Towards Ages: Gaia DR1, asteroseismology, precise abundances and stellar evolution models

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John Norris and Arlette Noels

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Gaia first data release and beyond

Antonella Vallenari†,

INAF, Osservatorio Astronomico di Padova,
Vicolo Osservatorio 5, 35122 Padova, Italy
email: antonella.vallenari@oapd.inaf.it

Abstract. The first Gaia data release took place in 2016, delivering astrometry and photometry for more than 1 billion sources in our Galaxy. After almost one year, Gaia data have already become the reference for astrometry, with applications in a wide range of topics. In this paper we summarize the impressive quality and the known limitations of the data; and we present the extensive validation work that was done by the Gaia Consortium before publication. We review a few results based on Gaia first data release, while looking ahead at the upcoming second data release

Keywords. astronomical data bases: catalogs, surveys, astrometry

1. Introduction

Understanding the formation and evolution of galaxies is a central topic to modern astrophysics. Observations of our own Galaxy provides a fossil record detailed enough to unravel its complex formation history. The ESA Cornerstone Gaia mission is meant to provide the required data in the form of parallaxes, space motions (proper motions and radial velocities) and astrophysical characterization (through photometry and spectroscopy) for more than one billion stars down to G=20.7 mag throughout most of the Galaxy. The first data release (DR1) was on September 2016, while the second (DR2) is planned on April 2018. In this paper we summarize the properties of the first Gaia Data Release, we outline the extensive validation work that was done by the Gaia Data processing and Analysis Consortium (DPAC), comparing the results with literature assessment of the Gaia DR1 quality, and we present the main properties of the second data release (DR2).

2. Gaia DR1 data quality and quality assessment

Gaia satellite was successfully launched in December 2013 and is now in operational phase, with a nominal mission period of 5 years. End of mission astrometric accuracies of better than $24\mu as$ for bright stars are expected. The final data release of the nominal mission is planned on 2022, after a post-operation processing of all the available data. To guarantee early data access to the scientific community, several intermediate data releases are planned. The first of those, Gaia DR1, was based on the data collected during the

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first 14 months of the nominal mission. Gaia DR1 supplied the astronomical community with astrometry, G-band photometry, and a modest number of variable star light curves, for more than one billion objects. In detail:

- The primary astrometric data set contains positions parallaxes, and mean proper motions for 2,057,050 stars that were derived using as priors the positions of the Hipparcos and Tycho 2 catalogs. Because of that, the derived parallaxes and proper motions are independent from Hipparcos and Tycho 2 corresponding quantities. This data set represents the realization of the Tycho-Gaia astrometric solution (TGAS). Methods, accuracy, and limitations are described in Lindegren *et al.* (2016). The typical uncertainty is about 0.3 mas for the positions and for the parallaxes, and about 1 mas/yr for the proper motions. The Hipparcos subset has much more precise proper motions, at about 0.06 mas/yr. A systematic component of the parallax zero point was detected during the DPAC validation. We will discuss it later. However, since the uncertainties on the astrometry were artificially inflated to be consistent with Hipparcos data, this systematic term is already included in the nominal errors;
- The secondary astrometric data set includes the positions for more than one billion sources, with typical uncertainty on the positions of $\sim$ 10 mas. The alignment of the reference frame with the International Celestial Reference Frame (ICRF) is given at 0.1 mas (or better) at epoch J2015.0 (see Mignard *et al.* 2016 for a detailed description);
- The mean Gaia G-band magnitudes are given for all the sources contained in Gaia DR1, in the magnitude range $3.2 < G < 21$, with an impressive accuracy of the order of a few milli-mag for $G < 13$ and of 0.03 mag at the faint end. More information about the photometric data processing, data quality and validation can be found in Van Leeuwen *et al.* (2017) and reference therein;
- The G-band light curves and characteristics of 599 Cepheid (43 newly discovered) and 2595 RR Lyrae (343 new) variables located around the south ecliptic pole are included. The variable star content is described in Eyer *et al.* (2017).

The quality of the data is already excellent. However, the performances were limited by the available data volume and sky coverage. The adopted calibrations are still immature, mainly due to an incomplete PSF model that does not account for color effects and variations in time and across the focal plane. In addition the attitude modeling within the astrometric solution includes only limited treatment of micro-meteoroid hits or micro-clanks. Correlations among the astrometric parameters are present. A proper treatment of these correlations, and their effects on the determination of average parallaxes of clusters, is described in Gaia Collaboration, Van Leeuwen, *et al.* (2017).

Fig. 1 shows the excellent quality of TGAS data in comparison to UCAC4, and the effects of the correlations on the uncertainty distribution in the case of the open cluster NGC 2360. While the cluster is not visible in the proper motion space in UCAC4, it clearly stands out in the TGAS data.

2.1. *DPAC Validation of the Catalog*

The Gaia Catalog comes at the end of a complex process combining the work of hundreds of people divided into dozens of groups working on complementary and independent pipelines (see Gaia Collaboration, Prusti, *et al.* 2016 for a detailed description of the DPAC). Clearly it is a challenging task to deliver high quality astrometry, photometry for every object in a billion source catalog that was obtained combining the output of so many different systems and groups. While building the acquisition and data processing systems, care is paid to verify the quality of the data. Two complementary approaches are followed aimed to answer two basic questions. First, at each step of the data processing, a rigorous verification of the results takes place to verify if the Catalog is correctly

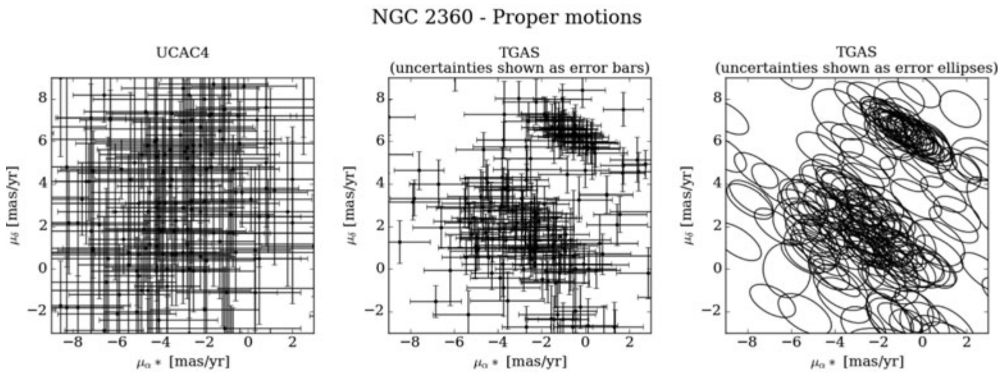

Figure 1. Proper motion distribution in the field of NGC 2360 from UCAC4 (left) and from TGAS (centre). The effect of the correlations on astrometric parameters on the error bars is shown in the right panel. Adapted from Cantat-Gaudin *et al.* (2017)

built. To this purpose the groups involved in the processing implement many tests, and depending on the results, they could update the pipeline. Second, at the end of the data process, when a consolidate Catalog has been built, and before the data release, the data are checked by an independent validation team, to ensure a fresh and unbiased view. To main goal is to verify if the final Catalog is correct. At this stage, no further processing is possible, but objects or fields showing problems can be rejected (filtering). After the filtering, the validation is performed again. The validation group has access to the same fields as published in DR1, and their work can be fully reproduced by the science users. More information can be found in Arenou *et al.* (2017). Quite a number of tests are applied during the validation, looking at the data from different points of view. This includes data integrity and consistency checks to ensure for instance that all the catalog entries are valid, self-consistent, in the expected range, that no data were missing, that the uncertainties behave as expected. Galaxy models were used to make a large scale comparison with the observational density of stars and the distribution of proper motions. This is especially useful in regions of the sky where external non-Gaia data are too scarce. Using star, QSO, and galaxy density in different regions of the sky, open, and globular clusters, the limiting magnitude, the photometric and astrometric quality are tested by comparison with a number of external Catalogs, among which we recall 2MASS, UCAC4, SDSS. Additionally, astrometric quality was assessed comparing with external Catalogs having high quality determination, such as HST, RAVE, APOGEE or VLBI compilation. Finally HST observations were used to assess the completeness and the photometric quality in well defined regions such as in globular clusters, the Galactic bulge, and the Magellanic Clouds.

The validation effort has put into evidence a number of minor issues, that were basically addressed by filtering the data before release or simply, by describing them in the documentation. More information on the major issues can be found in Gaia Collaboration, Brown, *et al.* (2016). Here we focus on two problems. Due to known limitations in the astrometric processing a global offset below 0.1 mas on the parallax zero point is found. A global estimate of the parallax zero point offset $\omega_G - \omega_C$ as given by the weighted average of the comparison with external catalogs is -0.036$\pm$ 0.002 mas, very close to the value obtained using quasar parallaxes. However, in specific regions, where the number of measurements is insufficient, parallax zero point differences can reach $\pm$0.36 mas. In addition, we detect color dependent, spatially correlated errors of $\pm$0.2 mas.

Due to the combined effect of the filtering, and of the limited sky coverage, the completeness of the Gaia data is a complex function of the position in the sky, of the star density, and of the magnitude. In dense areas on the sky such as the inner Bulge or globular clusters, having stellar densities above a few hundred thousand per square degree, the crowding results in the truncation of the observation windows for overlapping stars. Truncated windows were not used in DR1 data processing. As a consequence the number of useful passages decreases, leading to a poorer astrometric and photometric solution. Dense regions are affected by artifacts, holes, and stripes of missing stars. The filtering reflects the preliminary nature of the first Gaia data release. In the future the shortcomings in the data processing will be addressed; the calibrations will be more accurate, and more measurements will be added. We expect that while globally the quality of the results will improve, the level of filtering will go down. This will increase both the quality and the completeness of the Catalog in the coming data releases. It is expected however, that Gaia performances in high crowding regions will still be limited.

2.2. *Gaia DR1 quality assessment*

Independent verifications of the quality of the Gaia DR1 astrometry were performed by the scientific community. RR Lyrae (RRL) and Cepheids period-luminosity (PL) or period-luminosity-metallicity relation provide powerful means to calibrate astrometric data and related uncertainties, in the TGAS subset. Comparing Gaia parallaxes with a sample of nearby pulsating stars, no indication of a significant offset on the zero point was detected to a precision of a few dozens of μas (Sesar *et al.* 2017, Casertano *et al.* 2017, Gould *et al.* 2017). DR1 parallaxes are in remarkably good global agreement with the predictions, and suggestions were advanced that the published errors might have been conservatively overestimated.

Using Hubble Space Telescope Fine Guidance Sensor interferometric astrometry for a subset of 26 stars in common with Gaia DR1, Benedict *et al.* (2017) find no significant scale difference over a parallax range $2 < \omega < 40$ mas. The comparison with HST is very interesting, since the mean uncertainty of HST parallaxes is of the order of 0.17 mas. In the future, Gaia data releases should yield parallaxes far more precise than HST.

Asteroseismology has proved to be a relevant method to derive the fundamental properties of stars, including distances. Initial comparison of asteroseismic distances with Gaia DR1 parallaxes reveals a very good agreement for a sample of 20 nearby dwarfs (De Ridder *et al.* 2016). Subsequent work by Silva Aguirre *et al.* (2017) using a sample of 60 nearby dwarfs and by Stassun & Torres (2016) on sample of eclipsing binaries pointed in favor of a small offset of the order of 0.1-0.23 mas. A comparable offset was detected by De Ridder *et al.* (2016) on a sample of 900 giants. One of the most recent papers on this issue is by Huber *et al.*(2017) who make use of a larger sample and adopted a hotter temperature scale. They reach the conclusion that asteroseismic and TGAS parallaxes agreement is at a few % level. While the reasons of the different outcome must be found in the inherent uncertainties on asteroseismic parameter determinations, and possibly in the treatment of Gaia DR1 uncertainties, it should be mentioned that the derived offsets are consistent with the DPAC determinations of the zero point bias (Lindegreen *et al.* 2016). In addition the comparison between Gaia DR1 and APOKASC asteroseismic distances (as derived by Rodrigues *et al.* 2014) reveals that the median zero points difference is $(\omega_G - \omega_A) = -0.070 \pm 0.009$ mas (Arenou *et al.* 2017).

Recently, both observational and theoretical work has suggested that the zero-points of the asteroseismic scaling relations might be ill derived. From the study of star clusters and double lines eclipsing binaries Brogaard *et al.* (2015), Miglio et al. (2016) indicate that asteroseismic scaling tend to overestimate red-giant masses and radii by about +10% and

-5%, respectively. Such uncertainty is significantly impacting on the absolute age scale, leading to a $\sim 30\%$ overestimate. Using Gaia DR1 parallaxes Huber *et al.* (2017) find no evidence for systematic trends in the scaling relations as a function of metallicity in the range $-0.8 < [Fe/H] < +0.4$ dex. They estimate that Gaia DR2 will provide parallaxes for nearly 20,000 Kepler stars. Those data will have an enormous impact, allowing unprecedented scaling relation verification. When combined with frequency modeling, they will permit testing and improving the models of the stellar interiors from the main sequence to the red-giant branch.

3. Gaia DR1 Early Science

Gaia DR1 data have been extensively used in a wealth of papers, covering different topics. A comprehensive summary is outside of the scope of this review. Here we just recall a few cases.

3.1. *Stars and Clusters.*

DR1 astrometry and photometry have already become a reference in literature, and have been widely used for calibration (see for instance Magnier *et al.* 2017 concerning the survey Pan-STARRS, or Nidever *et al.* 2017 for SMASH). Hawkins *et al.* (2017) combine Gaia data on red clump stars with other photometric surveys (2MASS, WISE) to derive the mean and the dispersion in the absolute magnitude in several pass-bands. This ultimately leads to a new calibration of the red clump as standard candle allowing for a typical distance precision of $\sim 8\%$.

Gaia parallaxes have allowed the derivation of absolute luminosities of specific type of stars to be compared with model predictions (see Smith *et al.* 2017 for a sample of Luminous Blue variables) or to improve the knowledge of stellar parameters (Tremblay *et al.* 2017 for white dwarfs mass-radius relation; Eggleton & Yakut 2017 and Graczyk *et al.* 2017 for binaries; Stassun *et al.* 2017 on the model independent radius and masses determination of extrasolar transiting planets).

Gaia DR1 is clearly not ideal concerning globular clusters astrometry, since for the majority of them only positions and G magnitudes are available. As we have discussed in the previous Section, they are affected by crowding and their completeness is relatively poor. However, Watkins & van der Marel (2017) were able to detect in the TGAS data base, 20 good stars in 5 globulars, estimating the parallaxes and proper motions. Massari *et al.* (2017) combined the positions of the stars in the metal poor distant globular NGC 2419 with HST positions, obtaining high precision mean cluster proper motion. The derived orbit suggests that indeed this cluster might be associated to the Sagittarius dwarf spheroidal. More accurate distances and proper motions of Galactic globulars will be possible using future Gaia data releases, with an enormous impact on our understanding of the whole system.

Concerning open clusters, about 400 objects are present in the TGAS catalog, sampling the solar neighborhood up to 1-1.5 Kpc. For a large number of those objects only a few bright stars very available. However, Cantat-Gaudin *et al.* (2017) take advantage of the full astrometric solution available for TGAS stars to identify the members of 134 known open clusters leading to a revision of cluster properties such as membership, proper motions, parallaxes and as consequence ages. Combining TGAS data with spectroscopic radial velocities, cluster orbits were obtained. Gaia Collaboration, van Leeuwen *et al.* (2017) analyze 19 clusters closer than 500 pc, through a careful determination of the uncertainties due to the correlations between astrometric parameters. They find an excellent agreement with previous parallax and proper motion determination based on the Hipparcos catalog, for all the object, but the Pleiades. The new determination of the Pleiades parallax is in excellent agreement with previous literature determinations (Melis *et al.* 2017), solving the so-called "Pleiades problem". In the closest cluster, the Hyades, it was possible to resolve the internal kinematics. In almost all clusters, members were found at large distances from the center, up to 15 pc (see for instance Praesepe). Future Gaia releases will establish whether those candidate member stars are still dynamically bound to the clusters. Piatti (2017) confirme or disprove the nature of a number of stellar aggregates using Gaia DR1 parallaxes and proper motions. Finally two new clusters, Gaia 1 and Gaia 2 were discovered only using the excellent precision of the Gaia DR1 positions (Koposov *et al.* 2017).

3.2. *The Milky Way and the Local Group*

Exciting results on Galactic structure and kinematics were derived combining Gaia astrometry with other photometric or spectroscopic surveys (see for instance Helmi *et al.* this Volume). Here we recall a few.

Allende-Prieto *et al.* (2017) study the Galactic rotation velocity-metallicity (V-[Fe/H]) relations for the thin and thick disk from a sample of TGAS-APOGEE stars. They find that the (V-[Fe/H]) gradient follows as a direct consequence of the radial metallicity gradient and the correlation between Galactic rotation and mean Galactocentric distance.

Bovy (2017) selects a sample of more than 300,000 main-sequence TGAS stars with parallax uncertainties lower than $\sim 10\%$ from the Gaia DR1 TGAS solution to derive a precise measurement of the Oort constants at a heliocentric distance of 230 pc. Indeed Oort constants show a linear dependence on proper motions and parallaxes, and clearly benefit from high accuracy Gaia data. These measurements of the Oort constant A and B is are in agreement with those based on Hipparcos Cepheids. Only a few determinations of the C and K constant were previously derived in literature. The present values, both significantly non zero, give strong support to the idea that the local velocity field is shaped by non-axisymmetric forces.

Hunt *et al.* (2017) report on the detection of a small overdensity of stars in velocity space in TGAS data. Their Galactocentric rotation velocity is higher than the Sun by about 20 Km/s. Comparing this feature with numerical models, the authors come to the conclusion that these fast rotators can be generated by the co-rotation resonance of the Perseus spiral arm.

Monari *et al.* (2017) combine TGAS data with LAMOST DR2 radial velocities to discuss the properties of the Hercules stream. It is currently believed that moving groups in the solar vicinity are originated by the resonant interaction between the stars and non-axisymmetric patterns of our Galaxy. Using these data, the authors find that the Hercules stream is precisely following the prediction of models placing the Sun just outside the outer Lindblad resonance of the bar, when the corotation of the bar is close to a Galactocentric distance of ~ 4 Kpc. This would not support the presence of a slowly rotating bar with corotation around ~ 6 Kpc.

The exquisite quality of the Gaia's photometric catalog has lead to the identification of Miras and RRLyrae through their larger photometric uncertainties in the Magellanic Clouds. This in turn has allowed building detailed star-count maps of the Clouds, providing important constraints on the various models of the Magellanic system formation and evolution (Deason *et al.* 2017; Belokurov *et al.* 2017).

4. Gaia Second data release and beyond

The second data release (DR2) is currently planned on April 2018. As in the case of Gaia DR1, the Gaia Catalog is subject to an extensive validation by the DPAC. This is a mandatory step before any data release, and subject to the success of this, the Gaia DR2 will contain:

• For more than a billion sources having acceptable formal errors, the full five-parameter astrometric solutions will be delivered, based on 22 months of data. At the opposite of DR1, this solution will be fully stand-alone, based only on Gaia data, and calculated without imposing any priors. In addition positions (α, δ) will be available for sources for which parallaxes and proper motions cannot be derived. Preliminary verification has shown a significant improvement of the astrometric quality. Systematics will still be present, but at a lower level in comparison to DR1;

• For all the sources, G and integrated GBP and GRP photometric fluxes and magnitudes are derived using a more mature geometric and pass-band calibration, including large and small scale effects, time link, gate and window classes. This ensures a substantial reduction of the already small systematics still present in DR1, producing an exceptional photometry at a few milli-mag level, both in the G, and the GBP, GRP. We expect that the impact of such high quality on the study of the stellar astrophysics and stellar population in general would be enormous. Comparison with theory and synergy with asteroseismology will allow to refine stellar models in critical regions of the color-magnitude diagram, where large uncertainties are still present. This in turn will impact on our knowledge of the stellar populations in the Galaxy;

• Median radial velocities for sources brighter than GRVS=12 mag are delivered. Preliminary assessment of the quality of the radial velocities was obtained comparing ground-based determinations of reference stars.

• For stars brighter than G=17 mag estimates of the effective temperature and, where possible, line-of-sight extinction will be provided, based on the above photometric data.

• Photometric data for a sample of variable stars.

• Epoch astrometry for a pre-selected list of asteroids

The advanced stage of the Gaia data processing allows us to envisage a release scenario, based on our knowledge of the necessary steps. In the current planning, the third data release is targeted on late 2020, delivering improved astrometry, photometry, radial velocities and object classification, together with BP/RP spectra and/or RVS spectra for spectroscopic and photometrically well-behaved objects. In addition, we will release variable star classifications and the corresponding epoch photometry; Solar-system results with preliminary orbital solutions and individual epoch observations; and non-single star catalog. The final release for the nominal mission is planned at the end of 2022. We will provide an update of all the Gaia data products, based on a re-reduction of all the available data. The content will include exo-planets, and all the epoch and transit data for all sources. Clearly the effective release content is depending on the success of the validation work, and might be subject to changes. It is already clear from the DR1 and the preliminary DR2 solution that Gaia will keep its promises, and will have an huge impact on our understanding of many fields of astrophysics.

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