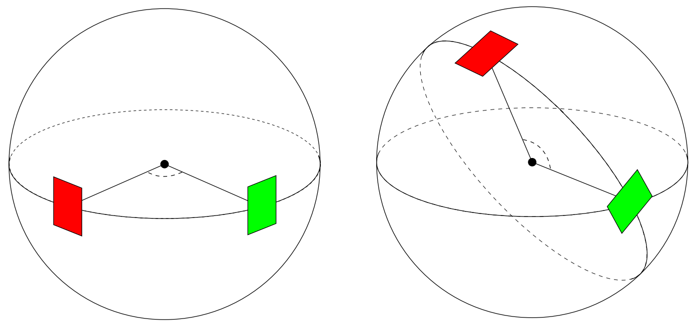

Figure 1. The key to global astrometry is to measure positions simultaneously in two fields separated by a large, fixed basic angle. By repeating this for a given field at different orientations (to give different reference stars) we can, in principle, determine absolute parallaxes.

some reference frame). Combined with the radial velocity, these yield six astrometric parameters comprising three position co-ordinates and their first order time derivatives (three velocity co-ordinates). †

Astrometry performed from the ground is done so over a narrow field. That is, stellar positions can only be measured accurately relative to nearby stars, typically within the field-of-view of the telescope. Thus the derived parallaxes (in particular) are only relative: all stars in the same direction share a common parallactic effect due to the motion of the Earth about the Sun. To perform *global astrometry* over the entire celestial sphere we must measure the positions of stars relative to other stars separated by a large angle on the sky, such that they have a different parallactic effect. Repeating this (for a given field) for many different positions angles ('reference fields'), and then measuring the positions of star in *those* reference fields with respect to yet other stars separated by large angles, we can eventually build up an entire grid of relative position measurements over the celestial sphere (Fig. 1). Note that we only accurately measure positions in one dimension, i.e. along the great circle arc connecting the two fields. Two dimensional positions are obtained from the fact that we measure along great circles inclined at a range of orientations. We know that there are 2π radians in any great circle so we can use this 'closure condition' to derive absolute positions of the objects. The choice of axes (e.g. RA and Dec) and zero point (first point of Aries) are then a matter of convention. In practice, the reduction of the data involves a large iterative solution to simultaneously derive the five astrometric parameters of a large number of stars.

The key to global astrometry is therefore to measure simultaneously the positions of stars in two widely separated fields-of-view and to observe stars spread over the entire celestial sphere several times every year for several years. (The last condition is imposed by the need to lift the degeneracy between parallax and proper motion.) To achieve this in practice we must observe from space (also to overcome complex refraction problems in the Earth's atmosphere).

This principle was used by the Hipparcos satellite, the first (and so far only) mission to perform global astrometry (Perryman et al. 1989, Kovalevsky 1995).

The *scanning law* describes how the satellite observes the sky, i.e. how the two fields shown in Fig. 1 move with time. With Gaia, it essentially consists of a three-axis motion. First, Gaia rotates about its spin axis with a period of six hours. The two viewing

† Deviations from this six parameter model are important for unresolved binary stars, which will show imposed Keplerian motions. Moreover, higher order time derivatives (e.g. accelerations) can in principle also be measured from an astrometric time series, and in fact will be important with Gaia for some bright, nearby stars (the *perspective acceleration*).

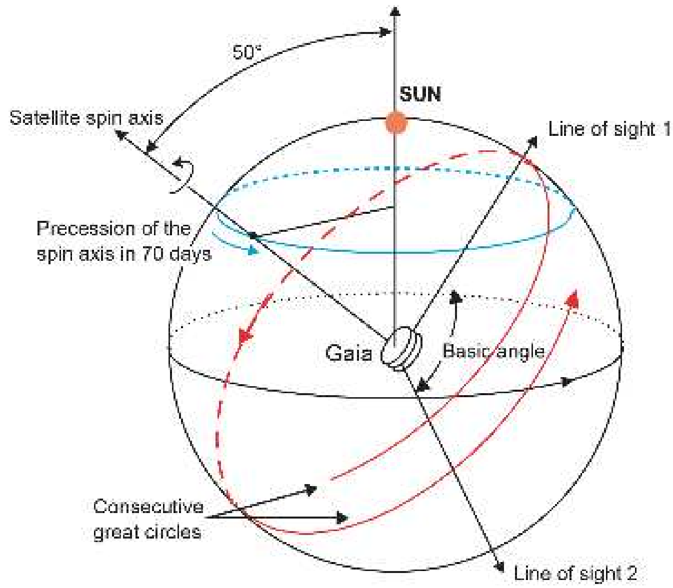

Figure 2. The Gaia measurement principle and scanning law. Gaia simultaneously observes in two viewing direction separated by a constant *basic angle*. Gaia continuously rotates about an axis perpendicular to these two viewing directions with a period of 6 hours. This axis precesses in such a way that it maintains a constant angle with respect to the Sun of 50°. The precession period is 70 days, so that every 6 hours Gaia traces a quasi-great circle across the sky. From the combination of these two motions Gaia can observe the whole sky. © ESA

directions lie in a plane perpendicular to this axis (Fig. 2). To ensure it can observe the whole sky, this spin axis simultaneously precesses (with a period of 70 days) such that it maintains a constant angle of 50° with respect to the Sun (the *Sun aspect angle*, SAA – the Sun is chosen for reasons which are described below). As it rotates and precesses, Gaia traces quasi great circles across the sky. Finally, the satellite orbits the Sun with a period of 1 year. The paths traced out by this somewhat complex motion are shown in Fig. 3.

The angle between the two viewing directions – the *basic angle* – is fixed. It is not necessary to know this angle exactly (it can be derived as part of the reduction given the close condition) but it is essential that it remain fixed, or at least that small variations of it be measured. Specifically, to reach microarcsecond accuracy, the basic angle must be constant to a few μas over the six hour spin period. This places extremely stringent requirements on the thermal and mechanical stability of the satellite. For example, thermal gradients across the optical bench must be kept below 25 μK. Mechanical drags (e.g. from the Earth's tenuous atmosphere) or thermal loads (e.g. from passing into the Earth's shadow) could make achieving this almost impossible. For this reason, Gaia will be placed in orbit about the Earth–Sun L2 Lagrange point, situated about 1.5 million km from the Earth (four times the Earth–Moon distance) in the antisolar direction.† As the Earth and Sun now lie in the same direction from Gaia, fixed in its rotating reference frame, it precesses about this axis in order to avoid ever observing the Earth or Sun. With SAA = 50° Gaia never observes closer than $90° - 50° = 40°$ from the Earth/Sun. Furthermore, with a flat sun shield deployed perpendicular to its spin axis (Fig. 4), this

† The L2 point itself in unstable so Gaia performs Lissajous orbits about it. The orbit is such that Gaia does not pass into the Earth's shadow during its five years of science operations.

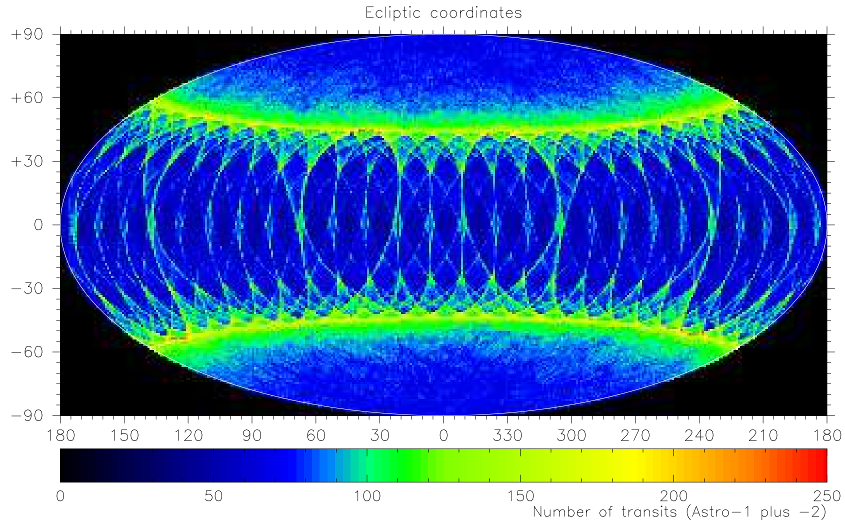

Figure 3. Sky coverage by Gaia. The two-axis motion of Gaia (rotation and precession) shown in Fig. 2 results in a non-uniform sky coverage. The coverage depends on the specific scanning law parameters, the size of the field-of-view and the duration of the mission. This shows the number of observations at each point on the sky for the nominal Gaia mission (5 years), plotted in ecliptic co-ordinates. © J. de Bruijne / ESA

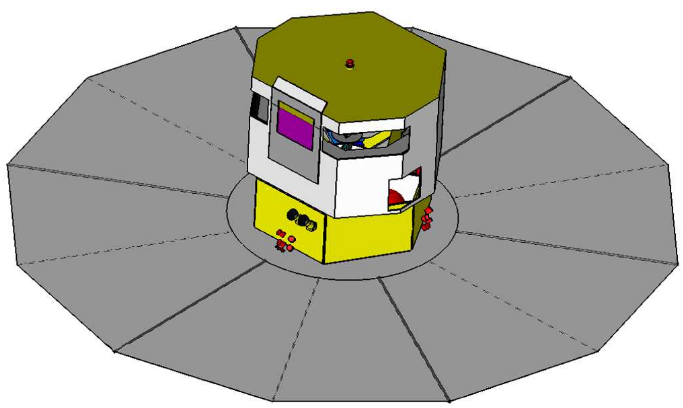

Figure 4. The Gaia satellite and sun shield. The payload module is 3.1m high and the sun shield has a diameter of 11m. Between the two entrance slits for the two astrometric fields at the top is the astrometric focal plane. © Astrium

arrangement also ensures that the solar flux on the spacecraft is constant as it precesses and orbits the Sun.

3. Gaia satellite

The scientific payload of Gaia is built around a rigid optical bench (Fig. 5). Onto this are mounted two astrometric telescopes which image the two viewing directions onto a common focal plane (together these form the *Astro* instrument). This focal plane consists of a very large number of CCD detectors: there are some 170 arranged into a rectangular grid. Each CCD contains 4500×1966 pixels with a pixel scale of $44\,\mathrm{mas} \times 133\,\mathrm{mas}$. As the satellite rotates, stars enter the focal plane from the left and drift across it at a rate of

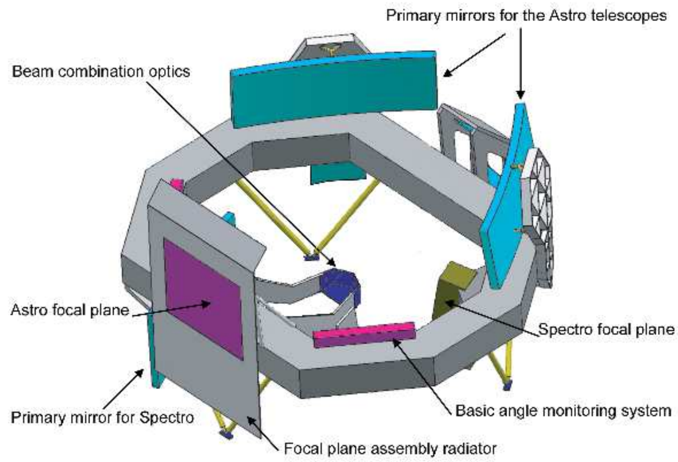

Figure 5. The Gaia payload. The two astrometric primary mirrors are $1.4\,\mathrm{m} \times 0.5\,\mathrm{m}$ in size. © Astrium

$1^\circ\,\mathrm{min}^{-1}$, crossing the focal plane in about 55 s. The CCDs are clocked in time-delayed integration (TDI) mode at the same rate to track the stars. The reason for having a large number of CCDs in the along-scan direction is to acquire a high signal-to-noise ratio (SNR) in the stars' point spread function (PSF). This is the key ingredient to precise centroiding of the PSF and hence precise angular measurements in the along scan (quasi-great circle) direction.

Gaia detects objects in real time. There is no input catalogue telling it approximately where the target objects are, as was the case with Hipparcos. With Gaia, anything with a point source magnitude of $G < 20$ is detected in real time (the G band is defined below). This is done by the *star mapper* CCDs at the leading edge of the focal plane: an initial strip of CCDs does the initial detection, and another the subsequent confirmation and rejection of cosmic rays etc. There is a separate strip of star mappers for each field-of-view, masked such that each can only see one field-of-view. The reason for these star mappers is two-fold. First, there exists no sufficiently accurate catalogue complete to G=20 over the whole sky at the required spatial resolution which could act as an input catalogue. Second, there is not enough bandwidth capacity in the Gaia antenna to transmit the entire sky to the ground. To do this we would require a data rate of around 1 Gb/s, whereas Gaia is limited to a few Mb/s, i.e. more than a hundred times lower.† Thus by using the star mapper detections, Gaia electronically allocates CCD windows (of size $265\,\mathrm{mas} \times 1590\,\mathrm{mas}$) to stars and transmits only these parts of the focal plane to the ground.

The CCDs in the main part of the astrometric focal plane are unfiltered to maximise the number of photons collected. The resulting photometric passband is determined by the CCD quantum efficiency curve and the reflectivity of the optics and is named the G band. To maximise sensitivity for the typical star (which is cool and/or reddened) the

† The reason for this limited capacity is that Gaia must use an electronically steerable array rather than a mechanically movable one, which would permit a larger data rate. A mechanically movable antenna is incompatible with the very severe requirements on mechanical stability onboard the satellite, which is essential for high accuracy astrometry.

mirrors are silver coated. The net passband therefore lies between 400 and 1000 nm. At the high level of centroiding accuracy required (ca. 1 part in 1000), chromatic effects in the optics with this broad passband are significant. The position of the centroid of the stellar PSF depends on the colour of the star and this must therefore be corrected for. This is the main task of the *Broad Band Photometer* (BBP), a set of four or five filters attached to the CCDs at the trailing edge of the focal plane. (A different colour filter is attached to each of the final strips of CCDs so that all five colours are determined essentially simultaneously with the astrometry.)

The spectroscopic instrument, *Spectro*, is a separate telescope mounted on the same optical bench as Astro (see Fig. 5). It is a 3-mirror telescope with a single viewing direction. At the focal plane, part of the field is intercepted by a dichroic mirror. This reflects the red part of the light into the *Radial Velocity Spectrograph* (RVS), described in the article by Mark Cropper in this volume. The blue transmitted light – as well as the white light in the other part of the field – arrives at another CCD focal plane, the *Medium Band Photometer* (MBP). As with Astro, this consists of an array of individual CCDs, although not as many and with a larger pixel scale than in the case of Astro. This CCD focal plane operates in the same way as the astrometric CCDs, namely clocked in TDI mode to track stars as the satellite rotates and also with an independent set of star mappers. Now, however, a different medium band filter is attached to each strip of CCDs. As a star traverses the focal plane we therefore sample its spectral energy distribution in some 10–12 passbands. The photometric system and number of filters is not finalised but it will cover most of the wavelength region between 250 and 1000 nm. The purpose of MBP is to classify the objects observed and determine the physical parameters (temperature, metallicity, surface gravity etc.) for the stars. Techniques for doing this are discussed by Bailer-Jones (2002, 2003).

4. Astrometric accuracy

The design of the Gaia satellite, in particular the size of the mirrors and focal plane, its scanning law and mission duration, are driven primarily by the astrometric accuracy we want to achieve. These in turn are dictated by the science goals, discussed in detail in the Gaia Concept and Technology Study Report (ESA 2000). Essentially, to be able to answer the main questions about the three-dimensional structure of the Galaxy and to establish the kinematics of tracer stars to sufficiently large distances and with sufficient accuracy, there are two main requirements. The first is to achieve an end-of-mission astrometric accuracy of 10 μas at G=15. The second is for the survey to extend to G=20 and still retain good accuracy.

To first order, the uncertainty in an astrometric parameter (position, parallax or proper motion), σ_a, is given by $\sigma_a \sim 1/\sqrt{N}$, where N is the number of photons collected (Lindegren 1978, ESA 2000). Large N is achieved with a large aperture, a large field-of-view (so that a given star will be observed more often with a given scanning law), a large focal plane (so that each star is observed for longer during a transit) and a long mission life (so each star is observed many times).

Denoting the uncertainty in a parallax measurement with $\delta\varpi$, the corresponding uncertainty in the distance, d, is $\delta d \sim d^2 \delta\varpi$ (for $\delta\varpi \ll 1$). Thus for a given parallax accuracy, the fractional distance accuracy decreases linearly with increasing distance. For a given type of star (fixed intrinsic luminosity), $N \sim 1/d^2$, and hence $\delta d \sim d^3$. Roughly speaking, given the five year mission of Gaia, the astrometric and parallax accuracy are the same as each other (e.g. 10 μas) and the same as the proper motion accuracy expressed per year (10 μas yr^{-1}). From this we can see how the distance accuracy varies with distance

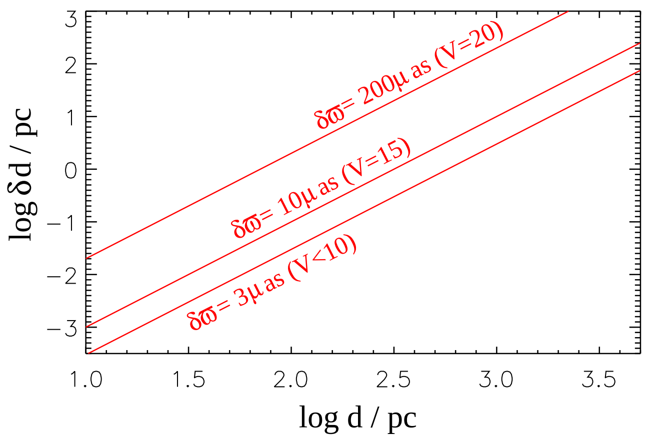

Figure 6. The Gaia distance accuracy at three magnitudes. To first order the uncertainty in the distance, d, is $\delta d \sim d^2 \delta\varpi$, where the parallax accuracy, $\delta\varpi$, depends only on the apparent brightness (to first order) as $\delta\varpi \sim 1/\sqrt{N}$ (N is the number of photons collected).

distance accuracy			*tangential velocity accuracy*		
0.2%	at d = 200 pc	at V = 15	0.1 $\mathrm{kms^{-1}}$	at d = 2 kpc	at V = 15
1%	at d = 1 kpc	at V = 15	1 $\mathrm{kms^{-1}}$	at d = 20 kpc	at V = 15
20%	at d = 1 kpc	at V = 20	1 $\mathrm{kms^{-1}}$	at d = 1 kpc	at V = 20
accuracies achieved			*accuracies achieved*		
< 0.1%	for 700 000 stars		0.5 $\mathrm{kms^{-1}}$	for 44 million stars	
< 1%	for 21 million stars		1 $\mathrm{kms^{-1}}$	for 85 million stars	
< 10%	for 220 million stars		5 $\mathrm{kms^{-1}}$	for 300 million stars	

Table 2. Predictions (from ESA 2000) of the distance and tangential velocity accuracy which Gaia will achieve. It may be useful to recall than at a distance of 200 pc, a velocity of 1$\mathrm{kms^{-1}}$ gives rise to a proper motion of 1 mas $\mathrm{yr^{-1}}$.

(Fig. 6). Combining these estimates with Galaxy models we can determine the number of objects which obtain various accuracy levels (Table 2). We see immediately the vast numbers of objects for which very accurate distances are determined, e.g. some 20 million with distances better than 1% (which includes stars down to G=20 and with distances of up to a few kpc). In comparison, Hipparcos only obtained this distance accuracy for stars brighter than V=10 which were nearer than 10 pc, a mere handful of objects (168 to be precise).

5. Scientific contributions

A brief overview of Gaia's capabilities and likely contributions in five scientific fields is now presented. For more information and references see the Gaia Concept and Technology Study Report (ESA 2000) and the summary by Perryman et al. (2001), from which much of this section has been drawn. For more up-to-date information see the Gaia website `http://www.rssd.esa.int/gaia`

5.1. *Solar system*

Due to its high proper motion sensitivity, Gaia will detect numerous minor planets in our solar system. In particular it is expected that it will detect some 10^5–10^6 new objects in the main asteroid belt, compared to fewer than 10^5 currently known. The detailed statistics of orbital elements so derived can be used to investigate the formation of the solar system. Knowing their distances, the apparent magnitudes of asteroids can be used to derive their albedos. The medium and broad band photometry from Gaia will be used to classify asteroids and thus derive their chemical compositions. Furthermore, it is expected that during the lifetime of Gaia some 100 close mutual encounters will be observed and their open (hyperbolic) orbits traced: from this asteroid masses can be determined. This would increase the number of directly (i.e. dynamically) determined asteroid masses from the present number of about 20. Combined with size measurements from stellar occultations, densities may be derived, thus providing insight into their chemical composition and thus that of the primordial solar environment.

Because Gaia will be able to observe nearer to the Sun (within 40°) and which much higher accuracy than is possible from the ground, it will make important contributions toward the study of Near Earth Objects (NEOs). Some of these asteroids, such as those of the Apollo and Athen groups, cross the Earth's orbit and so are potentially at risk of collision. As Gaia performs real-time onboard detection, it will detect and observe such objects many times over the course of its mission. It should be able to discover and determine accurate orbits for all NEOs with diameters larger than a few hundred metres.

The Trojans are asteroids situated around the Lagrange L_4 and L_5 points of planets, where stable orbits can be maintained for hundreds of millions of years. Planetary perturbations and mutual close encounters mean that they can have orbits elongated around the L_4 and L_5 points of their 'host' planet. Trojans are known for the outer planets, but in the inner solar systems the only known ones are two Martian Trojans. It is still not known whether the Trojans were captured or formed in situ, or even whether they have similar compositions to the main belt asteroids. Due to the large area it covers, Gaia will undertake a systematic survey for the Trojans of all planets, including, for the first time, for Venus.

Gaia will just about be sensitive enough to detect the very faint, red population in the Edgeworth-Kuiper Belt (EKB). The EKB, situated around 40 AU from the Sun, is a population of icy bodies which appear to be a remnant of the formation of the solar system. Pluto is its largest member. An improved census of the EKB members, their orbits and intrinsic properties will provide further insight into the formation of planetary systems. Although Gaia's sensitivity will not permit detections of large numbers of these very faint, cold objects, it is predicted to discover some 50 new objects. Of these, 5–10 are expected to be binaries.

5.2. *Exosolar planets*

Through its high precision, multi-epoch astrometry Gaia will be able to detect the positional 'wobble' of a star due to the gravitational force of a companion. Not only will this allow Gaia to detect hundreds of millions of visually unresolved binary stars, but the sensitivity is high enough to detect motions caused by planetary mass companions. To date, most exoplanets have been detected by the radial velocity method, i.e. the variable Doppler shift of spectral lines induced by relative motions, although a few have been detected by astrometry (see the article by F. Benedict in this volume) and via photometric detection of transits. The astrometric amplitude of the motion of a star of mass $M_{\rm s}$ due a planet of mass $M_{\rm p}$ orbiting at a distance a is

$$\alpha/'' = \left(\frac{M_{\rm p}}{M_{\rm s}}\right)\left(\frac{a/{\rm AU}}{d/{\rm pc}}\right)$$

where d is the distance to the system from the Earth. For example, the 47 Ursa Majoris system is predicted to give an amplitude of $360\,\mu$as. The astrometric method is most sensitive to large or long period orbits, which is the opposite of the radial velocity (RV) technique. Therefore the techniques are complementary. But because the astrometric signature is observed in a two-dimensional plane we can determine the inclination of the Keplerian orbit. This allows a determination of the mass of the planet without the $\sin i$ ambiguity inherent to the RV technique (in which we only observe the projected orbital velocities).†

Gaia will be most useful for finding planets around stars with V< 13, with good capabilities out to about d = 200 pc. This covers a vast number of stars – around 100 000, far more than have been observed with current RV planet surveys – over a wide range of spectral types. With a mission of five years, Gaia will be able to determine orbits for planets with periods of up to about 10 years. Extrapolating from current known systems (and only a limited part of the orbital parameter space has been explored), it is expected that Gaia will detect some 5000 new planetary systems (compared to some 120 known as of mid 2004) and determine accurate orbital elements for 1000–2000 of them. From the above equation, we see that for a given size of orbit and mass of star, the minimum mass planet which Gaia can detect decreases linearly with distance. For the nearest stars – closer than 10 pc – Gaia will be able to detect planets with 3% of the mass of Juipter, or 10 Earth masses.

This extensive exoplanetary survey will provide detailed statistics on the types of planetary systems which stars of different mass, metallicity, and age do and do not host. This will mark a major contribution to understanding the formation and evolution of planetary systems.

Gaia should also be able to detect some planets when they transit across their host stars and thus cause a dimming of the integrated light received by Gaia. Of course this only occurs for near edge-on orbits (i.e. $i \simeq 90°$). As Jupiter has a diameter about ten times smaller than the Sun, its transit would cause the Sun to dim by 1%. To detect this with a signal-to-noise of 10 in the G band requires a photometric precision of 1 millimag, easily achieved in single epoch photometry for stars brighter than about G = 13–14. Despite the relatively poor time sampling for transits, Gaia observes millions of such stars. Predictions have been made that of order 6000 planets around F–K type stars with semi-major axes in the range 0–2 AU will be detected this way. Incidentally, and in keeping with the theme of this conference, a transit of Venus across the Sun (radius ratio of 1/115) observed from a large distance (not from the Earth!) causes a maximum dimming of 0.08 millimag. This is at the level at which Gaia photometry will probably be dominated by systematic errors so is unlikely to be detectable even for the brightest stars.

† With both the astrometric and RV techniques we can only determine the mass of the planet (or rather $m \sin i$ for the RV method) if we assume a mass for the star: just astrometry or RV alone does not allow us to determine the individual masses of unresolved systems. However, in many cases, the stellar mass can be determined with reasonable accuracy from Gaia's photometry.

5.3. *Star formation and stellar clusters*

Most star formation occurs in cold, dense, dark molecular clouds. As gas is converted into stars via gravitational collapse (and quite possibly via the dissipation of supersonic turbulence), the cloud emerges from being an embedded cluster to an optically visible young star forming region or open cluster, such as the dense Orion Nebula Cluster or the less dense low mass star forming region Taurus–Auriga (with ages of a few million years). Such clusters evolve dynamically: internal encounters will slowly evaporate the lower mass members and interactions with the Galactic tidal field and passing interstellar clouds will disrupt all but the densest clusters. Surveys of stellar clusters show a mark drop off in numbers beyond a few hundred million years in age. Thus is appears that almost all clusters will disperse into the Galactic field population over a timescale somewhat less than 1 Gyr.

By studying the structure and content of clusters – in particular the initial mass function and binarity – at different ages and abundances we therefore study the recent star formation history of the Galaxy.

Gaia will make some of its most fundamental contributions in this area. First, by measuring very accurate distances for individual stars in clusters, it will allow an accurate determination of stellar luminosities across a wide range of evolutionary phases, thus making vital tests of theories of stellar structure and evolution. For the nearest clusters, such as the Hyades, Gaia will determine the IMF (corrected for binarity) down into the brown dwarf regime and down to a solar mass for cluster as far away as 3 kpc. By accurately determining the distances to subgiants, the position of the Main Sequence turn off can be determined to much higher accuracy than is presently possible, resulting in a significant improvement in age determinations through isochrone fitting.

Of the 1000 clusters currently known (mostly within 2 kpc), distances are only known to about half of them, of which many are still highly uncertain, by factors of two or more. According to WEBDA there are some 70 clusters within 500 pc, of which 20 are closer than 200 pc. For all of these, Gaia will determine distances to *individual* members brighter than $V = 15$ to better than 0.5%. This corresponds to a depth accuracy of 2.5 pc at 500 pc or better for nearer cluster and/or brighter stars. These data will provide a three dimensional map of clusters and their mass distribution. Combined with accurate three dimensional velocities from the radial velocities and proper motions, we will be able to study the dynamical evolution of clusters across a range of characteristics in much more detail than has previously been possible. Recalling that Gaia's distance accuracy, δd, depends on distance, d, as $\delta d \sim d^2$ for a star of given apparent magnitude, then at a distance of 100 pc the depth uncertainty is only 0.1% or 0.1 pc. For a given type of star, i.e. of given intrinsic luminosity, $\delta d \sim d^3$. Thus out to 200 pc, Gaia will measure the distances to all giants and all dwarfs earlier than about K5–M0V to better than 1 part in 250. In terms of kinematics, all these stars will have their tangential velocities determined to better than 1 kms^{-1}. Extending the range to 500 pc, then giant star kinematics are still measured with this precision or better, as are dwarfs earlier than mid A types. Armed with this information we can investigate mass segregation, ejection and the the dispersion of clusters.

The power of Gaia comes in the vast number of stars it observes over the whole sky with a well-defined selection function. By searching for clusterings in the multidimensional space formed by the 3D spatial co-ordinates, the 3D velocity co-ordinates, as well as "astrophysical co-ordinates" ($T_{\rm eff}$, [M/H] etc. obtained from Gaia photometry) we can use the Gaia archive to detect new clusters, associations and moving groups out to several kpc. This will provide a much more complete, systematic and reliable survey for stellar clusters than has hitherto been possible.

5.4. *Galactic structure*

Gaia's combination of 6D phase space information and astrophysical parameter determination make it a unique instrument for determining the large scale structure of our Galaxy. It is here that its faint limiting magnitude, all-sky coverage and determination of stellar properties (especially metallicity) are particularly important. We can, for example, investigate the age–metallicity relation (using long-lived K and M dwarfs) with a much larger sample than has been possible to date. A dynamical determination of the mass of the disk and its dark matter content will likewise be possible, as is a determination of the Galactic rotation curves out to large Galactocentric distances.

Within the Galactic disk, Gaia will provide an accurate mapping of star forming regions and spiral arms. Interstellar extinction will ultimately limit how far Gaia can see in the Galactic plane, but by identifying and measuring parallaxes of very luminous Cepheid variables, for instance, we can map out structure to large distances.

Moving to the halo, the Gaia database will allow us to search for stellar clusterings in the Galactic halo which may be hallmarks of merger events. In addition to the spatial overdensity searches generally carried out with existing star-count data sets, we can apply multidimensional cluster search algorithms to look for intrinsic patterns in a space–velocity–astrophysical parameter space. This would be relevant for finding halo streams which may not be spatially distinct but nonetheless share a common orbit and/or star formation epoch. Even at 10 kpc, Gaia can determine tangential velocities to $0.5\,\mathrm{km s^{-1}}$ for stars as faint as G=15 (i.e. with absolute magnitudes less than zero, such as OB main-sequence stars and K giants). In the outer halo (>20 kpc from the Galactic Centre), most stars will have relatively uncertain parallaxes (parallax errors of greater than 20% for $G>15$). However, photometric 'parallaxes' may then provide a reasonable distance estimate from which proper motions may still be converted to tangential velocities of useful precision. Moreover, as intervening foreground objects will have much larger (and accurate) parallaxes, these foreground 'contaminants' can be distinguished from the background tracers giants which may then be used as kinematic and density tracers in the halo.

5.5. *Extragalactic*

Beyond our Galaxy, the parallaxes of individual objects will be negligible. By averaging over a population, useful results may be obtained. For example, the Large Magellanic Cloud (LMC) has a parallax of about $20\,\mu$as. But by averaging over a suitable set of members, a geometric distance to the LMC with an accuracy of about 1% should be obtainable.

In studying local group galaxies, Gaia proper motions will permit a better distinction between stars in our Galaxy and those in external galaxies. With a reliable selection, mean distances and motions of local group galaxies can be determined. By determining 3D orbits within the local group out to 1–2 Mpc (which includes some 20 galaxies), it may be possible to probe fluctuations in the initial density distribution of matter on cosmological scales.

An important aspect of Gaia is its direct optical observations of quasars. From these, Gaia astrometry will be tied to a quasi-inertial reference frame with an accuracy of better than $1\,\mu\mathrm{as\,yr^{-1}}$. Down to its limiting magnitude of $G=20$, it is predicted that Gaia will detect around half a million quasars. These will be observed in all of Gaia's 15 photometric bands at some 100 epochs from which the classes of quasars and their variability may be studied. Interestingly, Gaia will be sensitive to the motion of the solar system barycentre about the Galactic Centre. This motion induces an aberration in the position of distant objects such as quasars. With the Sun moving at 220 $\mathrm{km s^{-1}}$ at a distance of 8.5 kpc about the Galactic Centre with a period of 250 Myr, quasars will show an apparent proper motion of about 4 μas $\mathrm{yr^{-1}}$.

Gaia performs real-time onboard detection of everything with a point source magnitude brighter than $G = 20$. Thus transient events, in particular supernovae, will be detectable. Based on the current known supernovae rate, Gaia will catch about 50 supernovae *per day.* A real-time classification and alerts system is envisaged for such events, from which rapid follow up by other observatories will be possible.

Finally, because Gaia will measure distances accurately to very large numbers of different types of stars, including RR Lyraes and Cepheids, it will permit a much better calibration of primary distance indicators than has hitherto been possible. This will provide a geometrically calibrated distance scale which is independent of CMB or cosmological models.

6. Current status and data analysis

At the time of writing (mid 2004) Gaia is planned for launch in 2011. Present efforts focus on several essential technology developments on the industrial side, related, for example, to the CCDs, SiC mirrors and FEEP thrusters. On the scientific side, the major on-going effort is preparation for the data analysis.

Gaia will produce data at a rate of about 1 MB/s for 5 years, producing a total of some 100 TB raw data. This quantity of data is not actually that large. The challenging issue with the Gaia data processing it the complexity of the data. Due to the continuous scanning of the satellite over a period of five years, the astrometric data stream essentially consists of a strip of data focal plane data 2.6 million degrees in length. Each object typically appears 100 times in this data strip. Thus the data reduction involves object matching in the 7000 or so different quasi-great circle scans making up this strip. The relative one-dimensional positions of a few hundred million stars must then be determined from which the five basic astrometric co-ordinates of each of these stars are solved for in the so-called *Global Iterative Solution* (GIS). This process must simultaneously solve for the attitude of the satellite and the various instrument calibration parameters. Numerous additional astrometric reduction tasks much be included, such as solving for higher order astrometric terms of binary star systems. Furthermore, the radial velocity data and photometric data must also be included, often simultaneously. For example, the colour of the star must be included in the astrometric reduction, as must be the radial velocity for nearby, high proper motion stars (as their parallaxes and proper motions will not be constant with time).

The data analysis with Gaia is therefore a major challenge. A data reduction prototype, GDAAS, has been running for a few years which is studying these problems. Beyond this, efforts are also ongoing to ensure that the resulting Gaia database can be properly exploited for subsequent scientific work. These include experiments in data mining and work on theoretical models against which Galactic structure and kinematic data may be compared.

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