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THE FIRST DATA FROM GAIA

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RESUMEN

La misión astrométrica *Gaia* está en su fase de operación científica desde julio de 2014. A un ritmo promedio de 50 millones de observaciones por día, *Gaia* explora el cielo completo cada seis meses. La primera publicación de datos (*Gaia* DR1), en septiembre de 2016, contiene los resultados astrométricos y fotométricos para más de mil millones de estrellas hasta magnitud 21, basados en los primeros 14 meses de operaciones. Para más de dos millones de las estrellas más brillantes que 11.5 mag se han obtenido posiciones, paralajes y movimientos propios con precisiones al nivel de Hipparcos mediante una combinación con las posiciones anteriores de Hipparcos y Tycho-2. Para las demás estrellas, hemos obtenido posiciones para la época J2015.0, básicamente ignorando sus paralajes y movimientos propios. Las posiciones y movimientos propios están dados en el marco de referencia ICRF radio/VLBI. Presentamos el estatus actual de la misión, los desafíos astrométricos, el consorcio de operaciones de procesamiento y análisis de datos, los procesos de validación, los contenidos del *Gaia* DR1 y las perspectivas para las publicaciones futuras de datos. Enfatizamos que aunque el *Gaia* DR1 se basa en calibraciones provisionales e incompletas del instrumento, los resultados representan una gran mejora en los datos estelares fundamentales disponibles y discutimos algunos de los primeros resultados.

ABSTRACT

The *Gaia* astrometric satellite is in its science operational phase since July 2014. At an average rate of 50 million observations per day, *Gaia* scans the full sky once every six months. The first data release (*Gaia* DR1), issued in September 2016, contains astrometric and photometric results for more than 1 billion stars brighter than magnitude 21 based on observations acquired during the first 14 months of operations. For more than two million stars brighter than 11.5 mag, positions, parallaxes, and proper motions have been obtained to Hipparcos-type precision through a combination with the earlier Hipparcos and Tycho-2 positions. For the remaining stars, positions at epoch J2015.0 have been obtained by essentially neglecting their proper motions and parallaxes. Positions and proper motions are in the ICRF radio/VLBI frame. We give an overview of the current status of the mission, the astrometric challenges, the Data Processing and Analysis Consortium operations, the validation processes, the contents of *Gaia* DR1, and the prospects for the coming releases. We emphasise that although *Gaia* DR1 data are based on provisional and incomplete calibrations of the instrument, the results represent a huge improvement in the available fundamental stellar data, and discuss some of the first results.

Key Words: astrometry — catalogs — parallaxes — reference systems — surveys

1. INTRODUCTION

The *Gaia* spacecraft of the European Space Agency (ESA) was launched from French Guiana on 19 December 2013 and started its scientific operational phase on 25 July 2014. The mission of *Gaia* is to produce a survey of our Galaxy, giving high precision astrometry of the brightest one billion stars, i.e. to about 20 mag. *Gaia* will in addition give broad-band photometry and spectrophotometry, and for the brighter sources also radial velocities.

The processing of the data from *Gaia* is in the hands of the Data Processing and Analysis Consortium (DPAC) consisting of several hundred scientists and computer engineers across Europe. The processing itself is carried out in six data processing centres with the European Space Astronomy Centre near Madrid as the central hub.

The first data release from *Gaia*, (*Gaia* DR1), was published on 14 September 2016. It contains positions and G magnitudes for 1142 million sources brighter than 20.7 mag, and for a subset of two million stars also proper motions and parallaxes with an accuracy comparable to or better than Hipparcos.

2. THE GAIA MISSION

An overview of the *Gaia* mission is given by Gaia Collaboration (2016a). The payload consists of two telescopes with 35 m focal length, separated an angle

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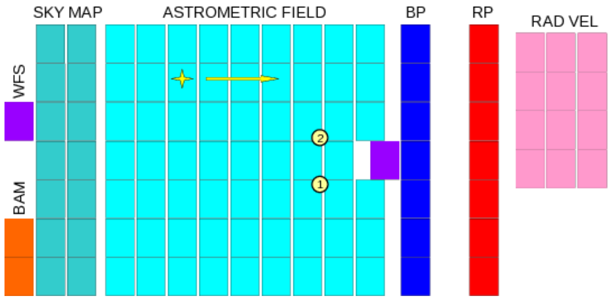

Fig. 1. Focal plane of the *Gaia* telescopes with its 106 CCDs. Stars cross from left to right. They are detected in the sky mapper CCDs, and followed in the astrometric field, and in the blue (BP) and red (RP) photometers. Brighter sources are also observed with the radial velocity instrument. Additional CCDs serve the basic angle monitor (BAM) and the wave front sensors (WFS). The field is 0°.7 high. The optical centres of the two telescopes are indicated with yellow circles.

–the basic angle– of 106°.5, and with a common focal plane as shown in Figure 1.

As the spacecraft spins at a rate of one revolution every six hours, the two telescopes scan a band around a great circle. Sources are detected in the sky mapper CCDs, with one strip for each telescope. Based on the detection, small areas –windows– centred on the images are read out from the following CCDs. The CCDs are read at a fixed rate of about one pixel row per millisecond, and the spacecraft rotation is maintained at the corresponding spin rate. The spin axis slowly precesses around the direction to the Sun at a fixed angle of 45° completing one cycle every few months and covering the entire sky in less than six months.

The astrometric measurements are basically carried out along the great circle scanned and consist in the transit times for each CCD. Measurements are partly local, for sources in the same field of view, and partly global, connecting the two viewing directions through the basic angle. Because it is essential for the astrometry that the basic angle is stable, a laser metrology system –the basic angle monitor– measures basic angle variations a couple of times per minute. For details on the astrometric principles of *Gaia* see Lindegren et al. (2012).

3. GAIA ASTROMETRY

The many processing steps needed to derive the transit times at each CCD are discussed in Fabricius et al. (2016). Both bias and background calibrations are highly non-trivial, but the more demanding calibration is for the point spread function (PSF) or for its one-dimensional equivalent: the line spread function (LSF), which is used for the majority of observations, where we only have the binned pixels. The PSF/LSF depend on the colour and also on the brightness due to non-linear effects in the charge transfer. However, for *Gaia* DR1, these subtle effects were not yet taken into account.

The astrometric processing is explained in Lindegren et al. (2016). Key difficulties have been a rather large variation of the basic angle and sudden, small relaxations of the telescope structure, known as micro-clanks. The basic angle variation has a component with an amplitude near 1 mas, that in the observations cannot be distinguished from a shift in the parallax zero-point. The variation is orders of magnitude larger than expected, but it can fortunately be compensated through the metrology system. The frequent micro-clanks are also of the order 1 mas, but they are less dangerous, because they only affect very short time intervals, and were not corrected for *Gaia* DR1.

3.1. *TGAS*

The Tycho Gaia Astrometric Solution (TGAS (Michalik et al. 2015a)) combines positions –and only positions– from the HIPPARCOS (van Leeuwen 2007) and Tycho-2 (Høg et al. 2000a) catalogues with the *Gaia* observations into a single astrometric solution. In this way it has been possible to obtain a full astrometric solution, including proper motions and parallaxes, with only about one year of *Gaia* observations. The residuals for individual CCD transits are around 0.6 mas (0.01 pixels) (Lindegren et al. 2016), which is much above what is needed to reach end of mission accuracies, but fully acceptable considering the several simplifications adopted for this first release.

3.2. *General Gaia DR1 sources*

For the general *Gaia* DR1 sources, i.e. the ones not in TGAS, only *Gaia* observations have been used, and with only 14 months of observations, it is not possible to derive reliable parallaxes and proper motions, so only the positions for the epoch J2015.0 are published. It is a delicate task to determine meaningful positions and meaningful uncertainties, when observations are of sub-mas precision while the effect of the proper motion and parallax can be much larger. An elegant Bayesian approach to this problem is described in Michalik et al. (2015b).

We can also foresee, that many sources in later data releases, especially very faint or transient sources, will not have sufficient observational coverage for the full five parameter solution, and will therefore obtain only a position and neither proper motion nor parallax.

TABLE 1

CONTENTS OF *Gaia* DR1

Catalogue	Entries	Contents
Gaia sources	1 142 679 769	α, δ, G
TGAS sources	2 057 050	$\alpha, \delta, \varpi, \mu_\alpha, \mu_\delta, G$
Variables	3 194	G
QSOs	2 191	α, δ, G

3.3. *Reference Frame*

For the reference frame of *Gaia* DR1, the choice was basically between using the HIPPARCOS frame or to align the catalogue with the radio based ICRF through QSOs. The former solution would have been in accordance with IAU recommendations, but the latter was in the end seen as the more convenient. HIPPARCOS is also aligned with ICRF at its mean epoch (J1991.25), and therefore the TGAS proper motions are absolute within 0.03 mas/yr (Lindegren et al. 2016), where the error is dominated by the alignment of HIPPARCOS to the ICRF.

The alignment of *Gaia* DR1 to the ICRF was carried out using 2191 suitable QSOs with a special astrometric solution which used their negligible proper motions as prior information (Lindegren et al. 2016). Details of the comparison between the *Gaia* results and the ICRF are discussed in Mignard et al. (2016).

4. GAIA DR1 RESULTS

The principal contents of *Gaia* DR1 is summarised in Table 1. Apart from the main catalogue and the TGAS subset, it also gives light curves for a set of Cepheids and RR Lyrae in the LMC, and the QSO positions from the special QSO solution used for the alignment of the reference frames. In addition, the release provides several cross match tables to ground based surveys. The LMC light curves basically cover the first month of mission where *Gaia* observed using a special ecliptic pole scanning law, thus covering the ecliptic poles, and thereby parts of the LMC, eight times per day.

4.1. *Proper Motions*

The TGAS proper motions are derived from sets of observations separated 24 years and therefore represent a longer timescale than was available for HIPPARCOS or will be available for future *Gaia* releases. For HIPPARCOS stars, both epochs have 1 mas or better accuracy, and the TGAS uncertainties are therefore at the 0.06–0.10 mas/yr level for this subset. A comparison between TGAS and HIPPARCOS (Lindegren et al. 2016) shows a rotation between the two systems of 0.24 mas/yr, which is within the error originally estimated for HIPPARCOS.

For the general Tycho-2 stars, the proper motion precision is dominated by the positional errors of Tycho-2, and there is therefore no gain in precision. For the accuracy, however, the gain is significant. Tycho-2 proper motions were constructed (Høg et al. 2000b) combining the Tycho-2 positions with positions in some 150 ground based catalogues, predominantly the Astrographic Catalogue observed near the beginning of the 20th century in declination zones assigned to the different participating observatories. It is therefore interesting that the comparison between TGAS and Tycho-2 proper motions presented by Lindegren et al. (2016) shows significant differences with a clear zonal pattern. These differences must therefore be due to errors in Tycho-2.

4.2. *Parallaxes*

A large number of different astrometric solutions were carried to validate the TGAS parallaxes and to obtain a realistic value for the size of the systematic parallax errors. Details are given in Lindegren et al. (2016), and their result is that the astrometric parameters may have systematic errors at the 0.3 mas level, depending on colour and position in the sky. This also means that one should not expect the errors on a mean value for a cluster to decrease below that level.

4.2.1. *QSOs*

A special QSO solution was made, as suggested in Michalik & Lindegren (2016), solving essentially only for position and parallax. This makes good sense because the proper motions are known to be negligible. It comprised 135 000 QSOs, mainly in the northern sky, and showed a non-zero median parallax of −0.04 mas. This confirms that the basic angle variations are largely understood, but leaves open the exact reason for the non-zero result.

We emphasise, that because of the different restrictions applied to the TGAS solution and the QSO solution, the QSO zero-point should not be interpreted as a zero-point for TGAS.

4.2.2. *Pleiades*

Soon after HIPPARCOS was published, doubts arose as to the reliability of the unexpectedly large parallaxes for the stars in the Pleiades and the corresponding short distance scale. The difference only shows up for the mean parallax, because for individual stars it is a mere one-sigma effect. An overview of the problem is presented by Makarov (2002), who also suggests a mechanism by which a small group of sufficiently bright stars can essentially decouple from the rest of the catalogue. Makarov also derives a tentative correction to the HIPPARCOS mean parallax, but does not claim to have found the ultimate HIPPARCOS results as that would require a large scale data treatment. The question is also addressed in the presentation of the *Gaia* DR1 by Gaia Collaboration (2016b), where the *Gaia* results as well as other newer observations all support the traditional distance. We show their illustration in Figure 2, where we have added the result from Makarov (2002). It seems clear from this result, that the mechanism proposed by Makarov deserves a more complete study in order to finally resolve the discrepancy and to see if there are lessons to be learned for *Gaia*.

4.3. *Completeness*

Because *Gaia* DR1 is based on only 14 months of observations, some areas of the sky have a much brighter limiting magnitude than can be expected in the future and these areas form irregular patterns, cf. Gaia Collaboration (2016b). In addition, crowded areas and binaries do not fare well in *Gaia* DR1. As discussed in Arenou et al. (2017), the current state of the data reductions does not allow colours to be determined for the fainter source in pairs closer than about two arcsec, a limit that rises to four arcsec in the densest areas. Because the colour is needed in the photometric calibration, many sources were left out from *Gaia* DR1, and the catalogue has therefore a maximum density of about 500 000 sources per square degree.

5. CONCLUDING REMARKS

The *Gaia* DR1 is a large catalogue, but represents only a small fraction of what will come in future releases. Already *Gaia* DR2, scheduled for late 2017, will contain parallaxes, proper motions, and colours for a billion sources, as well as radial velocities for the brighter ones. Variability analysis, stellar classification, solar system objects will follow soon, and later also low dispersion spectra, diffuse objects, binary systems, and astrometric exoplanets.

The mission is planned for five years, but if technical and economic resources allow, it may in principle continue for an additional four or five years with a significant gain for especially sources with a complex motion, like binaries and host stars of exoplanets.

The *Gaia* DR1 is available from the astronomical data centres and can be queried directly at `archives.esac.esa.int/gaia`.

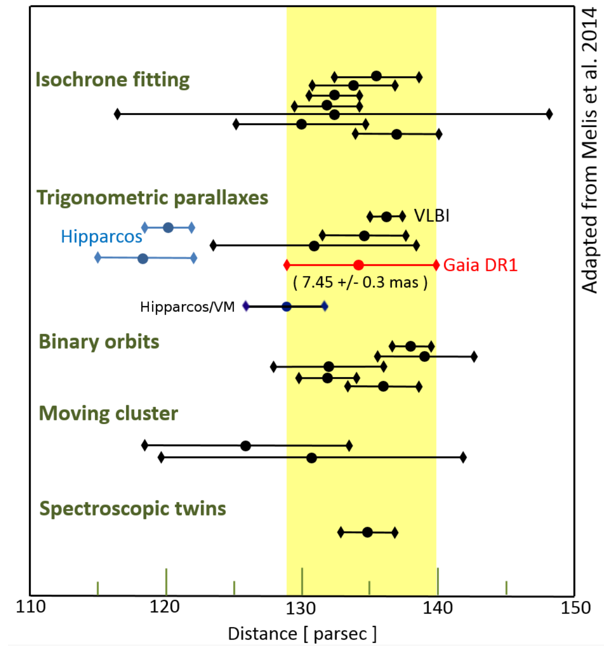

Fig. 2. Different distance estimates to the Pleiades cluster. Distances derived from the HIPPARCOS catalogues come out to the small side, except for an analysis by V. Makarov (2002) based on HIPPARCOS residuals (Hipparcos/VM). The figure is adapted from Gaia Collaboration (2016b).

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