

Gaia DR2 and Serbian-Bulgarian investigations

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Abstract. On April 25th 2018, the second release of the Gaia catalog (DR2) appeared. It is based on 640 days of Gaia satellite observations. The observing period was August 22nd 2014 - May 23rd 2016 (1.75 yr or 21 months with some interruptions). The reference epoch is J2015.5. The positions and proper motions refer to the ICRF. The DR2 is publicly available in the online Gaia Archive¹. After Hipparcos, it is the cornerstone mission of the European Space Agency (ESA). The next solution (DR3) is planned for the first half of 2021. The main results of DR2 with Serbian-Bulgarian investigations about it are presented.

Key words: Gaia DR2, Serbian-Bulgarian cooperation

Introduction

The first satellite mission of the European Space Agency (ESA) was the HIPPARCOS one (HIGH Precision PARallax COLlecting Satellite). That mission changed the astronomy at the end of the 20th century; about 118000 stars were observed (ESA, 1997). The reference frame in the optical domain was materialized via the Hipparcos positions of about 118000 stars at 1997 (and replaced the FK5 catalog). The Hipparcos was linked to the ICRF (International Celestial Reference Frame), and the ICRF is based on VLBI (Very Large Baseline Interferometry) observations in the radio domain of extragalactic objects. The new reduction of Hipparcos raw data was done by van Leeuwen (2007); mostly parallaxes are better than the Hipparcos Catalogue ones, but also positions and proper motions.

After Hipparcos, Gaia is the next cornerstone mission of the ESA. The spacecraft was launched in December 2013 (Gaia Collaboration, 2016). The nominal operations phase of the five-year was started in mid-2014. There is information that it could be longer than five-year period. The main goal is the determination of highly accurate positions (from milliarcsec to microarcsec astrometry), proper motions and parallaxes for about one billion sources brighter than $G = 20.7$ mag and for about 500000 quasars - QSOs (Prusti, 2012; Taris et al., 2018). The Gaia mission is surveying the full sky to collect three kinds of data: astrometry, photometry and spectroscopy ones. It is revolution in astronomy. There are two releases until now: Gaia DR1 (in September 2016) and Gaia DR2 (in April 2018). The Gaia DR1 is based on the first 14 months of Gaia observations (since July 2014), and DR2 on 22 months (Lindgren et al., 2018). The next one (Gaia DR3, as the final solution or Gaia catalog) is going to appear in the first half of 2021, and will be consisting of astrometric, photometric, and radial-velocity data, variable-star and non-single-star results, QSOs, galaxies, object classifications with multiple astrophysical parameters for stars, and unresolved binaries, exo-planets, epochs and transits for all objects.

¹ <https://archives.esac.esa.int/gaia>

The Gaia satellite rotates around itself with a 6^h period, and the period of the precession spin axis is 63 days. Its fields of view (FoV) are separated by a basic angle of 106°5. During the five-year observations, it has collected from 40 to 250 measurements per object. More about technical details can be found in Prusti, (2012).

On September 14th 2016, the first data of Gaia DR1 release appeared (Lindegren et al., 2016). That solution is Tycho-Gaia astrometric solution; it means that DR1 incorporated astrometric Hipparcos and Tycho-2 data for about two million stars. It was the first step of the future Gaia CRF (Celestial Reference Frame). Mignard et al. (2016) found that 2191 QSOs have good optical positions, and they match the ICRF2 radio-sources with high probability; it means, the optical and radio positions of mentioned QSOs are in good agreement.

On April 25th 2018, the second release of the Gaia catalog (DR2) appeared; it is based on 21 months of Gaia observations. The main catalog contains about 1.7 billion objects (G-mag from 3 to 21): the five astrometric parameters (positions, proper motions and parallaxes) for about 1.3 billion objects, and about 0.4 billion ones without all five parameters. The positions and proper motions refer to the ICRS, and the proper motions are based only on Gaia data (without Hipparcos and Tycho-2 data as it was the case for DR1). Also, in DR2 there are few other files: about RR Lyrae stars, Cepheid stars, etc.

A lot of open questions (about the Milky Way galaxy, stellar physics, the Solar system bodies, etc.) could be solved using Gaia data, and these data open many science areas to explore. Also, the synergy between ground-based and Gaia satellite astronomical observations is of importance. Our regional astronomical cooperation "Serbian-Bulgarian mini-network telescopes" (which was started in 2013) is in line with that.

1. Gaia DR2

The 2nd release of the Gaia catalog (Gaia DR2) is based on 640 days of Gaia satellite observations; it is 21 months or 1.75 yr. The period of Gaia operational phase is from 22nd August 2014 to 23rd May 2016 with some interruptions. The first month of Gaia observations was not good enough for DR2 solution. There are about 1.7 billion sources (for magnitude $3 < G < 21$) in the main file. All objects are reduced as single stars, as it was the case for DR1. About 1.3 billion ones are presented with all five parameters (positions in ICRS, proper motions in ICRS, and parallaxes); J2015.5 is the reference epoch, or JD2457206.375 TCB = 2nd July 2015 at 21 : 00 : 00 TCB. The TCB is barycentric coordinate time. The reference epoch of DR1 is J2015.0, and because of it there are positional differences DR1-DR2. Also, the proper motions of DR1 are based on combination Gaia-Hipparcos data, but DR2 is based only on Gaia data.

For about 0.4 billion sources of DR2 (mostly faint ones), the positions are approximate ones (Lindegren et al., 2018).

Using the online Gaia Archive², it is possible to get Gaia DR2 data. In

² <https://archives.esac.esa.int/gaia>

the case of unresolved binaries, some of them are done in line with a suitable photocentre. For resolved ones, some of them are done to each component. In Lindegren et al. (2012), it is possible to find the main steps (as models, algorithms, etc.) of astrometric solution. The principles of the photometric calibrations of the G-band are done in Carrasco et al. (2016).

Table 1. The median uncertainty

	Parallax, position(J2015.5) [mas]	Proper motions [mas/yr]
$G < 14$ mag	± 0.04	± 0.05
$G = 17$ mag	± 0.1	± 0.2
$G = 20$ mag	± 0.7	± 1.2

About the color information, mostly there are color data for presented sources (van Leeuwen et al., 2017). It was done via the photometric processing of data (using the blue BP and red RP photometers). Photometry of objects with unstable flux, time-series of Cepheids and RR Lyrae are presented in DR2, but not for QSOs.

The median uncertainty for parallaxes, positions (at the epoch J2015.5) and proper motions (via G-mag) is presented in Table 1; the best case is for $G < 14$ mag. The parallax systematics are ≤ 0.1 mas and in line with: positions, magnitudes, and color. The Gaia CRF (in the optical domain) is aligned with ICRS (radio domain); with respect to the QSOs, DR2 is non-rotating to within 0.15 mas/yr (Lindegren et al., 2018).

The primary coordinate system is the Barycentric Celestial Reference System (BCRS) with the origin at the solar system barycentre (the axes are aligned with the ICRS). The TCB is the time-like coordinate of the BCRS. Only the uniform space motion of the object (relative to the solar system) was considered (Lindegren et al., 2018), and non-linear motion is not included in DR2 even some well known cases (as binary stars, some perturbations, etc.). The prototype version of ICRF3 has got 2843 objects (mostly, QSOs) with optical counterparts of VLBI radio-sources. The prototype catalog ICRF3 contains 4262 accurate VLBI radio-positions of observed extragalactic sources.

The next Gaia DR3 solution is going to appear in the first half of 2021.

2. The Serbian-Bulgarian cooperation

After the installation of the 60 cm telescope at the Astronomical Station Vidojevica (ASV³ of Astronomical Observatory, Belgrade), we started astronomical observations and cooperation involving the Gaia and other projects. We started to use that instrument in 2011, and since mid-2016

³ <http://vidojevica.aob.rs>

there is a new 1.4 m ASV telescope (via Belissima project⁴). A new dome for 1.4 m ASV was finished on October 2018.

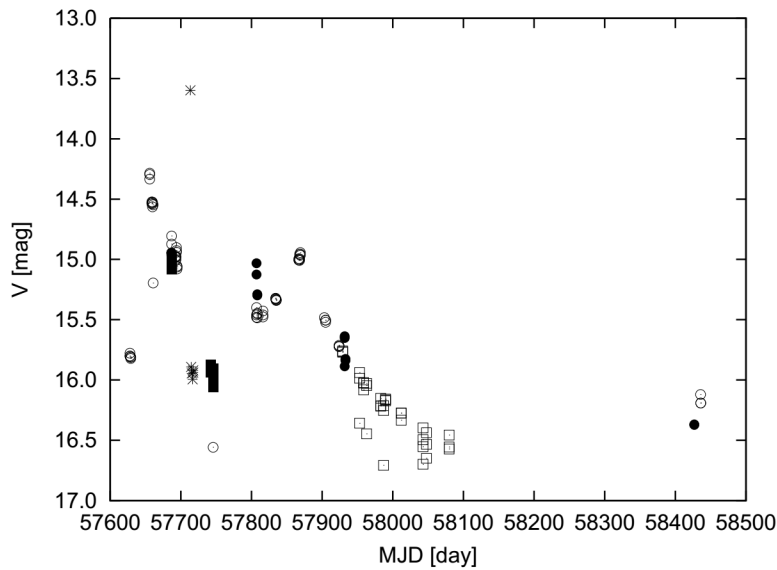


Fig. 1. The light curve of Gaia16aye in V-band using five telescopes: 1.31 m ARIES (*), 1.4 m ASV (open circle), 60 cm ASV (open rectangle), 2 m Rozhen (black circle), and 50/70 cm Schmidt-camera (black rectangle).

From Bulgarian side, there are two sites with four instruments of interest: Belogradchik and Rozhen. In Belogradchik there is a 60 cm instrument, and at the Rozhen Observatory there are three instruments: the Schmidt- 50/70 cm, a 60 cm telescope, and a 2 m one. More about these instruments can be found in paper Taris et al. (2018). To produce better observational data and results, we started the astronomical cooperation "Serbian-Bulgarian mini-network telescopes" in 2013, and continue with two SANU-BAN joint projects: "Observations of ICRF radio-sources visible in the optical domain" (2014-2016), and "Study of ICRF radio-sources and fast variable astronomical objects" (2017-2019). The Gaia astrometry and Gaia Alerts (or Gaia-FUN-TO) are the main tasks of our investigation and cooperation. During a four years period, from October 2014 until the end of 2019, about 75 Gaia Alerts objects were observed (about 15 objects per year). Some results were published (Damljanović et al., 2014; Taris et al., 2018) and presented at few conferences. We did our observations using the Johnson BV and Cousins R_c and I_c filters.

As an example, let us look at Gaia Alerts objects Gaia16aye, (Wyrzykowski et al., 2019). From mid-2016 until the end of 2018, during about 2.5 years

⁴ <http://belissima.aob.rs>

long interval, we observed that object using: Serbian 60 cm (109 epochs, points) and 1.4 m (261 points) ASV instruments, Bulgarian 2 m Rozhen (63 points) and 50/70 cm Schmidt- (48 points), and 1.31 m ARIES telescope (23 points) in India. All in all, we collected 504 points. In Fig. 1, only points of V-band are presented, but with an important peak near MJD 57713.5671 (21st/22nd November 2016); $V = 13.598 \pm 0.001$ mag was calculated using 1.31 m ARIES telescope. The ARIES means Aryabhata Research Institute of observational sciencES, and it is at Manora Peak (Nainital, central Himalayan region) with: longitude $\lambda = 79^{\circ}.6E$, latitude $\varphi = 29^{\circ}.35N$, and altitude $h = 2420$ m. The 1.31 m telescope is R.C. Cassegrain instrument with: 2048X2048 pixels of CCD cheap, pixel size is 13.5X13.5 mkm, scale is 0.541 arcsec per pixel, and $FoV = 18.5X18.5$ arcmin. We used that telescope (via our colleagues A. Gupta and A. Pandey, India) in the period 21st-25th November 2016, because of bad weather in Europe and not good visibility of that object, but extremely important period for the light curve of Gaia16aye (near the peak of the light curve); see Table 2 and Fig. 1. In our team there were 7 members: S. Boeva and G. Latev from Bulgaria, G. Damljanović, O. Vince and M.D. Jovanović from Serbia, A. Gupta and A. Pandey from India. The Astronomical Observatory in Belgrade (AOB) was the center for: collecting mentioned data, calibration and other necessary treatment of data, and finally sending to CPCS - Cambridge Photometric Calibration Server.

The Gaia16aye ($\alpha = 295^{\circ}.00474$, $\delta = 30^{\circ}.13149$, nicknamed Ayers Rock) is a binary microlensing rare event, and the second Gaia microlensing event. During observation, some object (which could be a star, a planet, or a black hole) is lying between a distant source (a star from our Galaxy or an extragalactic object) and the observer, and this causes a microlensing event. The light rays from a distant source are bent by the space-time curvature of an object. That hitherto unseen object is called the lens, and moving faster across the sky it leads to an increase (after increase, to decrease) in the brightness of the background object. Gaia16aye was found towards the Galactic spiral arms, and it is a little unusual. The central region of the Milky Way (the Bulge) is usual part for the lens.

The light curve shows characteristic U-shaped changes; sudden sharp increases and decreases in brightness, and it is the case when the lens is not a single object, but rather a pair. So, the lens could be a binary star system. This makes caustics, and they lead to sudden jumps in flux during the time the lens is crossing the light rays of the source (Damljanović et al., 2018).

In case of Gaia16aye, the great importance of ground-based follow-up of Gaia Alerts becomes apparent (and Serbian-Bulgarian mini-network telescopes). Without an extra follow-up, it is not possible to confirm Gaia16aye as a microlensing event, the binary nature of the lens, the system components, etc. More information about the Gaia16aye can be found in the paper by Wyrzykowski et al. (2019).

Table 2. The Gaia16aye results (via APASS catalog) using 1.31 m ARIES telescope during 21st-25th November 2016

MJD	day	Filter	Magnitude	mag
57714.5766	V		15.892	±0.010
57716.5421	V		15.944	±0.020
57717.5341	V		15.938	±0.020
57713.5671	V		13.598	±0.001
57715.5761	V		15.945	±0.010
57717.5311	V		15.921	±0.030
57714.5785	r		15.078	±0.010
57717.5325	r		15.106	±0.010
57715.5715	r		15.135	±0.001
57713.5675	r		12.797	±0.001
57716.5445	r		15.096	±0.010
57717.5315	r		15.118	±0.010
57717.5320	i		14.279	±0.010
57714.5800	i		14.329	±0.010
57716.5460	i		14.277	±0.001
57717.5310	i		14.285	±0.010
57715.5780	i		14.313	±0.001
57717.5348	B		17.318	±0.090
57713.5608	B		15.116	±0.001
57715.5735	B		17.323	±0.030
57717.5281	B		17.514	±0.110
57714.5780	B		17.433	±0.040
57716.5432	B		17.669	±0.100

Conclusion

The Gaia DR2 solution of 21 months Gaia satellite observations appeared in April 2018. There are about 1.7 billion objects, but 1.3 billion ones with all five parameters: positions, proper motions and parallaxes; the epoch is J2015.5. Results of DR2 are more accurate than DR1 ones, and independent of the Hipparcos data. The Gaia-CRF2 is the celestial reference frame of Gaia DR2 data, and it is aligned with ICRS. It is non-rotating frame with respect to the extragalactic objects (mostly, QSOs).

In accordance with Gaia, we started the cooperation "Serbian-Bulgarian mini-network telescopes" in 2013, and worked on Gaia astrometry, Gaia Alerts (or Gaia-FUN-TO), etc. Some results were published in Taris et al. (2018); Campbell et al. (2015); Damljanović et al. (2014), and presented at few conferences. Until now, there were two SANU-BAS projects: "Observations of ICRF radio-sources visible in optical domain" (2014-2016), and "Study of ICRF radio-sources and fast variable astronomical objects" (2017-2019). We did observations of about 15 Gaia Alerts objects per year (about 75 objects from October 2014). The paper on Gaia16aye describes our main efforts about that object (Wyrzykowski et al., 2019). We observed Gaia16aye for about 2.5 years, from mid-2016 until the end of 2018, using: Serbian 60 cm and 1.4 m ASV instruments, Bulgarian 2 m Rozhen and 50/70 cm Schmidt-camera, and 1.31 m ARIES telescope in India.

The Gaia five-year period of observations is going to prolong, and we continue our activities in accordance with that international ESA project.

The next solution, Gaia DR3, is planned for 2021. Random and systematic errors could be improved in DR3. The systematic part is based on the results about QSOs data. Together with improved astrometry and photometry, that solution will be consisting of: mean V_r values of stars, object classification and astrophysical parameters (spectra or spectroscopically sources), some Solar-system results (individual epoch observations, orbital solutions for some objects, etc.), non-single star catalogues, etc. It is necessary to improve the reduction model.

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⁵ <http://gsaweb.ast.cam.ac.uk/alerts>