SF2A 2013
L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

GAIA, COUNTING DOWN TO LAUNCH

Anthony G.A. Brown[1]

Abstract. In this contribution I provide an overview of the the European Space Agency's Gaia mission just ahead of its launch scheduled for November 2013.

Keywords: Gaia, space astrometry, Milky Way, photometry, spectroscopy, surveys

1 The Gaia mission

ESA's Gaia mission is the next European breakthrough in astrophysics, a cornerstone mission scheduled for launch in November 2013 which is designed to produce the most accurate 3D map of the Milky Way to date (Perryman et al. 2001). The scientific power of Gaia rests on the combination of three desirable qualities in a single mission: (1) the ability to make very accurate (global and absolute) astrometric measurements; (2) the capability to survey large and complete (magnitude limited) samples of objects; and (3) the matching collection of synoptic and multi-epoch spectrophotometric and radial velocity measurements (cf. Lindegren et al. 2008). The range of science questions that can be addressed with such a data set is immense and Gaia will revolutionize studies of the Milky Way. Moreover, such a massive survey is bound to uncover many surprises that the universe still holds in store for us. The numerous science cases for Gaia can be found in, for example, in the proceedings of the conferences 'The Three-Dimensional Universe With Gaia' (Turon et al. 2005) and 'Gaia: At the Frontiers of Astrometry' (Turon et al. 2011). A recent extensive description of the Gaia mission and its expected performances was provided by de Bruijne (2012).

The astrometric measurements are collected employing a wide photometric band (the Gaia G band) which covers the range 330–1000 nm. Multi-colour photometry will be obtained for all objects by means of low-resolution spectrophotometry. The photometric instrument consists of two prisms dispersing all the light entering the field of view. One disperser — called BP for Blue Photometer — operates in the wavelength range 330–680 nm; the other — called RP for Red Photometer — covers the wavelength range 640–1000 nm. In addition radial velocities with a precision of 1–15 km s^{-1} will be measured for all objects to 17$^{\rm th}$ magnitude, thus complementing the astrometry to provide full six-dimensional phase space information for the brighter sources. The radial velocity instrument (RVS) is a near-infrared (847–874 nm, $\lambda/\Delta\lambda \sim 11\,000$) integral-field spectrograph dispersing all the light entering the field of view.

The focal plane of Gaia comprises an array of 106 CCD detectors which serve the three instruments mentioned above. The observing programme is based on the autonomous on-board detection of celestial sources, which is unbiased and complete to $G = 20$ ($V \sim 20$–22). Gaia will be located at L2 and scan the sky with its two telescopes by continuously spinning around the axis perpendicular to the two lines of sight. The spin axis in addition makes a precessing motion around the spacecraft-sun direction, and as a result Gaia will scan the whole sky roughly every 6 months. Each celestial source will on average be observed about 70 times during the 5 year mission lifetime with a quasi-regular time sampling. The number of times a source is observed is not uniform across the sky as illustrated in figure 1. The regions in the annuli located 45° away from the ecliptic poles are observed most often, while the regions around the ecliptic are covered less often. The number of stars in the Gaia catalogue is estimated to be $\sim 7\times10^5$ to $G = 10$, 48×10^6 to $G = 15$ and 1.1×10^9 to $G = 20$. About 60 million stars are expected to be seen as binary or multiple systems by Gaia, among which about 10^6–10^7 eclipsing binaries. In addition the catalogue will contain astrometry and photometry for $\sim 3\times10^5$ solar systems bodies, $\sim 5\times10^5$ quasars, and some 10^6–10^7 galaxies. The sky survey by Gaia will also produce the most accurate optical all-sky map ever, with an angular resolution comparable to that of the Hubble Space Telescope.

[1] Sterrewacht Leiden, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands

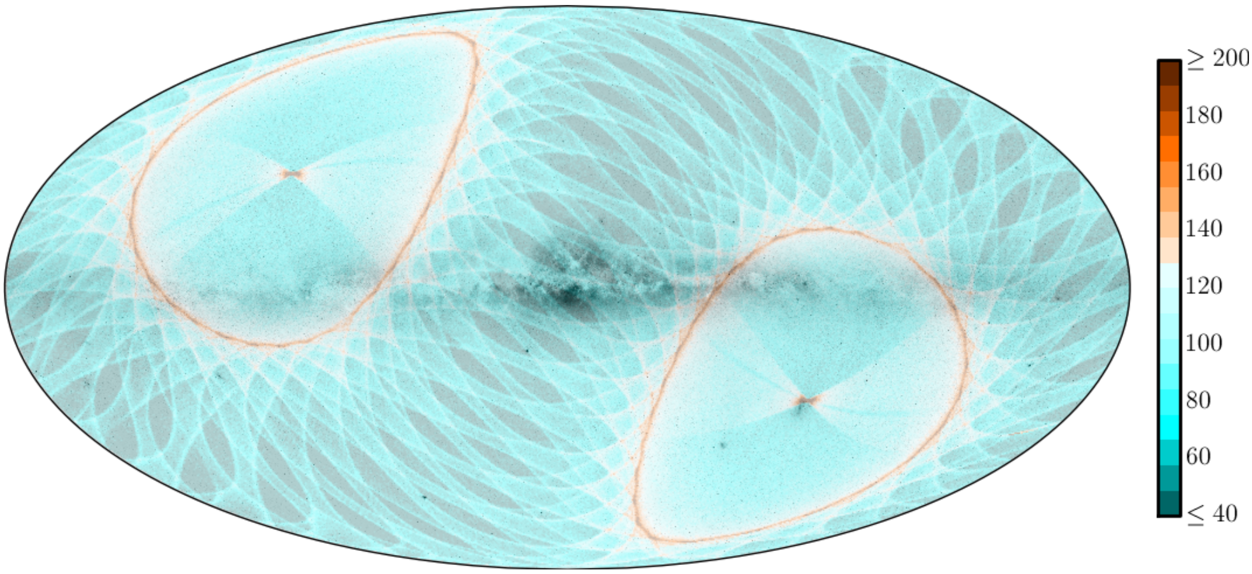

Fig. 1. The predicted sky coverage of Gaia in Galactic coordinates projected on an image of the night sky. The colours indicate the number of times a particular region on the sky is observed. The two annuli where most of the observations are reflect the constant 45° angle between the Gaia spin axis and the direction from the spacecraft to the sun. The extra coverage around the ecliptic poles reflects the early phases of the mission when these areas will be covered repeatedly. The scan law simulation was done with the DPAC AGISLab software (Holl et al. 2010). The background image is the red band of the ESO Milky Way panorama (ESO/S. Brunier).

2 Scientific performances

The expected scientific performance of Gaia in terms of the astrometric, photometric, and radial velocity accuracies achieved is described in de Bruijne (2012) and more details can be found on the Gaia web pages at the following link: `http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance`. The performance predictions have been confirmed following extensive tests conducted in December 2012 with the Gaia payload module in cold vacuum. Figure 2 shows the dramatic improvement over the Hipparcos mission, in both astrometric accuracy and survey depth, that will be achieved by Gaia.

The photometric capabilities of Gaia are described in detail in Jordi et al. (2010), while the expected accuracies to which stars can be characterized (in terms of temperature, surface gravity, metallicity, extinction) on the basis of the Gaia photometry can be found in Liu et al. (2012). The RVS instrument of Gaia and its science capabilities were most recently summarized by Cropper & Katz (2011) and Katz et al. (2011). Much more detail on the RVS can be found in Katz et al. (2004) and Wilkinson et al. (2005).

3 Launch and commissioning

Gaia will be launched on November 20 2013 from the European spaceport in French Guiana by a Soyuz-STB/Fregat rocket. After launch the spacecraft will be inserted into a trajectory to L2 where it will arrive in a few weeks. Soon after the commissioning of Gaia's scientific instruments will take place, an activity which is expected to take about 3–4 months. During this phase Gaia will be operated in a special survey mode which ensures that it repeatedly scans over the Ecliptic Pole regions which have been extensively surveyed from the ground in anticipation of the mission. The data so collected will allow a detailed check of the performances of the Gaia instruments in terms of the achieved source detection efficiency, image quality, photometric throughput, spectroscopic resolving power, and attitude noise. These ingredients will allow a detailed assessment of the expected Gaia astrometric, photometric and spectroscopic (radial velocity) performances.

During this phase the Gaia Data Processing and Analysis Consortium (cf. section 4) will process the Gaia telemetry and participate in the detailed performance verification for Gaia. The assessment of the Gaia instruments as they actually behave in flight and updated science performance predictions will be published in the course of 2014 in order to give the scientific community an early insight into what can be expected from Gaia.

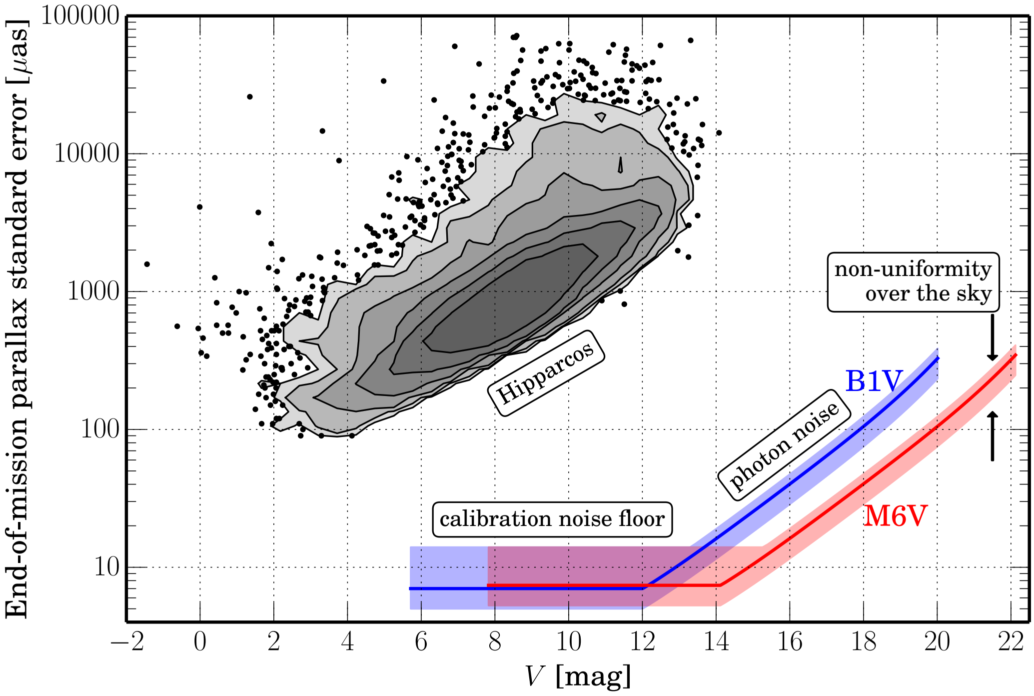

Fig. 2. Parallax accuracies as a function of source brightness in the V-band for Gaia and Hipparcos.The contours and dots show the Hipparcos parallax errors, where the values are taken from van Leeuwen (2007). The lines show the predictions of the Gaia sky averaged parallax standard errors. At the bright end calibration errors will dominate and the parallax accuracies will range from ~ 5 to ~ 14 μas. At the faint end the behaviour of errors as a function of V is dictated by photon noise. The parallax accuracies are shown for an early and a late spectral type star to illustrate that at a given V the astrometric accuracies are better for red stars. As a function of G the differences are negligible. The bands around the average relations reflect the uncertain calibration errors at the bright end and the variation in sky coverage at the faint end. The accuracy predictions (obtained from the Gaia web pages) include a rough estimate of the effects of radiation damage and a 20% margin (factor 1.2) to account for unmodelled effects. The standard errors in position and proper motion can be obtained by applying factors of ~ 0.7 and ~ 0.5, respectively, to the parallax standard errors.

4 Gaia data processing

The on-ground data processing for Gaia is a very large and highly complex task, linking all astrometric, photometric and radial velocity measurements into a large iterative solution. For the astrometric instrument the iterative solution is aimed at transforming the source image location measurements in pixel coordinates to angular field coordinates through a geometrical calibration of the focal plane, and subsequently to coordinates on the sky through calibrations of the instrument attitude and the basic angle between the lines of sight of the two telescopes. Moreover, corrections for systematic chromatic shifts need to be made (using the photometric measurements), as well as aberration corrections, corrections for perspective acceleration (involving the RVS measurements) and corrections for general-relativistic light bending due to the Sun, the major planets, some of their moons, and the most massive asteroids. Image location shifts caused by the radiation damage induced stochastic charge trapping and de-trapping in CCDs also need to be understood and calibrated with high precision. Repeated observations by Gaia of every star permit a complete determination of each star's five basic astrometric parameters — two angular positions, two proper motions and the parallax. More information on the astrometric processing can be found in Lindegren et al. (2012).

The treatment of the spectrophotometry (cf. Busso et al. 2012) starts with the pre-processing of the raw dispersed images (e.g., bias and sky background removal) and the disentangling of overlapping images in crowded fields. This is followed by an iterative process of internal calibration in which all measurements are transformed to the same mean instrumental system by accounting for differences across the focal plane in the prism dispersion curves, point spread function, and geometric calibration, as well as performing flat fielding and correcting for CTI effects. The last step is to perform and absolute calibration of the spectrophotometry using standard stars.

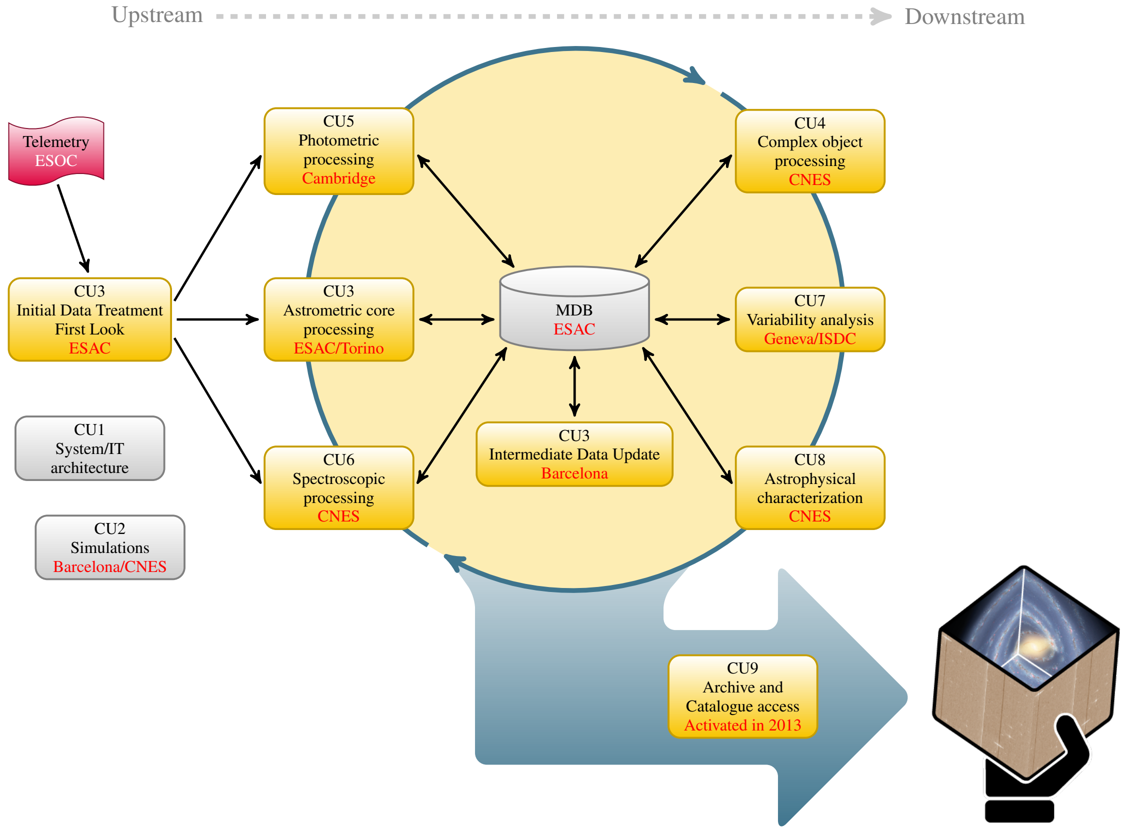

Fig. 3. Schematic overview of the organization of the data flow withing the Gaia Data Processing and Analysis Consortium. For each DPAC coordination unit the processing tasks listed in the boxes are carried out at the data processing centre indicated in red. See text for more explanations.

For the radial velocity spectrograph similar processing steps are taken (Katz et al. 2011). In addition the very low signal levels at the faint end of the RVS magnitude range mandate a careful 'stacking' of multiple spectra collected for each source in order to allow the determination of the radial velocity. At the bright end detailed epoch spectra can be obtained for each source. The RVS instrument is especially sensitive to the effects of CTI and electronic bias non-uniformities which have to be modelled and accounted for in the calibrations. The data processing for both the RVS and photometric instruments relies on the knowledge of source positions on the sky and of the spacecraft attitude, quantities that are derived in the astrometric data processing.

This highly interlinked 'upstream' processing produces raw astrometric, photometric and RVS results which are further processed. A detailed analysis will be made of multiple stars, extended sources, galaxies, exoplanets and solar system objects and the spectra from the photometers and RVS will be used to characterize the astrophysical properties of every source observed by Gaia. Finally the repeated observations of each source can be used to carry out a detailed variability analysis. More details on these 'downstream' processing tasks can be found in Pourbaix (2011) (double and multiple stars), Sozzetti (2013) (exoplanets) Tanga & Mignard (2012) (solar system objects), Tsalmantza et al. (2012); Krone-Martins et al. (2013) (galaxies), Bailer-Jones et al. (2013) (astrophysical parameters of Gaia sources), and Eyer et al. (2012) (variable stars).

The multitude of tasks described above will be undertaken by the scientific community in Europe which has organized itself into the Gaia Data Processing and Analysis Consortium (DPAC). The data processing activities will be structured around nine 'coordination units' (CUs) and six data processing centres. Each CU is responsible for delivering a specific part of the overall data processing system for Gaia. The role of each CU and of the data processing centres is illustrated schematically in figure 3.

In this diagram the flow of data within DPAC and between the data processing centres is shown. The Gaia telemetry is sent from ESOC to the Science Operations Centre at ESAC where it is unpacked and processed by the Initial Data Treatment and First Look pipelines. The latter serves to monitor the instrument health of Gaia in great detail while the former prepares the raw telemetry for further processing by CUs 3 (astrometry), 5 (photometry) and 6 (spectroscopy and radial velocities). The results from these 'upstream' CUs are then stored in the Main Data Base (MDB) housed at ESAC. The 'downstream' CUs 4, 7, and 8 then pick up the processing results from the MDB and carry out the processing of non-single stars and non-stellar sources, the classification and characterization of all sources, and the variability analysis (detection, classification, and derivation of variable source light curves). The results from these CUs also go back into the MDB. The iterative loop is closed by the intermediate data update in which improved instrument calibrations are derived (taking into account the results from all CUs 3/5/6 and 4/7/8) which are then applied to derive improved upstream and downstream data products. Finally, when a particular version of the Main Data Base contents is deemed of sufficient quality to warrant a data release the MDB contents are passed onto CU9 for extensive validation, documentation, and release of the Gaia processing results.

5 Data release scenario

The final Gaia catalogue release is foreseen to take place around 2022. This is of course still some time away and hence in the mean time intermediate data releases are foreseen. The data release scenario for Gaia can be found on the Gaia web pages at `http://www.rssd.esa.int/index.php?project=GAIA&page=Data_Releases`. The release scenario has been designed by carefully considering the complex data processing described above, the available staff effort within DPAC, and assuming smooth operations from the start. Hence, the precise times of data releases cannot be fixed at this moment.

The very first data to be released from the Gaia mission will be the data associated with the so-called Science and Solar System Alerts streams. The Science Alerts concern transient sources that should be followed up promptly from the ground, while the solar system alerts are intended for follow-up observations of newly discovered or very fast moving solar system objects.

The first catalogue release is foreseen to take place 22 months after launch (so roughly end 2015) and will consist of an all sky map (positions and magnitudes) for most of the Gaia sources. In addition, for stars in common with the Hipparcos Catalogue, Gaia and Hipparcos positions will be combined to give very accurate ($\sim$ 30–190 μas/yr) proper motions (see de Bruijne & Eilers 2012).

The list of subsequently planned data releases can be found on the pages above and will include data of increasing accuracy and diversity. It should be stressed here that none of the data releases will be preceded by a proprietary period for the DPAC. The releases are immediately publicly available world wide. This is in fact a unique aspect of the Gaia mission. More information on the expected Gaia catalogue contents and the ideas being developed for making the data available can be found in Brown (2012) and Luri et al. (2013).*

6 Preparing yourself for Gaia

The Gaia mission will result in a large catalogue (over 1 billion sources) containing a very rich diversity of information. Scientifically exploiting such a data set will not be trivial and thus some preparation within the astronomical community is required. The Gaia community will support this process and I give here some examples of activities that astronomers can profit from in their preparations for the use of the Gaia data.

- The Gaia Science Performance web pages† provide, among others, background information on the instruments and the error modelling, interpolation tables and formulae for simulating the errors, the predicted variations of errors over the sky, transformations from the Johnson and Sloan systems to Gaia photometric system, and references to the relevant literature. The information on these pages allows one to realistically simulate the performance of Gaia in order to prepare for the scientific exploitation of the data.

- Simulated Gaia catalogues are being created by DPAC and are made available through, for example, the Centre de Données astronomiques de Strasbourg (CDS). The Gaia Universe Model Snapshot has already been made available (see Robin et al. 2012). It contains a simulated 'universe' (i.e. true properties of sources observed by Gaia) from which the simulated Gaia catalogue is subsequently generated (observable quantities and their errors). The simulated catalogue is currently in production and will be made available later this year. These simulated data sets are representative of the actual Gaia catalogue and can be used to exercise one's data analysis algorithms.

*Available at `http://www.rssd.esa.int/SA/GAIA/docs/library/XL-033.htm`.

†`http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance`

- Since 2009 the Gaia Research for European Astronomy Training (GREAT) network[‡], funded through the European Science Foundation, has been stimulating activities in anticipation of the Gaia mission. Numerous workshops and conferences have been organized, focusing on Gaia science topics and how to prepare for exploiting the mission data. The topical working groups within the network are still open to new members, contributions, and ideas. Refer to the GREAT web pages for more information. A notable outcome of the GREAT networking activities is the Gaia-ESO survey (Gilmore et al. 2012).

- The Gaia community is now in the process of defining how the Gaia results will be made accessible to astronomers. This includes developing the data archiving and querying systems, as well as producing detailed documentation and providing sophisticated data analysis and data mining tools (Luri et al. 2013). The astronomical community was consulted, through the GREAT network, to collect requirements on the way the Gaia data should be made available. This was done by inviting the submission of 'use cases' which will drive the requirements specifications for the Gaia catalogue and archive access mechanisms. Your ideas are still welcome and can be submitted through the following wiki pages: `http://great.ast.cam.ac.uk/Greatwiki/GaiaDataAccess`.

References

Bailer-Jones, C. A. L., Andrae, R., Arcay, B., et al. 2013, arXiv:1309.2157

Brown, A. G. A. 2012, Science from Gaia: How to Deal with a Complex Billion-Source Catalogue and Data Archive, ed. L. M. Sarro, L. Eyer, W. O'Mullane, & J. De Ridder, 17

Busso, G., De Angeli, F., & Montegriffo, P. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8442, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series

Cropper, M. & Katz, D. 2011, in EAS Publications Series, Vol. 45, EAS Publications Series, 181–188

de Bruijne, J. H. J. 2012, Ap&SS, 341, 31

de Bruijne, J. H. J. & Eilers, A.-C. 2012, A&A, 546, A61

Eyer, L., Palaversa, L., Mowlavi, N., et al. 2012, Ap&SS, 341, 207

Gilmore, G., Randich, S., Asplund, M., et al. 2012, The Messenger, 147, 25

Holl, B., Hobbs, D., & Lindegren, L. 2010, in IAU Symposium, Vol. 261, IAU Symposium, ed. S. A. Klioner, P. K. Seidelmann, & M. H. Soffel, 320–324

Jordi, C., Gebran, M., Carrasco, J. M., et al. 2010, A&A, 523, A48

Katz, D., Cropper, M., Meynadier, F., et al. 2011, in EAS Publications Series, Vol. 45, EAS Publications Series, 189–194

Katz, D., Munari, U., Cropper, M., et al. 2004, MNRAS, 354, 1223

Krone-Martins, A., Ducourant, C., Teixeira, R., et al. 2013, A&A, 556, A102

Lindegren, L., Babusiaux, C., Bailer-Jones, C., et al. 2008, in IAU Symposium, Vol. 248, IAU Symposium, ed. W. J. Jin, I. Platais, & M. A. C. Perryman, 217–223

Lindegren, L., Lammers, U., Hobbs, D., et al. 2012, A&A, 538, A78

Liu, C., Bailer-Jones, C. A. L., Sordo, R., et al. 2012, MNRAS, 426, 2463

Luri, X., O'Mullane, W., Alves, J., et al. 2013, Delivering the promise of Gaia. Proposal for the Gaia Archive

Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, A&A, 369, 339

Pourbaix, D. 2011, in American Institute of Physics Conference Series, Vol. 1346, American Institute of Physics Conference Series, ed. J. A. Docobo, V. S. Tamazian, & Y. Y. Balega, 122–133

Robin, A. C., Luri, X., Reylé, C., et al. 2012, A&A, 543, A100

Sozzetti, A. 2013, in European Physical Journal Web of Conferences, Vol. 47, European Physical Journal Web of Conferences, 15005

Tanga, P. & Mignard, F. 2012, Planet. Space Sci., 73, 5

Tsalmantza, P., Karampelas, A., Kontizas, M., et al. 2012, A&A, 537, A42

Turon, C., Meynadier, F., & Arenou, F., eds. 2011, EAS Publications Series, Vol. 45, Gaia: at the Frontiers of Astrometry

Turon, C., O'Flaherty, K. S., & Perryman, M. A. C., eds. 2005, ESA Special Publication, Vol. 576, The Three-Dimensional Universe with Gaia

van Leeuwen, F. 2007, Astrophysics and Space Science Library, Vol. 350, Hipparcos, the New Reduction of the Raw Data

Wilkinson, M. I., Vallenari, A., Turon, C., et al. 2005, MNRAS, 359, 1306

[‡] `http://www.ast.cam.ac.uk/GREAT`