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Prospects for Gaia and other space-based surveys

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Abstract. Gaia is a fully-approved all-sky astrometric and photometric survey due for launch in 2011. It will measure accurate parallaxes and proper motions for everything brighter than G=20 (ca. 10^9 stars). Its primary objective is to study the composition, origin and evolution of our Galaxy from the 3D structure, 3D velocities, abundances and ages of its stars. In some respects it can be considered as a cosmological survey at redshift zero. Several other upcoming space-based surveys, in particular JWST and Herschel, will study star and galaxy formation in the early (high-redshift) universe. In this paper I briefly describe these missions, as well as SIM and Jasmine, and explain why they need to observe from space. I then discuss some Galactic science contributions of Gaia concerning dark matter, the search for substructure, stellar populations and the mass–luminosity relation. The Gaia data are complex and require the development of novel analysis methods; here I summarize the principle of the astrometric processing. In the last two sections I outline how the Gaia data can be exploited in connection with other observational and theoretical work in order to build up a more comprehensive picture of galactic evolution.

Key words. Space vehicles – Methods: data analysis – Surveys – Astrometry – Galaxy: general

1. Why observe from space?

Observing from space is not merely desirable. It is *essential* for certain types of observation or instrumentation. The Earth's atmosphere strongly absorbs over much of the electromagnetic spectrum, in particular in the X-ray, UV and near- and far-infrared. Most of these regions cannot be observed from the ground at all. Even in regions which are accessible from the ground (such as various near-infrared windows), the background in space is much fainter, permitting deeper observations. Above the atmosphere we can also achieve diffraction-limited imaging. As well as increasing the spatial resolution, this has the additional advantage that deeper observations of point sources are possible (because less background light is integrated into the smaller point-spread function). Temporal and spatial variations in the refractivity of the Earth's atmosphere limit the accuracy of wide-field astrometry to about 1 mas. It is primarily for this reason that all accurate optical wide-field astrometry projects must be performed from space.

Space offers a stable environment in a more general sense. Weather and the diurnal and annual cycles on the Earth give rise to significant temperature variations, creating significant problems in accurate metrology (required in astrometry or interferometry). To avoid these disturbances, instruments have to be placed in large (and expensive) isolating vessels and/or the variations must be carefully monitored and calibrated. Human and seismic activity adds further mechanical disturbances. Various orbits in space offer an environment which is mechanically and thermally much more stable. Suitable orbits include the L1, L4 and L5 Lagrange points of the Earth–Sun system. (L3 is not visible from the Earth so is of limited use.) The L2 point actually sits in the shadow of the Earth, and is dynamically unstable (as are L1 and L3) but Lissajous orbits about this point is stable for extended periods and can avoid eclipses (by the Earth, but not necessarily the Moon) for many years. These orbits are far from any residual Earth atmospheric drag and so offer very stable environments. They are attractive for astrometric and interferometric instruments which require stability or control at levels which are difficult to achieve on the ground. Herschel, Planck, Gaia and JWST will all be placed in L2 orbits (WMAP is already in one) and LISA Pathfinder will be (and SOHO already is) in an L1 orbit. Other orbits offer similar conditions, such as an Earth-trailing heliocentric one (used by Spitzer and planned for SIM).

A space telescope can access the entire sky over a short time period. This is important for global astrometry (see section 3.7). Finally, space allows multiple satellites to be manoeuvred into arbitrary three-dimensional configurations (“formation flying”), as will be required by planned interferometers (LISA, Darwin).

Observing from space also brings with it disadvantages. After launch the instruments are inaccessible, making maintenance and upgrades impossible. (The serviceability of HST came at an enormous cost: A single Space Shuttle launch alone cost about half a billion US dollars, so this will surely not be repeated in a hurry.) Therefore the instruments, telescope and other systems must be very robust, and this increases the cost. Even then, cosmic radiation degrades electronic components – in particular the CCDs – and the optics, degrading performance and complicating calibrations. Once instruments are placed in distant orbits, e.g. the Earth–Sun L2 orbit, the available bandwidth for data transfer is reduced (because for a given mass/size/cost of satellite the power available is limited). This may restrict the amount of science data which can be transmitted to the ground or it may impact the observing strategy (both are the case for Gaia).

2. Upcoming missions

I now describe some upcoming missions which have a significant Galactic astrophysics component. I limit myself to a selection of missions not yet launched, omitting projects in the very early planning stage.

2.1. Herschel

Herschel is a far infrared and sub-mm ESA observatory due for launch in 2008. It comprises several imaging and spectroscopic instruments operating between 60 and 670μm and is the only space facility dedicated to this part of the spectrum. The key science objective of Herschel is the formation of stars and galaxies. Its major mode of operation will be deep, multi-band photometric surveys (plus follow-up spectroscopy) to search for proto-galaxies. In this way it will investigate the formation and evolution of galaxy bulges and elliptical galaxies during the first third of the present age of the universe, determining how the galaxy luminosity function and star formation rate has evolved with time. Herschel will also study the physics and chemistry of the interstellar medium (both in our Galaxy and nearby galaxies) and address the question of how stars form out of molecular clouds. While surveys are expected to occupy much of its science time, Herschel is a multi-user observatory, with two thirds of its time open via competitive application. Website: http://www.rssd.esa.int/herschel

2.2. JWST

The James Webb Space Telescope will also be an infrared imaging and spectroscopic facility but operating at shorter wavelengths than

Herschel, between 0.6 and 27μm. It is optimized for diffraction limited imaging in the 2–5μm region. With a 6.5m diameter primary mirror it will be able to perform very deep imaging in "pencil beam" surveys (the field-of-view of each instrument being just a few arcmin). It has four instruments operating over different wavelength ranges, three of which have spectroscopic modes with resolving powers between 100 and 7000. Although JWST was once conceived as the successor to HST this is no longer the case, because it operates over a different wavelength range (HST operated between 0.1–2.5μm; JWST lacks blue and UV sensitivity). One of the main science objectives of JWST is to study the early universe, in particular the epoch of the first stars and the formation of the first galaxies. The other major theme concerns star and planet formation in our own Galaxy and the study of exoplanetary systems. JWST will be a multi-user observatory and so inevitably will be used for a very wide range of topics. Under the present plan, JWST should be launched in around 2013. Website: http://www.jwst.nasa.gov/

2.3. SIM PlanetQuest

The Space Interferometry Mission plans to be the first long-baseline, space-based interferometer. The original concept of synthetic imaging has been dropped; the goal now is to perform astrometry to a limiting precision of 4μas over a wide field (15°) and 1μas over a narrow field (1°). Unlike Hipparcos and Gaia, SIM is a pointed-mission, so the integration time can be set according to the target magnitude and precision required. Several key programmes have been approved which relate mostly to planet finding and to Galactic structure. The latter includes calibration of the stellar Mass–Luminosity relation, measuring the distances and ages of globular clusters and measuring the Galactic potential via stellar proper motions. Dedicated observations taking about a quarter of the mission's time will be used to measure reference frame objects to achieve absolute astrometry. Many of these science objectives will be covered "automatically" by Gaia (because it is an all-sky survey), and with many more stars. However, SIM would be a natural follow-up to Gaia, because, as a pointed mission, SIM could observe selected sources more accurately. This complementarity with Gaia should be taken into account when specifying the SIM science programme and reviewing detailed proposals (a third of the observing time will be open to competition). At the time of writing (August 2006), the SIM (NASA) funding situation is rather "chaotic" (to quote a senior scientist close to the mission). It is unclear whether SIM will receive funding or when, but the best estimate is for a launch no earlier than 2015. Website: http://sim.jpl.nasa.gov/

2.4. Jasmine

Jasmine is a project near infrared astrometry project. The current design is based on CCD detectors operating in the z-band with the Galactic bulge as the target. Although its observing method does not permit it to independently determine "absolute" proper motions, by observing stars with proper motions accurately determined by Gaia an external calibration is achieved. If approved by the Japan Aerospace Exploration Agency (JAXA) when proposed in 2010, it could launch by 2015. A related mission, Nano-Jasmine, operating on the principle of Hipparcos and Gaia, will perform 1 mas optical astrometry using a 5 cm telescope and should launch in 2008. Jasmine is the subject of several poster papers at this Joint Discussion and reported on in these proceedings. Website: http://www.jasmine-galaxy.org/index.html

3. Gaia

3.1. Gaia in a nutshell

Gaia is an all sky astrometric and photometric survey complete to magnitude G=20 (V=20–22), which covers 10^9 stars, a million quasars and a few million galaxies. Gaia will achieve an astrometric accuracy of 12–25 μas at G=15 (providing a distance accuracy of 1–2% at 1 kpc) and 100–300 μas at G=20. These numbers are also the approximate parallax accuracy in μas and the proper motion accuracy in

μas/year. The range reflects the colour dependency: larger accuracy is achieved for redder sources. Astrometry and photometry are done in a broad ("white light") band (G). Gaia will also measure radial velocities to a precision of 1–15 km/s for stars with V=17 via R=11 500 resolution spectroscopy around the CaII triplet (the "Radial Velocity Spectrograph", RVS). To characterize all sources (which are detected in real time), each is observed via low dispersion prism spectrophotometry over 330–1000 nm with a dispersion between 3 and 30 nm/pixel. From this we will estimate the "usual" astrophysical parameters, $T_{\rm eff}$, $\log g$ and [Fe/H], but also [α/Fe] and the line-of-sight extinction to stars individually. (The radial velocity spectrograph helps the parameter determination plus the detection of emission lines and abundance anomalies.)

Gaia is a fully-funded ESA mission due for launch in late 2011. With a nominal mission of five years and three years planned for post-mission processing, the final catalogue will be available in about 2020. It is the only large scale, high-accuracy astrometry mission under construction. For more information on the satellite, science and data processing see http://www.rssd.esa.int/Gaia and (Turon et al. 2005) (also available from the website). In the rest of this section I describe how Gaia will contribute to some important topics in Galactic astronomy.

3.2. Distances

Distances are vital in every area of astronomy. We need them to convert 2D angular positions to 3D spatial coordinates, allowing us to reveal the internal structure of stellar clusters or map the location of the spiral arms, for example. Knowing the distance we can convert 2D (angular) proper motions to physical velocities, and the apparent luminosity to the intrinsic luminosity, a fundamental quantity in stellar structure and evolution studies. Parallaxes are essentially the only method of direct distance determination, and the only one which does not make assumptions about the target source. We can measure parallaxes to virtually anything (not just, say, eclipsing binaries) and virtually all other rungs in the distance ladder are ultimately calibrated by them.

The impressive astrometric accuracy of Gaia is better illustrated when convolved with a model of the Galaxy. This shows that Gaia will yield distances with an accuracy of 1% or better for 11 million stars. This compares to fewer than 200 stars now with a parallax of this accuracy obtained from Hipparcos, all of which lie within 10 pc. Some 100 000 stars will have a distance accuracy better than 0.1% and about 150 million better than 10%. Gaia goes far beyond anything we currently have in both accuracy *and* statistics and hardly any field of astrophysics will remain untouched.

3.3. Galactic structure and formation

One of the most important questions Gaia will address is that of how and when the Galaxy formed. ΛCDM models of galaxy formation predict that galaxies are built up by the hierarchical merger of smaller components (Freeman & Bland-Hawthorn 2002). Indeed, models predict that the halo is composed primarily of the remains of mergers. From extragalactic observations there is good evidence for both the accretion of small components and for the merging of similar-sized galaxies. Within our own Galaxy, recent surveys over the past ten years – 2MASS and SDSS in particular – have found the fossils of past and ongoing mergers in the halo and possibly also the disk of our Galaxy. They have all been identified as spatial overdensities in two-dimensional (angular) photometric maps of large areas of the sky. In some cases, distance measures have been included by taking magnitude as a distance proxy (Belokurov et al. 2006) or by examining the 2D density of a limited range of spectral types (i.e. using a spectroscopic parallax of some tracers stars) (Yanny et al. 2000). But because merging satellites are disrupted by the Galactic potential and the material spread out after several orbits, density maps are a limited means of finding substructure. Without an accurate distance the interpretation of 2D maps is plagued by projection effects. Even with perfect 3D maps, the contrast against the background (including other streams) is often low

(Brown et al. 2005). To improve this, we need 3D kinematics, i.e. radial velocities and proper motions (combined with distances). In an axisymmetric potential the component of angular momentum parallel to this axis (L_z) of a merging satellite is an integral of motion. In a static potential, the energy (E) is also an integral of motion (Binney & Tremaine 1987). Thus while a merging satellite could be well-mixed spatially, it would remain unperturbed in (L_z, E) space. Of course, the Galactic potential is neither time-independent nor perfectly axisymmetric and Gaia has measurement errors, but simulations have demonstrated that Gaia will be able to detect numerous streams 10 Gyr or more (i.e. many orbits) after the start of disruption (Helmi & de Zeeuw 2000).

Gaia will perform a 5D phase space survey over the whole sky, with the sixth component – radial velocity – being available for stars brighter than V=17. At this magnitude, spectral types A5III, AOV and K1III (which all have $M_V \simeq 1.0$) are seen at a distance of 16 kpc (for zero extinction). The corresponding proper motion accuracy is about 50 μas/yr, or 4 km/s. In converting proper motions to velocities the dominant source of uncertainty (in this case) is the parallax error, which is about 100% for G=17 at 16 kpc. In such cases, Gaia would rely on a "spectroscopic" parallax (calibrated, of course, with Gaia observations). In addition to the 5D or 6D phase space information, Gaia provides abundances and ages for individual stars. Search for patterns in this even higher dimensional space permits an even more sensitive (or reliable) search for substructure. To properly exploit this data it will clearly be necessary to develop dynamic models of the Galaxy with include stellar and chemical evolution.

3.4. Dark matter

Two distinct aspects of the Gaia mission permit us to study the mass and distribution of dark matter in our Galaxy. First, from the 3D kinematics of selected tracer stars, Gaia will map the total gravitational potential (dark and bright) of our Galaxy, in particular the disk. Second, from its parallaxes and photometry Gaia will make a detailed and accurate measurement of the stellar luminosity function. This may be converted to a (present-day) stellar mass function via the Mass–Luminosity relation (see section 3.6). From this we can infer a stellar mass distribution. Subtracting this from the total mass distribution obtained from the kinematics yields the dark matter distribution. This will be the first time that the distribution of dark matter is accurately mapped on small length scales (less than 1 Mpc).

3.5. Stellar structure, evolution and clusters

Stellar luminosity is one of the most fundamental predictions of a stellar model. Its measurement across a range of masses, ages and abundances is a critical ingredient for testing and improving these models. In open and globular clusters an accurate determination of luminosities and effective temperatures (which Gaia also provides) gives us the HR diagram for different stellar populations. (To derive an accurate luminosity we also need an accurate estimate of the line-of-sight extinction. This will be obtained star-by-star from the Gaia spectrophotometry.) We may then address fundamental questions of stellar structure, such as the bulk Helium abundance (which is not observable in the spectrum), convective overshooting and diffusion. One of the main uncertainties in the age estimation in clusters is accurately locating the main sequence (for open clusters) or main sequence turn off (for globular clusters). Gaia's accurate parallaxes and unbiased (magnitude-limited) survey will greatly improve this.

In addition to using clusters as samples for refining stellar structure and evolution, we can also study them as populations. Gaia will observe many hundreds of clusters, allowing us to determine the (initial) mass function into the brown dwarf regime and examine its dependence on parameters such as metallicity, stellar density and environment. There are perhaps 70 open clusters and star formation regions with 500pc. Gaia will provide distances to better than 1% individually for *all* stars brighter than G=15, and to 0.1% or better for slightly brighter or nearer stars. This will permit us, for the first time, to map the 3D spatial structure of many clusters, with a depth accuracy as good as 0.5–1 pc for clusters at 200 pc. From the 3D kinematics we can likewise study the internal dynamics of a cluster. Recall that a proper motion of 1 mas/yr at a distance of 1 kpc corresponds to a speed of about 5 km/s. A G=15 star will have its proper motion measured with an accuracy of 20 μas/yr, corresponding to a speed uncertainty of 0.1 km/s at this distance (half this for a red star). The speed uncertainty varies linearly with the distance for a fixed magnitude, so at 200 pc the speed uncertainty is just 20 m/s. With this accuracy[1] we can measure the internal kinematics of the cluster and so investigate the phenomena of mass segregation, low mass star evaporation and the dispersion of clusters into the Galactic field.

Just as Gaia is an ideal tool for identifying the fossils of past mergers from their phase space substructure (section 3.3), so the 6D phase space data plus astrophysical parameters for tens of millions of stars will allow Gaia to detect new stellar clusters, associations or moving groups based on their clustering in a suitable multi-dimensional parameter space. (It can likewise confirm or refute the existence of controversial clusters.) Work is ongoing to develop and apply machine learning techniques to this problem.

3.6. Stellar mass–luminosity relation

Gaia will detected many binary systems. These are found primarily via the astrometry (nonlinear astrometric solutions which do not fit the standard 5-parameter model), but also as spectroscopic binaries in the RVS, eclipsing binaries in the photometry, or as unresolved binaries from the detection of two spectral energy distributions as part of the classification work. For those systems with orbital periods of about ten years or less, Gaia can solve for the orbital elements and for the total mass of the system. If the components of the system are spatially resolved then we may determine their individual masses. Gaia furthermore measures accurate intrinsic luminosities. Together these allow us to determine the stellar Mass–Luminosity relation, and to do it with more stars and over a wider mass range that has yet been performed.

3.7. Data processing

Gaia observes in two fields of view separated by a fixed *basic angle* of about 100°. It continuously rotates around an axis perpendicular to the plane formed by these two viewing directions. In a single rotation period of six hours Gaia therefore observes (in each field) a great circle on the sky. In addition, the rotation axis precesses (with a period of 70 days) such that the rotation axis keeps a constant angle with respect to the Sun of 45°(see Fig. 1). This two axis motion, plus the orbit of Gaia about the Sun, defines the nominal scanning law, i.e. how Gaia observes the sky. The Gaia focal plane is covered with just over 100 CCD detectors (with a total of 1 Gpix) clocked and read out in synchrony with the satellite rotation ("time-delayed integration"). Over the course of its five-year mission[2] the raw data product from each field of view is essentially an image 7000° long by 0.7° wide (the field width), in which each source appears an average of 40 times (it varies between 20 and 100 because the nominal scanning law does not give uniform sky coverage). Each time the source is observed it will be displaced relative to the others due to the orbit of Gaia (parallax, aberration), the source's intrinsic motion (proper motion; orbital motion if it's a binary) and gravitational light bending.

The goal of the astrometric data processing is to convert the 2D focal plane positions in the two scanning strips into 2D angular positions, parallaxes and proper motions. The steps in the reduction are: (1) Determine the source centroid from the image. Because Gaia is continuously scanning, the position is actually the

[1] This accuracy applies if the uncertainty in the transverse velocity is dominated by the proper motion error and not the distance error. This will be the case both for sufficiently nearby stars, or for clusters, in which a common distance can be assumed for the sake of proper motion to velocity conversion.

[2] in which it really will "boldly go where no-one has gone before", scientifically at least.

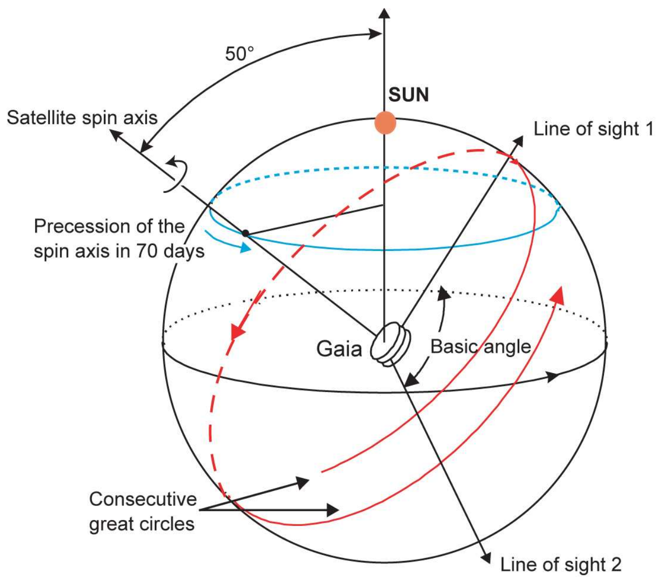

Fig. 1. The Gaia measurement principle and scanning law

time of the transit and its across-scan position. (2) Knowledge of the calibration parameters for the CCDs and optics allows us to transform the focal plane coordinates into field angles (ξ, η). (3) If the satellite attitude is known, the field angles may then be converted to the proper directions. (4) Correction of aberration and light bending (global parameters) converts these field angles into astrometric positions. By observing simultaneously in two fields separated by the large basic angle, Gaia is able to measure the *relative* positions between widely separated objects. For any one object, the multiple scans are obtained at a wide range of position angles and thus link this object to many different objects on the sky. As we have measurements over the whole sky, this allows us to link all objects and put all the astrometry on a common system. From this multi-epoch absolute astrometry we can derive, for each object, the five astrometric parameters (mean position, parallax, proper motions) by fitting a five parameter model to the 80 2D observations (160 measurements). The mapping of the 2D on-board positions to absolute astrometry requires that a large number of CCD/optical calibration and satellite attitude parameters are known. However, given the very high accuracy which Gaia aims to achieve, the nominal values of these parameters cannot be measured on ground to sufficient accuracy. Gaia must be *self-calibrating*. This is achieved in the data processing with the *Astrometric Global Iterative Solution* (AGIS). In this we solve for one set of parameters (e.g. the attitude parameters) while holding the others (source, calibration, global) fixed. We then iterate around the different sets of parameters until convergence. The AGIS is run over a set of about 100 million stars (those with good fits to the 5-parameter model, selected iteratively), and involves several million calibration parameters and tens of million of attitude parameters. A prototype AGIS has been demonstrated to work on simulated data of 1.1 million stars "observed" for 5 years. It is even possible to solve for some of the global parameters, in particular the γ parameter (which parametrizes the accuracy of General Relativity (GR) in the Parametrized Post-Newtonian formulation), and thus make an accurate test of GR via light bending from the Sun and planets in the solar system. Once we have solved for all parameters, we use these to derive source parameters for the (majority) of stars which do not accurately fit the 5-parameter solution, including variable and binary stars (or exoplanetary systems).

The heart of AGIS is a vast least-squares problem. While conceptually straight-forward, it is computationally intensive and to run in a reasonable time must be split into parallel operations. The AGIS is, furthermore, just a small part of the total data processing. There are many other operations including: object cross-matching; photometric processing; extraction, combination and calibration of the spectrophotometry and RVS spectra; calibration of the CCDs in the face of radiation damage; attitude modelling; GR effects; astrometric solutions for binary stars; object classification and the estimation of astrophysical parameters; spectrophotometric variability analysis; tracking and determining orbits for solar system objects. All of the data processing – from telemetry stream to final catalogue – will be undertaken by the Gaia Data Processing and Analysis Consortium (DPAC). Following five years of studies, this consortium was formally started in mid June 2006. It comprises some 250 members (not all full time) across 15 countries.

3.8. Scientific exploitation of Gaia

The Gaia data processing is a complex and challenging task. It demands the development of novel methods for processing, analysing and mining the data. Gaia will collect scientific data between 2012 and 2017, so the final catalogue will only be available in about 2020 (although intermediate data releases are planned). The final catalogue will be publicly available and will contain positions, parallaxes, proper motions, photometry, spectroscopy, radial velocities, classifications, stellar astrophysical parameters and variability information. This will give us the first opportunity to undertake accurate, high-dimensional analyses (3D positions, 3D velocities, ages, abundances etc.) of the Galaxy with large (tens/hundreds of millions) numbers of stars. To properly exploit these data with the goal of understanding the Galaxy's origin and evolution, much more sophisticated dynamical models of the Galaxy will have to be developed (see James Binney's contribution to Turon et al. (2005)). The sheer size and accuracy of the Gaia data will require a fundamental rethinking of how we analyse and model data in this and many of the other scientific areas.

Despite its impressive capabilities, Gaia does not do everything. In crowded areas of the sky not all stars can be downloaded (and the focal plane will eventually saturate), so regions of the Galactic plane and the centres of globular clusters will remain unexplored. RVS has a limiting magnitude of V=17 (ultimately for cost reasons), so most stars will not have radial velocities. There are several complementary surveys which should be undertaken to fully exploit the Gaia data. In particular, radial velocities for fainter stars should be obtained with wide-field multi-object fibre spectrographs on ground-based 4m or 8m class telescopes. Planned projects can realistically observe a few million stars per year. Stellar parameters and individual chemical abundances could be extracted from the same data. More accurate follow-up astrometry could be performed on selected faint targets or in more crowded regions, either with SIM or the Large Binocular Telescope, for example (and Pan-STARRS and LSST will provide proper motions for stars fainter than G=20). Infrared parallaxes in the Galactic plane (to see further through the extinction) would extend Gaia's survey of the thin disk, spiral arms and star forming regions. This may be done by Jasmine, but a deeper survey at, say, 2 μm would be even better. Gaia also will require some ground-based observations for the calibration of its photometry, spectroscopy and stellar parametrization algorithms. Ultimately, a full exploitation of the Gaia data requires us to combine it with other data. We should start to think now about what other data will be available in the timeframe 2015–2020, and if crucial data will be lacking, to start making plans now to remedy this.

4. In conclusion

The next significant advance in understanding the formation, structure and evolution of galaxies will come about from three lines of pursuit. The first is detailed astrometric and chemical abundance surveys of our own Galaxy (the only galaxy where we can presently hope to make very detailed surveys). This is addressed primarily by Gaia, but also by SIM and Jasmine if they fly. Gaia will deliver parallaxes accurate to 10–20 μas at G=15, yielding distances better than 1% for some ten million stars. While our Galaxy retains fossils of its evolution, these will only ever tell us part of the story, and then only for one galaxy. The second line of pursuit is the observation of different galaxies at different stages of their life, i.e. at a range of redshifts. Several ground- and space-based surveys are already addressing this, but the next generation of satellites, in particular JWST and Herschel (operating in the infrared out to 670 μm) will focus much more on the earliest epochs of galaxy formation (and extragalactic star formation) in the high-redshift universe. Space-based platforms are indispensable for accurate parallaxes and for accessing most of the infrared, and so are essential for the first two lines of pursuit. Together they will significantly advance our understanding of galaxy formation, dark matter, chemical evolution and stellar structure and evolution (to know galaxies we must know stars). The third line is the development of powerful models and data analysis tools. These are essential for processing and then exploiting the Gaia data, but will also be required to draw together knowledge obtained from our 'near-field' cosmological studies (our Galaxy) and high-redshift galaxies. Effort must be invested into developing models and techniques with as much zeal as the instrumentation and space platforms.

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