Publ. Astron. Obs. Belgrade No. 100 (2021), 75 - 83 *Invited Lecture*

TOWARDS GAIA DR3 AND SOME RESULTS OF COMPARISON BETWEEN GAIA DR2 AND GROUND-BASED DATA

G. DAMLJANOVIĆ
Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
E–mail: gdamljanovic@aob.rs

Abstract. Gaia satellite of European Space Agency (ESA) was launched at the end of 2013, and the astronomical observations were started in mid-2014. The first Gaia data release (Gaia DR1) appeared on 14^{th} September 2016, and the second one (Gaia DR2) on 25^{th} April 2018. The next result, the third Gaia solution splits into an early Gaia EDR3 (it appeared on 3^{rd} December 2020) and Gaia DR3 (it is going to appear during the first half of 2022). The main information about Gaia DR3, and some results of comparison between the Gaia DR2 and independent ground-based data of common stars are presented, here.

1. INTRODUCTION

The Gaia result is a unique time-domain space survey, and Gaia is well into its extended mission lifetime. The plan of Gaia was to repeatedly map all sky during its 5-year lifetime (from mid-2014 to mid-2019), but the last extension was given for Gaia from 1^{st} January 2023 to 31^{st} December 2025. After the first Gaia data release – DR1 (on 14^{th} September 2016), the second one – DR2 (on 25^{th} April 2018), and the early release called Gaia early third data release – EDR3 (on 3^{rd} December 2020), the full Gaia data release – DR3 or the catalogue is planned for the first half of 2022. Both solutions (EDR3 and DR3) are based on 34 months of Gaia observations, and feature the same source list.

Before the Gaia mission of the European Space Agency (ESA) it was the Hipparcos (High Precision PARallax Collecting Satellite) ESA mission as the predecessor of Gaia (ESA 1997; van Leeuwen 2007). It means, the Gaia is another big mission of the ESA, and the next step of the European pioneering high-accuracy astrometry. The Gaia satellite was launched at the end of 2013, and the plan was to survey all objects to ≈ 20 mag in V-band for astrometry and photometry or ≈ 1 billion sources, and to ≈ 16 mag in spectroscopy or ≈ 150 million ones (Prusti 2012)), but now there are more than six years after the first astronomical observations of Gaia (in mid-2014). The mentioned releases (DR1, DR2, and EDR3) are a few important steps for the final Gaia catalogue and the Gaia reference frame. The Gaia has got an interdisciplinary character, and Gaia-based results are useful for all the relevant scientific communities. The Gaia is doing revolution in astronomy, our understanding of the Milky Way galaxy, stellar physics and the Solar System bodies.

Mainly, the Gaia EDR3 catalogue contains the improved astrometry and photometry of DR2, but the Gaia DR3 catalogue is going to contain the Gaia EDR3 and other data: mean radial velocities for stars (with atmospheric-parameter estimates), variable-star classifications with the epoch photometry, Solar-System results (some orbital solutions, epoch observations, etc.), double and multiple stars, quasars and results of extended objects, etc. The photometry for all astrometrically detected objects was done. The orbital parameters could be calculated with much higher precision for the binary and multiple stars using the Gaia high spatial resolution. About the exoplanets, it is expected to find several thousands of systems. In stellar astrophysics, the improvement in the distances will allow to obtain models of stars at different steps of evolution using the improvement of parallaxes via Gaia observations. The Gaia will be of importance in the case of faint rare objects (as brown or white dwarfs). It is detecting the Solar System objects, a few millions of galaxies (as not points, but extended objects), quasars, etc. About asteroids, there is an improvement of their ephemerides, masses, etc. About the quasars, they are of importance for reference systems and fundamental physics.

Gaia has two fields of view separated by 106.5 degrees, and rotates around itself with a period of 6^h. As a result, a sequence of measurements consists of several transits separated successively by 1^h46^m and 4^h14^m, which correspond to the times elapsed from one field to the other. The next sequence of transits appears about 1 month later, due to the rotation axis precession and the satellite orbital motion. There are from 40 to 250 measurements per observed object (Prusti 2012) during the five-year observations.

2. GAIA DR1

The Hipparcos result was the Hipparcos Catalogue with $\approx$ 118000 stars. The Hipparcos changed the astronomy at the end of the last century, but the Gaia is the cornerstone mission of ESA at the beginning of 21^{st} century. The goal of the Gaia mission was $\approx$ 1 billion stars and $\approx$ 500000 extragalactic sources (Prusti 2012), or to observe the mentioned extragalactic sources and stars in our Milky Way galaxy: astrometry, photometry, and spectroscopy. The astrometry is going from milliarcsec to microarcsec, plus the data of radial velocities V_r. Finally, to produce the Gaia Catalogue in the optical domain and in line with the International Celestial Reference Frame – ICRF (which is based on the VLBI observations). The VLBI coordinates of extragalactic sources at J2000.0 materialize the International Celestial Reference System – ICRS which is kinematically defined by: the origin of its axes (the barycentre of the Solar System), a principal plane (close to the mean equator at J2000.0), and an origin of right ascensions (close to the dynamical equinox at J2000.0).

The first release of the Gaia catalogue (DR1) is the main goal of that ESA mission and the first step of the future Gaia celestial reference frame (Gaia CRF). The Gaia CRF is going to link to the ICRF. The Gaia is determining the high accurate positions, proper motions and parallaxes (five-parameter astrometric solution) of observed objects. Plus, the G magnitudes for these objects; the Gaia G-band is the white-light photometry band. In the DR1, there are $\approx$ 2 million stars using Tycho-Gaia solution, and it is based on the first observational period ($\approx$ 14 months). Also, in that solution, only data were published about flux time-series variability detection for Cepheids and RR Lyrae, but not for AGNs and quasars. The DR1 is not an independent solution, but it is the Tycho-Gaia astrometric solution (Lindegren et al. 2016). More about the DR1 could be found in (Lindegren et al. 2016).

3. GAIA DR2 AND EDR3

The useful data for the second Gaia solution - DR2 are from August 2014 even the start of astronomical observations was in July 2014 (the first month of Gaia observations was not included in the DR2 because the data quality is not good enough). The main part of the DR2 catalogue is five-parameter astrometric solution for ≈ 1.3 billion stars: positions (α_{ICRS} and δ_{ICRS}), parallax, and proper motions (μ_α and μ_δ). It is of importance to mention that the parallax values (given in DR2) could be less than zero, which, though meaningless, is due to the calculation procedure. Also, it was the case in the Hipparcos Catalogue for some stars. The DR2 is based on 640 days or 1.75 years of Gaia operational phase (≈ 21 months with some interruptions) or the period from 22^{nd} August 2014 to 23^{rd} May 2016. It contains results for 1.693 billion sources in the G magnitude range 3 to 21, but for 1.332 billion sources there are all mentioned five astrometric parameters. Its reference epoch is $J2015.5 = JD2457206.375$ TCB or 2^{nd} July 2015 at $21^h0^m0^s$ TCB; it is about half-way through the observational period. That epoch is 0.5 years later than the DR1 one, and there are some differences in the positional data between the DR1 and DR2 releases. The reference epoch was chosen to get minimal correlations between the positions and proper motions.

The positions (α_{ICRS}, δ_{ICRS}) and proper motions (μ_α, μ_δ) refer to the ICRS. Plus, for an additional 0.361 billion mostly faint objects, there are the approximate α_{ICRS} and δ_{ICRS} (Lindegren et al. 2018); the DR2 is available in the online Gaia Archive. In both, DR2 and DR1 cases, there are only photometric data as time-series for Cepheids and RR Lyrae, but no quasars and other objects with unstable flux.

The DR2 catalogue does not include any other astrometric data (Hipparcos or Tycho ones). It means, it is independent (in contrast to the DR1 solution). In DR1 and DR2 solutions, all sources are reduced as single stars. The main values are presented by the five astrometric parameters. In the case of unresolved binaries, the results of some binary stars refer to the photocentre or to either component for resolved ones. The main steps (of the models, algorithms, and astrometric solution) are described in Lindegren et al. (2012; 2016). By using the photometric processing of data via the blue BP and red RP photometers, the colour information in DR2 for most of the sources could be found. The median uncertainty is near 0.04 mas in parallax and position for bright sources ($G < 14$ mag) at reference epoch of DR2 ($J2015.5$), 0.1 mas for $G = 17$ mag, and 0.7 mas in the case of $G = 20$ mag. The mentioned values for proper motions (μ_α and μ_δ) are: 0.05, 0.2, and 1.2 mas/yr, respectively. In the case of binary stars and other perturbations, the non-linear motions are not included in DR2. It means, only the uniform space motion of the object relative to the Solar System barycentre was considered. In line with Lindegren et al. (2018), the mentioned motions are going to be included into the Gaia DR3 solution.

The IAU Working Group "Third Realization of ICRF" is responsible for the ICRF3 catalogue. Mignard et al. (2018) used an ICRF3 prototype with 4262 sources observed in X/S bands, and 2820 quasars matched the ICRF3 prototype. Moreover, the number of extragalactic sources was updated by Charlot et al. (2020). Currently, there are 4536 objects at S/X, 824 objects at K, 678 objects at X/Ka. In line with Lindegren et al. (2018), the optical Gaia DR2 CRF is aligned with ICRS. It is non-rotating to within 0.15 mas/yr with respect to the quasars. Using the extragalactic objects visible in the optical and radio domains, the primary solution was linked to the ICRS; the DR2 is aligned with ICRS and non-rotating with respect to the quasars (as quasars are distant objects) and the Gaia-CRF2 is the celestial reference frame of Gaia DR2. The astrometric calibration parameters of the CCDs were determined via an astrometric solution for $\approx 1\%$ of the input data (≈ 16 million selected objects). In line with Lindegren et al. (2018), the astrometric parameters were calculated for the other sources. In that way, the systematic effects in the parallaxes are less than 0.1 mas (depending on positions, magnitude and colour). The Barycentric Celestial Reference System – BCRS is the primary coordinate system; the axes are aligned with the ICRS and its origin is at the Solar System barycentre. The barycentric coordinate time – TCB is the time-like coordinate of the BCRS. A consistent theory of relativistic astronomical reference systems was used during the processing of the Gaia data in line with Soffel et al. (2003).

The third Gaia data release splits into two solutions: the early release (EDR3), and the full Gaia data release (DR3). The EDR3 consists: astrometric, photometric, and radial-velocity data (V_r), variable-star and non-single-star results, object classifications with multiple astrophysical parameters for stars, quasars, galaxies, and unresolved binaries, exo-planets, epochs and transits for all objects, etc. The five-parameter astrometric solution of the EDR3 (positions, proper motions, and parallaxes) is done for around 1.5 billion sources. The limiting G magnitude is of about 21 and a bright limit of about 3. Just positions on the sky (α and δ) or two-parameters solutions are presented for around 300 million additional objects. The G magnitudes are done for both sets of data; they are presented for around 1.8 billion sources, but G_{BP} and G_{RP} magnitudes for around 1.5 billion sources. It is necessary to be careful about G, G_{BP}, and G_{RP} bands because the EDR3 photometric system is different from the system in DR1 and DR2. There are about 1.5 million objects useful for the Gaia celestial reference frame (Gaia CRF). The source list for Gaia EDR3 is independent of DR2 and of DR1; from DR2 to EDR3 the changes impact until 5% of the sources.

4. GAIA DR3

Some data (variables, Solar System objects, astrophysical parameters) are not presented in the Gaia EDR3, but they are going to be a part of the Gaia DR3 (together with "new" V_r values). Both data sets, EDR3 and DR3, are based on the data collected between 25^{th} July 2014 and 28^{th} May 2017 (a period of 34 months). The DR2 was based on 22 months of data, and DR1 on 14 months (the first ones). The Gaia DR3 (and EDR3) reference epoch is $J2016.0$; for DR2 it was $J2015.5$ and for DR1 it was $J2015.0$. The Gaia EDR3 optical reference frame is aligned to the ICRS (it will be the case of DR3, also), and because of this the positions and proper motions are referred to the ICRS.

At the first place, the Gaia DR3 solution is going to contain the improved astrometry and photometry of DR2. Also, it will be consisting of: the epoch photometry and variable-star classifications, mean V_r velocities for stars without detected variability, BP/RP and RVS spectra for spectroscopically objects or the object classification and astrophysical parameters, preliminary orbital solutions and individual epoch observations for the Solar-System results, non-single star catalogues, etc.

Table 1: The $D = 1.4$ m telescope of ASV.

Site Telescope $D(cm)/F(cm)$	longitude - $\lambda(^o)$ latitude - $\varphi(^o)$ altitude - h (m)	CCD camera pixel array and scale $('')$ pixel size (μm) and field of view - FoV $(')$
ASV (AOB) Ritchey-Chrétien 140/1142	21.6 43.1 1143	1. Apogee Alta U42 (mid-2016 – mid-2018) 2048x2048, 0.24 13.5x13.5, 8.3x8.3
		2. Andor iKon-L (from mid-2018 until now) 2048x2048, 0.24 13.5x13.5, 8.3x8.3

5. SERBIAN-BULGARIAN TELESCOPES IN LINE WITH GAIA MISSION

After launching the Gaia satellite, the astrometry with ground-based optical telescopes (of small and medium size) has become very actual part of astronomical investigation. Some ground-based observations started in accordance with the Gaia ESA mission using these telescopes. Some tasks are: the photometry of Gaia Alerts objects, the astrometric monitoring of Gaia satellite, the link between radio and optical positions of quasars, the realisation of a catalogue of quasars, etc. In Table 1, the main information about the $D = 1.4$ m telescope of Astronomical Station Vidojevica – ASV (of Astronomical Observatory in Belgrade – AOB, Serbia) is presented; see Fig. 2. It is the main AOB instrument at the new ASV site.

In 2013, we established the "Serbian – Bulgarian mini-network telescopes" (using 6 telescopes) to do the observations of Gaia Alerts and other objects in accordance with the Gaia mission (Damljanović et al. 2014). Also, these activities are in line with the bilateral Serbian-Bulgarian joint research SANU-BAN project "Gaia Celestial Reference Frame (CRF) and fast variable astronomical objects" during three years period (from 2020 to 2022, the head is G. Damljanović). SANU and BAN are the Serbian Academy of Sciences and Arts and Bulgarian Academy of Sciences. The $D = 60$ cm Bulgarian telescope is at the Astronomical Observatory Belogradchik (see Fig 1.), the other three Bulgarian instruments of Gaia Alerts interest ($D = 2$ m, $D = 60$ cm and 50/70 cm Schmidt-camera) are at the Rozhen Observatory, and one $D = 60$ cm telescope is at ASV. These instruments and their CCD cameras were described in the paper (Damljanović et al. 2020; Taris et al. 2018). From 2005 there is $D = 40$ cm MEADE instrument at AOB which was moved from AOB (Belgrade city) to ASV site (near Prokuplje) during 2020; the new dome for that instrument is ready at ASV in 2020 (Fig. 3) and the first data using it are expected in 2021.

Figure 1: The Astronomical Observatory Belogradchik between famous rocks.

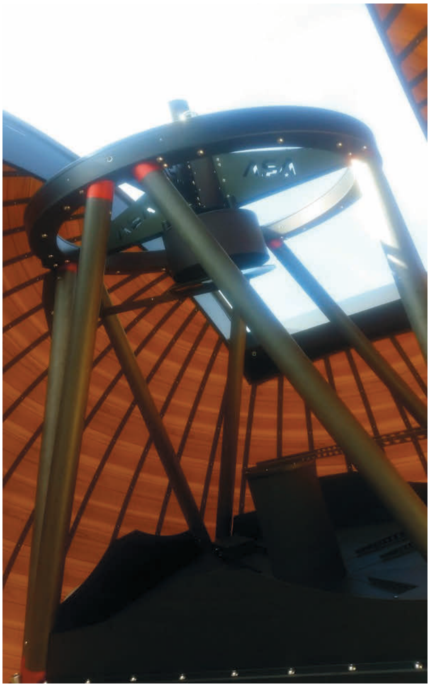

Figure 2: The telescope $D = 1.4$ m of Astronomical Station Vidojevica – ASV.

Figure 3: The dome for $D = 40$ cm MEADE telescope of ASV.

6. SPIN INVESTIGATION OF THE BRIGHT GAIA DR2 USING SOME INDEPENDENT GROUND-BASED DATA

About the spin (with components ω_X, ω_Y and ω_Z) investigation of the bright Gaia DR2 reference frame, the independent proper motion in declination μ_δ ground-based data were used (to determine ω_X and ω_Y). They are the μ_δ values of: 387 stars of the International Latitude Service – ILS catalogue, and 682 stars of the independent latitude stations – INDLS catalogue. Both catalogues (the ILS and INDLS) data are available in the Strasbourg astronomical Data Center: the ILS data at https://doi.org//10.26093/cds/vizier.36310145, and the INDLS data via ftp://cdsarc.u-strasbg.fr/pub/cats/J/AN/341/8. It is a contribution to a possible validation of the Gaia astrometry. Also, the new Hipparcos – NHIP (van Leeuwen 2007) values μ_δ were used for the same stars. The mean accuracy of the ILS μ_δ values is 0.21 mas/yr and of INDLS μ_δ values is 0.51 mas/yr; the stars are from 4 to 8 magnitude in V-band. An indication (Lindegren 2020) that the bright reference frame of Gaia DR2 rotates relative to the faint DR2 (of the order of 0.1 mas/yr) is supported using the ILS and INDLS data (Damljanović and Taris 2019; Damljanović 2020). The bright reference frame of Gaia DR2 is based on stars with $G \leq 13$ mag, the faint part of DR2 (quasars based one) on stars with $G \geq 16$ mag, and the faint part of DR2 is aligned with the ICRS via quasars (Lindegren et al. 2018) because these quasars with optical counterparts are visible in the optical domain mostly with $G \geq 17$ mag. Also, the DR2 stars with $G \leq 6$ mag mostly have inferior astrometry (Lindegren 2018).

The mentioned spin components ω_X and ω_Y could be calculated using μ_δ (of ILS and INDLS catalogues) and μ'_δ values (of DR2 for the same stars) via Lindegren formula (2020)

$$\mu_\delta - \mu'_\delta \approx -\omega_X \sin\alpha + \omega_Y \cos\alpha,$$

where (after the least squares method – LSM): ω_X is not significant on the 2σ level, but ω_Y is of the order of 0.1 mas/yr and it is significant on the 2σ level (Damljanović and Taris 2019; Damljanović 2020). The value ω_Z is close to zero (Lindegren 2020). The right ascension α is from the DR2 catalogue.

The ILS and INDLS data are in the Hipparcos celestial reference frame, and the calculated ω_Y value is the component of the spin between that frame (or catalogue) and the bright DR2 frame (or catalogue). A part of ω_Y belongs to the ILS and INDLS catalogues (because ω_Y is about -0.2 ± 0.08 mas/yr for μ_δ differences ILS$-$NHIP and INDLS$-$NHIP), but another one (ω_Y is about -0.5 ± 0.08 mas/yr for ILS$-$DR2 and INDLS$-$DR2) belongs to the bright DR2 frame (Damljanović 2021). For the case NHIP$-$DR2 and same stars, ω_Y is about -0.4 ± 0.08 mas/yr. It means, the value ω_Y is of the order of 0.1 mas/yr for DR2 stars in V-magnitude from 4 mag to 8 mag.

7. CONCLUSIONS

After the first Gaia data release (Gaia DR1) and the second one (Gaia DR2), the third Gaia solution splits into two parts: an early Gaia EDR3, and Gaia DR3. EDR3 appeared on 3^{rd} December 2020, and the final solution (Gaia DR3) is going to appear during the first half of 2022. The main information about these solutions and Serbian-Bulgarian telescopes in line with the Gaia mission is presented, here. Also, some original results about the spin investigation of the bright Gaia DR2 (stars with $G \leq 13$ mag) are achieved using the independent ILS and INDLS catalogues of μ_δ values. These results (Damljanović and Taris 2019; Damljanović 2020) support an indication that the bright reference frame of Gaia DR2 rotates relative to the faint DR2 (stars with $G \geq 16$ mag) of the order of 0.1 mas/yr (Lindegren 2020). The ILS and INDLS catalogues data are available in the Strasbourg astronomical Data Center: the ILS data at https://doi.org//10.26093/cds/vizier.36310145, and the INDLS data via ftp://cdsarc.u-strasbg.fr/pub/cats/J/AN/341/8.

Acknowledgements

The author thanks the referee for the very constructive comments, which helped substantially improve the manuscript. This research was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (contract No 451-03-68/2020-14/200002). This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the DPAC (https://www.cosmos.esa.int/web/gaia/dpac/consortium , Gaia Data Processing and Analysis Consortium).

References

Charlot, P., Jacobs, C. S., Gordon, D. et al.: 2020, A&A, **644**, A159.
Damljanović, G., Vince, O., Boeva, S.: 2014, Serb. Astron. J., **188**, 85 – 93.
Damljanović, G., Taris, F.: 2019, A&A, **631**, A145.
Damljanović, G.: 2020, AN, **341**, 770 – 780.
Damljanović, G., Bachev, R., Boeva, S, et al.: 2020, Publ. Astron. Soc. "Rudjer Bošković", **20**, 15 – 22.
Damljanović, G.: 2021, AcA, in procedure.
ESA: 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200.
Lindegren, L., Lammers, U., Hobbs, D. et al.: 2012, A&A, **538**, A78.
Lindegren, L., Lammers, U., Bastian, U. et al.: 2016, A&A, **595**, A4.
Lindegren, L., Hernandez, J., Bombrun, A. et al.: 2018, A&A, **616**, A2.
Lindegren, L.: 2020, A&A, **633**, A1.
Mignard, F., Klioner, S. A., Lindegren, L. et al.: 2018, A&A, **616**, A14.
Prusti, T.: 2012, AN, **333**, No. 5/6, 453.
Soffel, M., Klioner, S. A., Petit, G. et al.: 2003, AJ, **126**, 2687.
Taris, F., Damljanović, G., Andrei, A. et al.: 2018, A&A, **611**, A52.
van Leeuwen, F.: 2007, Hipparcos, the New Reduction of the Raw Data, Springer, Dordrecht.