Proceedings of the XII Serbian-Bulgarian Astronomical Conference
(XII SBAC) Sokobanja, Serbia, September 25-29, 2020
Editors: L. Č. Popović, V. A. Srećković, M. S. Dimitrijević and A. Kovačević
Publ. Astron. Soc. "Rudjer Bošković" No 20, 2020, 5-14

GAIA DR3 AND SOME RESULTS OF SERBIAN-BULGARIAN COOPERATION

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Abstract. After ESA Gaia DR1 (First Release, 14^{th} September 2016) and Gaia DR2 (Second release, 25^{th} April 2018) the Third Release is going to be available, soon. At the end of 2020, an early Gaia EDR3 is expected, and the Gaia DR3 catalog is expected after July 2021. Mainly, the Gaia EDR3 catalog will be consisting of improved astrometry and photometry, but the Gaia DR3 catalog contains 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, QSOs and results of extended objects, etc. Some results of the Serbian-Bulgarian cooperation in line with Gaia mission are presented.

1. INTRODUCTION

Gaia is well into its extended mission lifetime, now. The predecessor of Gaia, the Hipparcos (High Precision PARallax Collecting Satellite) of the European Space Agency - ESA, with ~118000 stars, changed the astronomy at the end of the last century (ESA 1997; van Leeuwen 2007), but the Gaia with ~1 billion stars and near 500000 extragalactic sources (Prusti 2012), from milliarcsec to microarcsec astrometry (plus the radial velocities Vr), is going to be a revolution in astronomy. It is a cornerstone mission of ESA, and the spacecraft was launched at the end of 2013. The start of normal operations was in mid-2014 (from August 2014, the data are useful for the Gaia Second release - DR2). The nominal Gaia operations phase was five-year for the observations, but now it is longer than the predicted period.

The plan was to observe the stars in our Milky Way galaxy: astrometry, photometry, and spectroscopy; plus, about 500000 extragalactic sources (Prusti 2012). The goal is to produce the Gaia Catalogue in optical domain, and to replace the International Celestial Reference Frame – ICRF. The ICRF is based on the VLBI observations in the radio domain. The accuracy of positions and parallaxes are at the level of accuracy far away from the ground ones; the Gaia is scanning the full sky with very high precision. The photometry for all astrometrically detected objects was done, and in spectroscopy the goal is to get the catalogue of Vr for ~150 million sources, etc. In stellar astrophysics, the improvement in the distances (using the improvement of parallaxes via Gaia observations) will allow to obtain models of stars at different steps of evolution. About the binary and multiple stars, the orbital parameters could be calculated with much higher precision using the Gaia high spatial resolution, and about the exoplanets, it is expected to find several thousands of systems. Also, the Gaia will be of importance in the case of faint rare objects as brown or white dwarfs. It is detecting not only point sources, but the solar system objects (with an improvement of asteroid ephemerides, to determine the masses of the objects, etc.), galaxies (the few million ones), quasars – QSOs (of importance for reference systems and fundamental physics), etc.

The period of the Gaia precession spin axis is 63 days because there are two Gaia fields of view (they are separated by a basic angle of 106.º5), and Gaia rotates around itself with a period of 6 hours. In line with that, for each observed object, it is collecting between 40 and 250 measurements during the five-year observations (Prusti 2012; Taris et al. 2018). The estimated Gaia end-of-life is still end-2024, but the process of extending the mission for the period 2023-2025 will start, soon. The data processing for the Gaia early release (EDR3) has almost finished, and the Third Gaia Release (DR3) or catalog is expected after July 2021. Both solutions are based on 34 months of Gaia observations, and feature the same source list.

2. FIRST AND SECOND GAIA DATA RELEASES

The First Release of the Gaia catalogue (DR1) was available since 14th Sept. 2016. It was the first step of the future Gaia celestial reference frame (Gaia CRF). The ICRF is based on the VLBI radio observations of extragalactic sources, and the Gaia CRF is going to link to the ICRF; the Gaia catalogue is the main goal of that ESA mission. The Gaia is collecting data for more than one billion of sources (the number of QSOs is about 500000); the G is the white-light photometry band of Gaia. It is determining the high accurate positions, proper motions and parallaxes (five-parameter astrometric solution). In the DR1, there are ~2 million stars using Tycho-Gaia solution, and it is based on the first observational period (~14 months). Also, in that solution, only data were published about flux time-series variability detection for Cepheids and RR Lyrae, but not for AGN and QSOs. More about the DR1 could be found in Taris et al. (2018).

The Second solution of the Gaia catalogue (DR2) was released on 25 April 2018.

The list with DR2 files is presented in Table 1. At the top of that list is the file with the main part of the DR2 catalog (five-parameter astrometric solution for ~1.5 billion stars). The main data of some star (positions RA_ICRS and DE_ICRS, parallax, proper motions pmRA and pmDE) are presented in Table 2.

The parallax values given in DR2 could be less than zero, which, though meaningless, is due to the calculation procedure (as some cases in the Hipparcos Catalog). The DR2 is based on ~21 months (1.75 yr or 640 days) with some interruptions (period 22nd August 2014 – 23rd May 2016) of Gaia operational phase, even the start of astronomical observations was in July 2014. The first month of Gaia observations was not included in the DR2 solution because the data quality is not high enough. That catalogue contains results for 1.693 billion sources in the G magnitude range 3 to 21. For 1.332 billion sources there are five astrometric parameters: positions, proper motions, and parallaxes. The reference epoch is J2015.5 = JD 2457206.375 TCB = 2 July 2015 at 21:00:00 TCB, and it is about half-way through the observational period used in the DR2 solution (that epoch is 0.5 yr later than the DR1 one). Because of its, 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.

Table 1: The second Gaia data release (DR2).

VizieR

Simple Target | List Of Targets — Fast Xmatch with large catalogs or Simbad

Target Name (resolved by Sesame) or **Position**: Clear | J2000 — Target dimension: 2 arcmin — Radius / Box size

I/345 — Gaia DR2 (Gaia Collaboration, 2018) — Similar Catalogs — 2018A&A...616A...1G — ReadMe+ftp — timeSerie
acknowledge and cite Gaia DR2
1 annotation(s) (on 1 specific record(s))

1.I/345/gaia2	(c)Gaia data release 2 (Gaia DR2). (**Download** all Gaia Sources as VOTable, FITS or CSV here. **Query from the command line using find_gaia_dr2 available in cdsclient** here) (original column names in green) *(1692919135 rows)*
2.I/345/rvstdcat	(c)Mean radial velocities on absolute scale (original column names in green)**[timeSerie]** *(4813 rows)*
3.I/345/rvstdmes	Original ground-based radial velocity measurements (original column names in green) *(71225 rows)*
4.I/345/allwise	Allwise AGN Gaia DR2 cross-identification (aux_allwise_agn_gdr2_cross_id) (original column names in green) *(555934 rows)*
5.I/345/iers	IERS GaiaDR2 cross-identification (aux_iers_gdr2_cross_id) (original column names in green) *(2820 rows)*
6.I/345/cepheid	(c)Cepheid stars (vari_cepheid) (original column names in green)**[timeSerie]** *(9575 rows)*
7.I/345/rrlyrae	(c)RR Lyrae stars (vari_rrlyrae) (original column names in green) *(140784 rows)*
8.I/345/lpv	(c)Long Period Variable stars (vari_long_period_variable) (original column names in green) *(89617 rows)*
9.I/345/varres	(c)Variability classification results of all classifiers, identified by the classifierName column (vari_classifier_result) (original column names in green) *(363969 rows)*
10.I/345/shortts	Short-timescale sources (vari_short_timescale) (original column names in green) *(3018 rows)*
11.I/345/tsstat	Statistical parameters of time series, using only transits not rejected (vari_time_series_statistics) (original column names in green) *(550737 rows)*
12.I/345/numtrans	Calibrated FoV transit photometry from CU5, consolidated and provided by CU7 for variable stars in Gaia DR2 (epoch_photometry, part 1) (original column names in green)**[timeSerie]** *(550737 rows)*
13.I/345/transits	Calibrated FoV transit photometry for CU5, consolidated and provided by CU7 for variable stars in Gaia DR2 (epoch_photometry, part 2) (original column names in green) *(17712391 rows)*
14.I/345/rm	Rotation period in segment, part 1 (vari_rotation_modulation) (original column names in green) *(147535 rows)*
15.I/345/rmseg	Rotation period in segment, part 2 (vari_rotation_modulation) (original column names in green) *(583988 rows)*
16.I/345/rmout	Rotation period in segment, part 3 (vari_rotation_modulation) (original column names in green) *(990561 rows)*
17.I/345/ssoobj	*Data related to Solar System objects observed by Gaia (sso_source) (original column names in green) *(Note)* *(14099 rows)*
18.I/345/ssoorb	*Auxiliary information on asteroid orbits and basic photometric parameters (aux_sso_orbits) (original column names in green) *(Note)* *(14099 rows)*
19.I/345/ssores	*Residuals with respect to an orbital fit considering only the Gaia observations (aux_sso_orbit_residuals) (original column names in green) *(Note)* *(1977702 rows)*
20.I/345/ssoobs	(c)*Solar System object observations (sso_observation) (original column names in green) *(Note)* *(1977702 rows)*

The positions (RA_ICRS, DE_ICRS) and proper motions (pmRA, pmDE) refer to the ICRS; see Table 2. An overview of Gaia EDR3 is done in Table 3. There are the approximate RA_ICRS and DE_ICRS for an additional 0.361 billion mostly faint objects (Lindegren et al. 2018). The DR2 is available in the online Gaia Archive[1]. In DR2 (as in DR1 case) there are only photometric data as time-series for Cepheids and RR Lyrae, but no QSOs and other objects with unstable flux.

Table 2: The coordinates (RA_ICRS, DE_ICRS), parallax, proper motions (pmRA, pmDE), Gmag, and other results of Gaia DR2.

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The 3 columns in *color* are computed by VizieR, and are *not part of the original data*.

I/345/gaia2 — Gaia DR2 (Gaia Collaboration, 2018) — 2018A&A...616A...1G — ReadMe+ftp
1 annotation(s) - post
Gaia data release 2 (Gaia DR2). (**Download** all Gaia Sources as VOTable, FITS or CSV here. **Query from the command line using find_gaia_dr2 available in cdsclient** here)

(original column names in green) *(1692919135 rows)*

start AladinLite — plot the output — query using TAP/SQL

Full	RA_ICRS deg	e_ mas	DE_ICRS deg	e_ mas	Source	Plx mas	e_ mas	pmRA mas/yr	e_ (...)	pmDE mas/yr	e_ (...)	Dup	FG e-/s	e_ e-/s	Gmag mag	e_ mag
☐	038.20256418497	0.2024	+20.28818994203	0.1823	86621076520103680	-0.0469	0.2274	-0.082	0.509	-0.616	0.432	0	1.4657e+03	1.7194e+01	17.7733	0.0127

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The DR2 catalogue is independent because it does not include any other astrometric data (Hipparcos or Tycho ones), in contrast to the DR1 which is the Tycho-Gaia astrometric solution (Lindegren et al. 2016). All sources are reduced as single stars (as in DR1 solution) and the main values are presented by the five astrometric parameters, but the results of some binary stars refer to the photocentre (in the case of unresolved binaries) or to either component (for resolved ones). The models, algorithms, and the main steps of astrometric solution are described in Lindegren et al. (2012). Also, there are some additions since 2012. The color information in DR2 for most of the sources could be found; it was obtained by using the photometric processing of data via the blue BP and red RP photometers. For bright sources, it means G < 14 mag, the median uncertainty is near 0.04 mas in parallax and position (at J2015.5 – reference epoch of DR2). For G=17 mag, it is 0.1 mas, and 0.7 mas in the case of G=20 mag. About the pmRA and pmDE, the mentioned values are: 0.05 mas/yr, 0.2 mas/yr, and 1.2 mas/yr, respectively. The optical Gaia DR2 CRF is aligned with ICRS, and in line with Lindegren et al. (2018), it is non-rotating to within 0.15 mas/yr with respect to the QSOs. Using QSOs the primary solution was linked to the ICRS, and the astrometric calibration parameters of the CCDs were determined via an astrometric solution for 16 million selected objects, ~1% of the input data. Then, for the other sources astrometric parameters were calculated (Lindegren et al.

[1] https://archives.esac.esa.int/gaia

2018). Depending on positions, magnitude and color, the systematic effects in the parallaxes are less than 0.1 mas. The Barycentric Celestial Reference System – BCRS is the primary coordinate system: the origin is at the solar system barycentre, the axes are aligned with the ICRS, the barycentric coordinate time – TCB is the time-like coordinate of the BCRS. In line with Soffel et al. (2003), a consistent theory of relativistic astronomical reference systems was used during the processing of the Gaia data.

Table 3: The overview of Gaia EDR3[2].

	# sources in Gaia EDR3	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	≈ 1,800,000,000	**1,692,919,135**	**1,142,679,769**
Number of 5-parameter sources	≈ 1,500,000,000	1,331,909,727	2,057,050
Number of 2-parameter sources	≈ 300,000,000	361,009,408	1,140,622,719
Sources with mean G magnitude	≈ 1,800,000,000	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	≈ 1,500,000,000	1,381,964,755	-
Sources with mean G_{RP}-band photometry	≈ 1,500,000,000	1,383,551,713	-
Gaia-CRF sources	≈ 1,500,000	556,869	2,191
Sources with radial velocities	expected with Gaia DR3 / ≈7,210,000 from Gaia DR2 in Gaia EDR3	7,224,631	-
Variable sources	expected with Gaia DR3 / see Gaia DR2	550,737	3,194
Known asteroids with epoch data	expected with Gaia DR3 / see Gaia DR2	14,099	-
Effective temperatures (T_{eff})	expected with Gaia DR3 / see Gaia DR2	161,497,595	-
Extinction (A_G) and reddening ($E(G_{BP}-G_{RP})$)	expected with Gaia DR3 / see Gaia DR2	87,733,672	-
Sources with radius and luminosity	expected with Gaia DR3 / see Gaia DR2	76,956,778	-
and more...	expected with Gaia DR3	-	-

The non-linear motions, the case of binary stars and other perturbations, are not included in DR2; only the uniform space motion of the object relative to the solar system barycentre was considered. The future Gaia release is going to include the mentioned motions (Lindegren et al. 2018). The DR2 is aligned with ICRS and non-rotating with respect to the QSOs as distant objects; the Gaia-CRF2 is the celestial reference frame of Gaia DR2. In a prototype version of ICRF3 there are 2843 sources (mostly QSOs), the optical counterparts of VLBI radio objects. The IAU Working Group "Third Realization of ICRF" is responsible for the ICRF3 catalogue which contains 4262 sources with accurate VLBI radio positions.

[2] https://www.cosmos.esa.int/web/gaia/earlydr3

3. THIRD GAIA DATA RELEASE (EDR3 AND DR3)

The Third Gaia Data Release is split into two releases: the early release (EDR3), and the full Gaia Data Release (DR3). The EDR3 will be consisting of: astrometric, photometric, and radial-velocity data, variable-star and non-single-star results, object classifications with multiple astrophysical parameters for stars, QSOs, galaxies, and unresolved binaries, exo-planets, epochs and transits for all objects; see Table 3. The early Gaia EDR3 is going to appear at the end of 2020. The Gaia DR3 catalog is expected after July 2021.

The DR3 solution (with improved astrometry and photometry of DR2 solution) will be consisting of: mean Vr velocities for stars without detected variability, object classification and astrophysical parameters (BP/RP and RVS spectra for spectroscopically objects), the epoch photometry and variable-star classifications, Solar-system results (preliminary orbital solutions, individual epoch observations), non-single star catalogues, etc.

Figure 1: The Belogradchik AO and famous rocks.

4. GAIA AND SERBIAN-BULGARIAN COOPERATION

A few years after the installation of the fist instrument (D=60 cm telescope, during 2011) at the Serbian new site (at the Astronomical Station Vidojevica – ASV) the Gaia satellite was launched (at the end of 2013) and during 2013 the local cooperation “Serbian-Bulgarian mini-network telescopes” was established; the Serbian-Bulgarian observational activities and investigation about the Gaia mission were started. The ASV belongs to Astronomical Observatory in Belgrade

– AOB[3]. At the two Bulgarian sites, Belogradchik (see Figure 1) and Rozhen, there are another 4 instruments of our interest. At Belogradchik it is the D=60 cm telescope, and at the Rozhen Observatory there are three instruments: the Schmidt – camera 50/70 cm, D=2 m, and D=60 cm telescopes. Since mid-2016 there is another ASV instrument (D=1.4 m telescope) via Belissima project[4] (see Figure 2). Using these 6 telescopes (Damljanović et al. 2014; Damljanović et al. 2018a; Damljanović et al. 2018b; Taris et al. 2018) we started astronomical observations in line with: the Gaia astrometry (QSOs useful for Gaia CRF and the link ICRF - Gaia CRF), Whole Earth Blazar Telescope - WEBT objects (mostly blazars), Gaia Alerts or Gaia-Follow-Up Network for Transients Objects (Gaia-FUN-TO), etc.

Our activities about the Gaia tasks are in line with the bilateral Serbian-Bulgarian joint research projects: “Observations of ICRF radio-sources visible in optical domain” during three-year period 2014-2016, “Study of ICRF radio-sources and fast variable astronomical objects” (2017-2019), and the actual one “Gaia Celestial Reference Frame (CRF) and fast variable astronomical objects” (2020-2022, the leader is G. Damljanović). These projects are within the framework between the Serbian Academy of Sciences and Arts – SASA (or SANU in Serbian language) and Bulgarian Academy of Sciences – BAS (or BAN in Bulgarian language).

The QSOs optical flux variations were investigated by using the original observations of QSOs (period 2013-2019), and it is in accordance with the future Gaia reference frame (Taris et al. 2018). That frame will be materialized by the optical positions of the objects, and it is going to link to the ICRF. The ICRF is based on the VLBI radio positions of mostly QSOs. Because of its, it is necessary to investigate flux variability of QSOs. The unstable flux of QSOs indicates changes in the source structure. It is of importance for the position of the target photocentre (also, the evolution in time of that center).

Flux variations of 47 objects, mostly QSOs (Bourda et al. 2008 and 2011) which are suitable for the mentioned link, are presented in (Taris et al. 2018) and are based on the data in line with the “Serbian-Bulgarian mini-network telescopes”.

About the Gaia Alerts, during six-year period (Oct. 2014 – Oct. 2020) we observed ~90 objects (or ~3300 CCD images) using mentioned 6 telescopes; it is ~15 objects per year (or ~550 images per year). There are a few published papers about Gaia Alerts (Campbell et al. 2015; Damljanović et al. 2014), and some results were presented at a few conferences. We are doing with the Johnson BV and Cousins RcIc filters, and the seeing is between 1."0 and 3."5 at the Serbian-Bulgarian sites: the mean value at ASV is 1."2, and it could be 0."7 at Rozhen and ASV. Using the 2 m Rozhen and 1.4 m ASV telescopes we could observe the objects until V=20 mag with Exp.~5 min (until 19 mag using smaller instruments).

[3] http://vidojevica.aob.rs
[4] http://belissima.aob.rs

In line with an indication that the bright DR2 reference frame (stars with G≤13 mag) rotates by about 0.1 mas/yr relative to the faint quasar frame, the amplitude A=0.5±0.1 mas/yr of the sinusoidal curve of pmDE differences INDLS-DR2 was calculated (Damljanović 2020) using the original INDLS catalog of 682 stars.

5. CONCLUSIONS

The Gaia DR2 sources have full astrometric data (proper motions and parallaxes, also), and the DR2 contains a vastly increased number of sources in comparison with DR1. The data of bright sources (G < 12 mag) were included already in DR1, but the results in DR2 are generally more accurate, and the results of DR2 are independent of the Hipparcos and Tycho catalogues. The Gaia CRF2, reference frame, is defined by Gaia data of QSOs. Also, the optical counterparts of VLBI objects in a solution of the ICRF3 were used.

Figure 2: The 1.4 m ASV telescope in its dome.

The astrometric results in Gaia DR2 are based on ~2 years of observations, and the random and systematic errors are still higher than it can be expected for the final solution. The calibrations are very preliminary. There are possibilities for improvements (Lindegren et al. 2018), and there are many investigations to be done for the next solution (DR3). Also, all objects beyond the solar system are treated as point sources in DR2 and this is necessary to improve in the reduction model, there are the unresolved binaries (the photocentre was calculated instead of each separate star of the system), the systematic errors are mainly based on the analysis of QSOs data, etc. There are a lot of parts for improving Gaia DR3.

In line with Gaia the cooperation "Serbian-Bulgarian mini-network telescopes" was established during 2013, SANU-BAN project was started at 2014. Then, the investigations in accordance with Gaia astrometry (Taris et al. 2018) and Gaia Alerts (Campbell et al. 2015; Damljanović et al. 2014) were done. The first SANU-BAS project was "Observations of ICRF radio-sources visible in optical domain" (2014-2016), the second one was "Study of ICRF radio-sources and fast variable astronomical objects" (2017-2019), and the actual one is "Gaia Celestial Reference Frame (CRF) and fast variable astronomical objects" (2020-2022). During six-year period ~90 Gaia Alerts (or ~3300 CCD images) were observed.

The amplitude A=0.5± 0.1 mas/yr of the sinusoidal curve of pmDE differences INDLS-DR2 was obtained using the original INDLS catalog of 682 stars; it is in line with an indication that the bright reference frame of DR2 (stars with $G \leq 13$ mag) rotates by about 0.1 mas/yr relative to the faint quasar frame (Damljanović 2020). We continue activities and investigation in line with that ESA mission.

Acknowledgements

I acknowledge the observing grant support from the Institute of Astronomy and Rozhen NAO BAS through the bilateral joint research project "Gaia Celestial Reference Frame (CRF) and fast variable astronomical objects" (2020-2022, leader is G. Damljanović), and support by the Ministry of Education, Science and Technological Development of the Republic of Serbia (contract No 451-03-68/2020-14/200002).

References

Bourda G., Charlot P., Le Campion J.: 2008, *Astronomy and Astrophysics,* 490, 403.

Bourda G., Collioud A., Charlot P., et al.: 2011, *Astronomy and Astrophysics,* 526, A102.

Campbell H.C., et al.: 2015, *MNRAS,* 452, 1960.

Damljanović G., Vince O., Boeva S.: 2014, *Serb. Astron. J.,* 188, 85-93.

Damljanović G., Taris F., Andrei A.: 2018a, *Astronomy and Astrophysics in the Gaia sky Proc., IAU Sym. No.,* 330 (2017), A. Recio-Blanco, P. de Laverny, A.G.A. Brown and T. Prusti, eds., 88-89.

Damljanović G., Latev G., Boeva S., Vince O., Bachev R., Jovanović M.D., Cvetković Z., Pavlović R.: 2018b, *Publ. Astron. Obs. Belgrade,* 98, 277-280.

Damljanović G.: 2020, *Astron. Nachr.,* 341, 770-780.
ESA: 1997, *The Hipparcos and Tycho Catalogues, ESA SP-1200.*
Lindegren L., Lammers U., Hobbs D., et al.: 2012, *Astronomy and Astrophysics,* 538, A78.
Lindegren L., Lammers U., Bastian U., et al.: 2016, *Astronomy and Astrophysics,* 595, A4.
Lindegren L., Hernandez J., Bombrun A., et al.: 2018, *Astronomy and Astrophysics,* 616, A2.
Prusti T.: 2012, *Astron. Nachr.,* 333, No. 5/6, 453–459.
Soffel M., Klioner S.A., Petit G., et al. : 2003, *AJ,* 126, 2687.
Taris F., Damljanovic G., Andrei A., Souchay J., Klotz A., Vachier F. : 2018, *Astronomy and Astrophysics,* 611, A52.
van Leeuwen F.: 2007, *Hipparcos, the New Reduction of the Raw Data, Astrophysics and Space Science Library, ed..,* 350.