Article

Verification of photometric parallaxes with Gaia DR2 data

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Abstract: Results of comparison of *Gaia* DR2 parallaxes with data derived from a combined analysis of 2MASS (Two Micron All-Sky Survey), SDSS (Sloan Digital Sky Survey), GALEX (Galaxy Evolution Explorer), and UKIDSS (UKIRT Infrared Deep Sky Survey) surveys in four selected high-latitude $|b| > 48^o$ sky areas are presented. It is shown that multicolor photometric data from large modern surveys can be used for parameterization of stars closer than 4400 pc and brighter than $g_{SDSS} > 19.^m6$, including estimation of parallax and interstellar extinction value. However, the stellar luminosity class should be properly determined.

Keywords: parallax; photometry; interstellar extinction; surveys; Gaia

1. Introduction

One of the main problems of astrophysics is the study of the physical properties belonging to the surface layers of stars. Because these stars are observed through interstellar dust, their light is dimmed and reddened, complicating their parameterization and classification. The parameters of a given star (temperature, gravity, metallicity, etc.), as well as the interstellar reddening, may be obtained from its optical, infrared and ultraviolet spectrum. However, one must either use large telescope or bright objects in order to get spectral energy distributions with good resolution and sufficient accuracy. For instance, spectroscopic observations with 1-hour exposure time on a 2-m telescope with low ($R \sim 1000$) and high ($R \sim 100\,000$) resolution allow limiting magnitudes of 16 – 17 mag and 11 – 12 mag, respectively. An 8-m telescope adds 3 mag to these estimations. This work was performed by various authors, and a number of empirical atlases were constructed (Straizys and Sviderskiene [1], Glushneva *et al.* [2], Alekseeva *et al.* [3], Alekseeva *et al.* [4], Pickles [5], Bagnulo *et al.* [6], Le Borgne *et al.* [7], Valdes *et al.* [8], Heap and Lindler [9], Falcón-Barroso *et al.* [10], Wu *et al.* [11]). However

Mironov *et al.* [12] made a critical analysis, compared data for stars included in several atlases, and found a large number of discrepancies.

Another way to construct a map of interstellar extinction is its estimation (as well as stellar parameters) from evolutionary tracks. Corresponding procedures were developed in Sichevsky and Malkov [13], Sichevskij [14], Sichevskij [15] and applied to LAMOST data by Sichevskij [16]. However, a knowledge of stellar atmospheric parameters is highly desirable for the application of these procedures, limiting the number of stars available for such a parameterization.

Therefore, the solution of the problem of parameterization of stars based on their photometry is a topical issue [17]. A great variety of photometric systems (see, e.g., Straižys [18] for references) and recently constructed large photometric surveys (like SDSS [19] and GALEX [20]) as well as VO-tools for cross-matching surveys' objects provide with a possibility to get multicolor photometric data for millions of objects. Consequently, it allows the user to parameterize objects and determine interstellar extinction in the Galaxy.

A comparative analysis of available 3D maps of interstellar extinction was made by Kilpio and Malkov [21], and contradictory results were found. As a temporary solution of that problem, a synthetic map of the galactic interstellar extinction can be compiled (see, e.g., [22], [23], [24]).

Early dust maps used the correlation between the dust column density and the distribution of neutral hydrogen [25]. These data were supplanted by the dust maps produced by Schlegel *et al.* [26], who used full sky microwave data made available by the IRAS (Infrared Astronomical Satellite) mission and the DIRBE (Diffuse Infrared Background Experiment) instrument on the COBE (Cosmic Background Explorer) mission. Mapping the dust column densities via the calibrated dust temperature, the extinction maps, assuming a standard reddening law, were shown to be at least twice as accurate as those of Burstein and Heiles [25]. An advantage of this method is that it does not rely on a predefined model for the stellar population.

The successful implementation of the European astrometric space mission *Gaia* (the second version of the mission catalog, *Gaia* DR2, was published in April 2018 [27]) allows the solving of a number of stellar astronomy problems, like determination of stellar mass, age estimation and others. In particular, it became possible to improve the results of the parameterization of stars, carried out from multicolor photometry.

In this paper, the verification of the method and stellar sample analysed in Paper18 using *Gaia* DR2 data is described. We also discuss how including the *Gaia* parallaxes into the procedure would improve the accuracy of parameterization, and how to select/process objects with unknown *Gaia* parallax for parameterization.

This paper is organized as follows. Data and methods are described in Section 2, Section 3 contains results and conclusions.

2. Data and method

In Malkov *et al.* [28] (hereinafter — Paper18) objects in four selected areas in the sky were cross-matched (see details of the procedure in [29], [30], [31]) with 2MASS (Two Micron All-Sky Survey) [32], SDSS (Sloan Digital Sky Survey) [19], GALEX (Galaxy Evolution Explorer) [20], and UKIDSS (UKIRT Infrared Deep Sky Survey) [33] surveys, and multi wavelength photometric data were used to determine the parameters of stars. The galactic coordinates of the areas are (334, +61.9), (257, +48.7), (301, +62.1), and (129, −58.1). For the studied objects MK (Morgan-Keenan) spectral types (SpT), distances (d) and interstellar extinction values (A_V) were estimated, minimizing the function

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{m_{obs,i} - m_{calc,i}}{\sigma m_{obs,i}} \right)^2 , \qquad (1)$$

where $m_{obs,i}$ and $\sigma m_{obs,i}$ are the apparent magnitude and its observational error, respectively, in the i-th photometric band from a given survey, and the summation is over up to N=14 photometric bands (JHK_S from 2MASS, ugriz from SDSS, FUV and NUV from GALEX, YJHK from UKIDSS), and

$$m_{calc,i} = M_i + 5\log d - 5 + A_i, \tag{2}$$

or

$$m_{calc,i} = M_i - 5\log \varpi - 5 + A_i. \tag{3}$$

Here $A_i = f(A_V)$ is the extinction in the i-th photometric band, and can be determined from the interstellar extinction law. To retrieve A_i from A_V we have used data from Yuan *et al.* [34] for 2MASS [32], SDSS [19] and GALEX [20], whereas data for UKIDSS [33] and Johnson V-band were adopted from Schlafly and Finkbeiner [35]. Both teams made A_i calculations for SDSS photometry, and our comparison shows a very good agreement between their results (see Paper18 for details).

$M_i = f(\mathrm{SpT})$ is the absolute magnitude in i-th photometric band taken from calibration tables. To obtain absolute magnitudes for stars of different spectral types in the corresponding photometric systems M_i, we have compiled a table of absolute magnitudes in 2MASS, SDSS and GALEX surveys using Kraus and Hillenbrand [36], and Findeisen *et al.* [37] data. Due to lack of published data, UKIDSS absolute magnitudes were calculated from 2MASS magnitudes and 2MASS-UKIRT relations from Hodgkin *et al.* [38].

The distance d and parallax ϖ are expressed in parsec and arcsec, respectively. It should be noted that Eq. 3 is not correct when using observational data. The mean value of the parallax is not enough and their errors should be considered to derive a good value for the distance to be substituted in Eq. 2 to derive Eq. 3 (see Bailer-Jones *et al.* [39]).

Altogether 251 objects were found in at least three of the four surveys and cross-matched in the four areas, but only 26 of them were successfully parameterized. The following reasons to remove objects from further consideration were considered.

First, the original surveys contain various flags which allow us to remove unsuitable objects, namely, "Binary object" (2MASS, UKIDSS), "Non-stellar/extended object" (2MASS, SDSS, GALEX, UKIDSS), "Observation of low quality" (SDSS). Secondly, overly bright objects and objects with large observational errors were not considered.

Also, only areas located at relatively high galactic latitudes ($|b| > 48^o$) are considered in this work. Consequently, A_V is assumed to be smaller than 0.5 mag, and distance d is assumed to be closer than 8000 pc. Objects which presented larger values for those parameters were removed from further consideration.

Finally, for every object a rough parameterization was performed (based on 2MASS+SDSS photometry only) with Covey *et al.* [40] absolute magnitude tables. An object was removed if this procedure showed that there was a high probability for it to be a non-MS star (giant or supergiant). It should be reminded that in the current study only MS (Main Sequence) stars are considered.

A comparison of our results for 26 selected stars with independent results obtained from the LAMOST (Large Sky Area Multi-Object Fibre Spectroscopic Telescope) [41] for some of the studied stars has demonstrated a good agreement. Interstellar extinction as a function of distance ($A_V(d)$) was constructed for the four selected areas (see Figs. 1 – 4 in Paper18). These relations were extrapolated to infinity ($d \to \infty$). Note that the extrapolation is formal, and can introduce some uncertainty. For the resulting $A_V(\infty)$ values in three of the four areas (Nos 1, 5, and 6 in Paper18), a good agreement was found with the data used in the study of supernovae [42] to confirm the accelerated expansion of the Universe. For the remaining area, No 2, an agreement was not achieved (see Table 2 in Paper18).

To identify the conditions under which stars are properly parameterized from multicolor photometry, we relied upon the results obtained in our pilot study of interstellar extinction in four areas (see Paper18), and *Gaia* data. A cross-matching of Paper18 objects with *Gaia* DR2 catalogue was made. Among 251 objects, studied in Paper18, only 72 were found in *Gaia* DR2 (such a very small fraction is understandable, as about 80% of the Paper18 objects are fainter than $19.^m5$ g_{SDSS}), and seven of them have no *Gaia* parallaxes. Among 26 objects, selected in Paper18 for construction of $A_V(d)$ relation, one is absent in *Gaia* DR2, and two more objects have no parallaxes.

The *Gaia* trigonometric parallaxes (hereafter ϖ_{tr}) are compared with photometric parallaxes obtained in Paper18 (hereafter ϖ_{ph}). When analyzing *Gaia* data, the recommendations published in [43] were considered. In particular, the filters, designed on the basis of the photometric and astrometric flags contained in *Gaia* DR2, were taken into account. They were used to construct a so-called astrometrically clean sample, hereafter ACS.

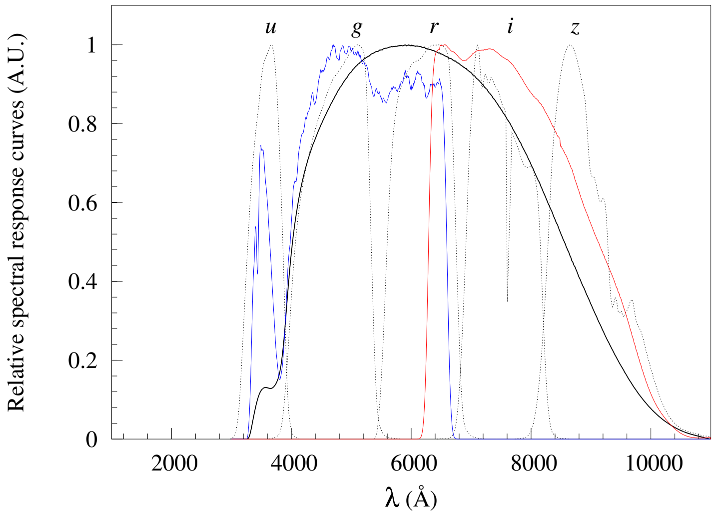

Figure 1. SDSS ugriz (gray dashed curves) and *Gaia* G (black solid curve), G_{BP} (blue solid curve), and G_{RP} (red solid curve) photometric passbands.

Photometric passbands used in SDSS [44] and *Gaia* DR2 [45] are presented in Fig. 1. In this work, we deal with g_{SDSS} and *Gaia* G, BP and RP magnitudes of the studied stars.

121 ## 3. Results and conclusions

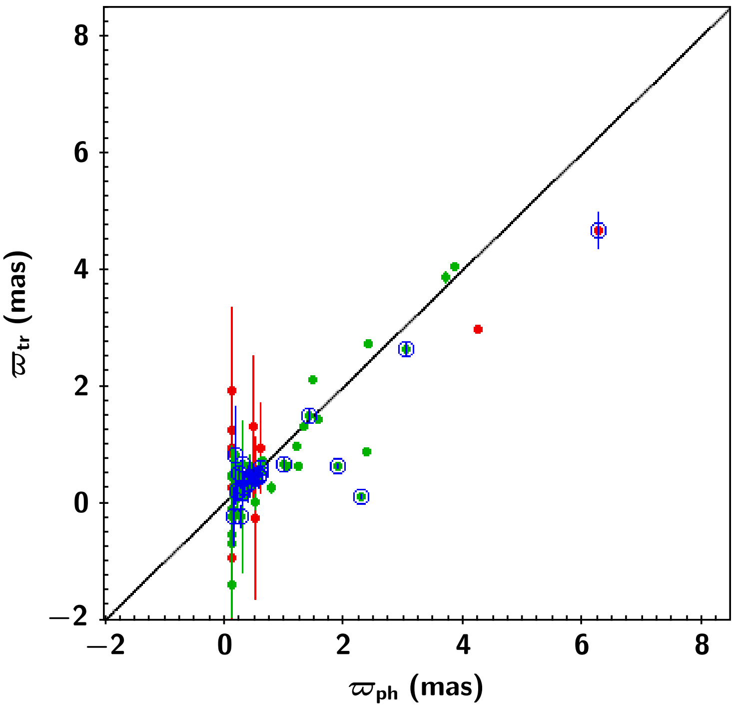

Figure 2. Photometric parallax (ϖ_{ph}) from Paper18 and trigonometric parallax (ϖ_{tr}) from *Gaia* for all stars in common to Paper18 and *Gaia* DR2 that satisfy (green points) and do not satisfy (red points) the ACS requirements. Blue circles are the stars used in Paper18 for the $A_V(d)$ construction. "$\varpi_{tr} = \varpi_{ph}$" is indicated as a black line.

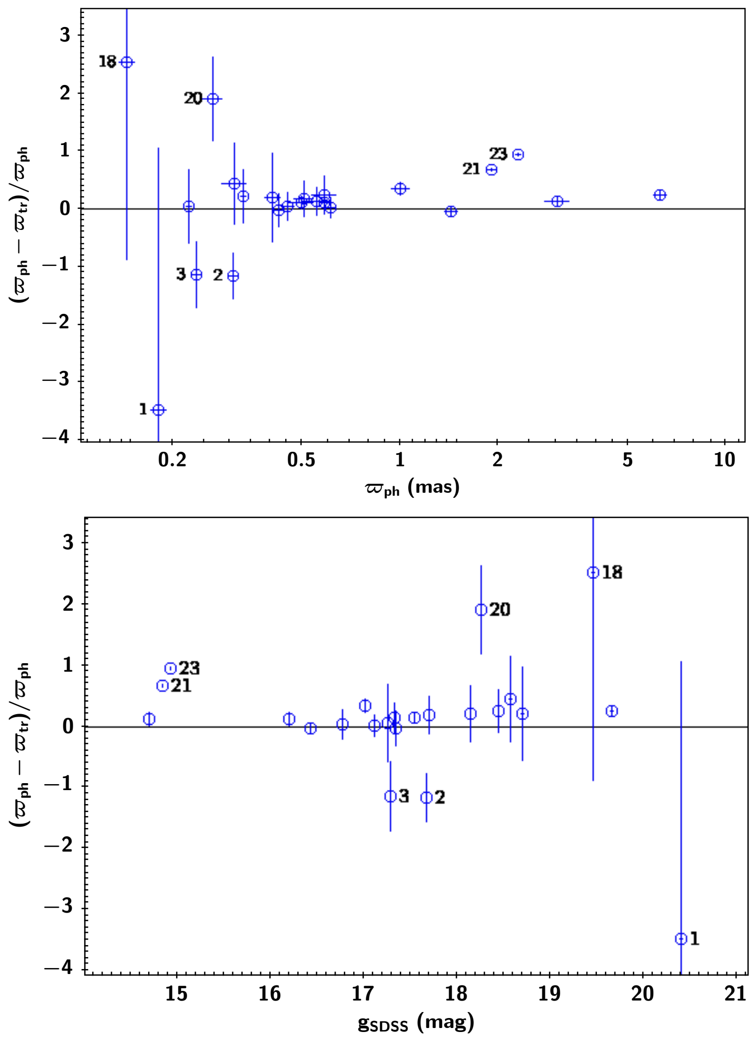

Figure 3. The ratio between the difference in parallax $\varpi_{ph} - \varpi_{tr}$ and the photometric parallax ϖ_{ph} vs. ϖ_{ph} (upper panel) and vs. g_{SDSS} (lower panel) for the stars used in Paper18 for the $A_V(d)$ construction. Labels correspond to running numbers of stars in Table 1

A comparison of the photometric and trigonometric parallaxes of stars used in Paper18 for the $A_V(d)$ construction is shown in Fig 2. The ratio between the difference in parallax $\varpi_{ph} - \varpi_{tr}$ and the photometric parallax ϖ_{ph} as a function of ϖ_{ph} and g_{SDSS} is shown in Fig. 3. In the current study observational photometric errors are considered to be the only source for the resulting parameters errors. Consequently, here we underestimate the error values. To calculate errors more correctly, one should take into account also calibration tables errors and relations errors.

The majority of stars demonstrate a satisfactory agreement but with some outliers which require an explanation. The Hertzsprung-Russell diagram (HRD) was constructed for *Gaia* DR2 stars with trigonometric parallax $\varpi_{tr} > 10$ mas, with relative parallax uncertainty $\sigma\varpi_{tr}/\varpi_{tr} < 10\%$, with relative error of BP and RP fluxes better than 10%, and satisfying the ACS requirements (Fig. 4). The studied stars were added to the plot, and their positions on HRD were analysed. Data for the studied stars are presented in Table 1.

Stars 21 and 23 belong to red giants. Obviously they were wrongly accepted as Main-Sequence stars in Paper18, which resulted in erroneous ϖ_{ph} values.

According to Fig. 4, stars 1, 2 and 3 are sub-dwarfs, and, if that is true, they have erroneous ϖ_{ph} for the same reason as above. However, we pay attention to their relatively large trigonometric parallax errors (see $\sigma\varpi_{tr}$ values in Table 1), which could lead to their shift under the Main Sequence in HRD.

Lastly, stars 18 and 20 have negative parallaxes and for that reason their absolute magnitudes can not be calculated and, consequently, they are not shown in Fig. 4. Apparently the negative parallaxes indicate that these stars belong to supergiants. Again, they were wrongly accepted to be Main-Sequence stars in Paper18, which resulted in erroneous ϖ_{ph} values.

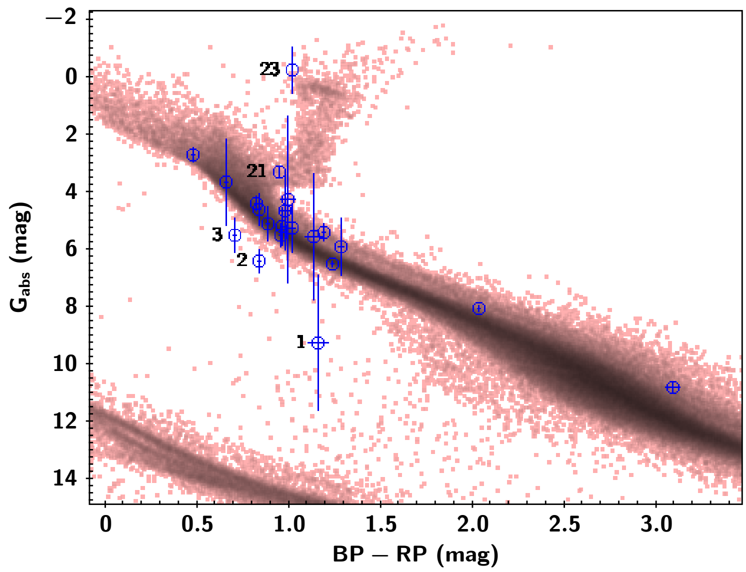

Figure 4. Stars used in Paper18 for the $A_V(d)$ construction (blue circles) on the HRD. Labels correspond to running numbers of stars in Table 1. Pink points are nearest ($\varpi_{tr} > 10$ mas) stars from *Gaia* DR2. Absolute magnitude G_{abs} is calculated from G_{Gaia} and ϖ_{tr}, interstellar extinction is neglected. *Gaia* G, BP and RP curves are presented in Fig. 1.

The results of the comparison allow us to make the following conclusions.

1. A parameterization of stars with $\varpi_{ph} < 0.225$ mas (i.e., closer than about 4400 pc) and $g_{SDSS} > 19.^{m}6$ (see Fig. 3) is successful, subject to a proper determination of luminosity class.
2. A rough estimate of the probability of stars belonging to the Main Sequence was carried out in Paper18 (basing on 2MASS and SDSS photometry data), and only MS-stars were parameterized. Obviously, for several stars that estimation turned out to be erroneous (see Fig. 4). It seems appropriate to include in the parameterization procedure information about the photometry of non-MS stars (sub-dwarfs, giants and supergiants), drawn from the literature or determined by our own efforts.

Table 1. Stars used in Paper18 for the $A_V(d)$ construction. Upper part: running number, SDSS and *Gaia* identifiers, RA and DEC (2000) coordinates. Lower part: running number, SDSS (g) and *Gaia* (G) photometry with errors, photometric and trigonometric parallax with errors, spectral type estimated in Paper18 and corresponding M_{bol}.

N	SDSS	*Gaia* DR2	RA2000(deg)	DEC2000(deg)
1	752-301-2-0325-0286	3683644191076349312	192.1701	-0.8165
2	6005-301-2-0158-0092	3689648868888993920	192.2168	-0.7911
3	6005-301-2-0158-0061	3683643881838700800	192.1728	-0.8335
4	1241-301-1-0173-0042	3801228953847961600	164.2724	-3.5562
5	752-301-2-0324-0052	3683656594941905920	192.0763	-0.7852
6	1462-301-4-0543-0082	3665039324758041600	206.7882	2.4288
7	6121-301-2-0157-0087	3683657110337986048	192.1002	-0.7568
8	6121-301-2-0157-0037	3683644569033472512	192.1050	-0.8108
9	1462-301-4-0543-0066	3665227032008658560	206.7471	2.4403
10	2194-301-1-0361-0007	3801228683265104640	164.1956	-3.5772
11	1241-301-1-0173-0102	3801228610250558848	164.2084	-3.5842
12	7727-301-3-0174-0108	2552008097711479808	16.2328	4.5274
13	2194-301-1-0361-0119	3801227819976566272	164.2968	-3.5978
14	752-301-2-0325-0136	3689650277638267392	192.1738	-0.7430
15	1462-301-4-0543-0182	3665226581036533504	206.7508	2.4200
16	756-301-1-0510-0121	3683643679975511808	192.1394	-0.8415
17	7727-301-3-0174-0122	2552021880262020608	16.2512	4.6030
18	1462-301-4-0544-0120	3665040626132812800	206.8532	2.4438
19	7727-301-3-0175-0149	2552009442036732416	16.2885	4.5344
20	752-301-2-0324-0183	3689662230532099200	192.0995	-0.7200
21	1462-301-4-0543-0079	3665039290398303104	206.7741	2.4244
22	2194-301-1-0361-0077	3801228644610295680	164.1954	-3.5860
23	1462-301-4-0543-0060	3665226615396253824	206.7224	2.4265

N	g	σ_g	G	σ_G	ϖ_{ph}	$\sigma\varpi_{ph}$	ϖ_{tr}	$\sigma\varpi_{tr}$	Sp	M_{bol}
1	20.384	0.021	19.718	4.3E-3	0.1811	0.0097	0.8123	0.821	G8	5.3
2	17.674	0.005	17.260	8.4E-4	0.3086	0.0115	0.667	0.1211	G0	4.47
3	17.269	0.005	16.974	8.7E-4	0.2375	0.0067	0.5096	0.1363	F5	3.61
4	16.408	0.003	15.646	1.4E-3	1.4285	0.0592	1.4892	0.0784	K2	6.08
5	17.335	0.005	16.882	7.4E-4	0.4255	0.0168	0.4383	0.1179	G5	4.89
6	17.076	0.005	16.597	1.2E-3	0.6116	0.0219	0.6022	0.1014	G8	5.3
7	17.251	0.005	16.998	7.8E-4	0.2252	0.0047	0.2149	0.1413	F5	3.61
8	16.788	0.004	16.387	6.3E-4	0.4524	0.0191	0.4361	0.1048	G0	4.47
9	14.645	0.003	14.512	6.5E-4	0.4975	0.0421	0.439	0.0439	F2	2.89
10	16.200	0.003	15.816	7.9E-4	0.5882	0.0159	0.5176	0.0594	G0	4.47
11	18.110	0.006	17.596	1.9E-3	0.3300	0.0066	0.2585	0.1536	G5	4.89
12	17.327	0.005	16.824	1.0E-3	0.5571	0.0541	0.4783	0.1317	G8	5.3
13	18.699	0.009	18.025	3.2E-3	0.4048	0.0206	0.3235	0.3079	K0	5.69
14	17.689	0.005	17.169	8.9E-4	0.5102	0.0343	0.4149	0.153	G8	5.3
15	18.616	0.008	18.106	2.0E-3	0.3095	0.0258	0.1714	0.217	G8	5.3
16	18.440	0.007	17.658	1.2E-3	0.5865	0.0510	0.4417	0.1949	K2	6.08
17	17.004	0.004	16.281	9.1E-4	1.0050	0.0601	0.6621	0.0933	K2	6.08
18	19.437	0.012	19.017	4.1E-3	0.1455	0.0075	-0.2226	0.4955	G0	4.47
19	17.547	0.005	15.965	9.4E-4	3.0303	0.2470	2.6283	0.102	M0	7.6
20	18.248	0.006	17.784	1.2E-3	0.2673	0.0174	-0.2431	0.1933	G0	4.47
21	14.820	0.003	14.332	4.9E-4	1.9047	0.0447	0.626	0.0398	G8	5.3
22	19.643	0.015	17.431	7.7E-3	6.25	0.2734	4.6726	0.2955	M4	9.92
23	14.901	0.003	14.361	3.7E-4	2.2988	0.0497	0.1203	0.0418	K2	6.08

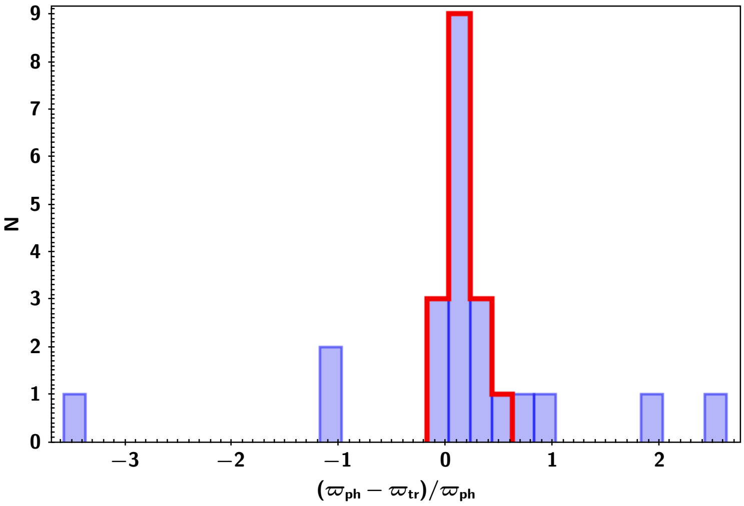

Figure 5. Distribution of stars used in Paper18 for the $A_V(d)$ construction by the ratio between the difference in parallax $\varpi_{ph} - \varpi_{tr}$ and the photometric parallax ϖ_{ph}. Subsample, designated by the red contour, does not include stars 21, 23 (red giants), 1, 2, 2 (possible sub-dwarfs) and 18, 20 (apparently supergiants), discussed in the text.

The distribution of stars used in Paper18 for the $A_V(d)$ construction by the ratio between the difference in parallax $\varpi_{ph} - \varpi_{tr}$ and the photometric parallax ϖ_{ph} is presented in Fig. 5. Seven outliers demonstrate $|(\varpi_{ph} - \varpi_{tr})/\varpi_{ph}| > 0.6$, they were discussed above (stars 1, 2, 3, 18, 20, 21, 23).

The remaining stars distribution is shown with the red contour. For them mean value of $(\varpi_{ph} - \varpi_{tr})/\varpi_{ph}$ is 0.15 with standard deviation of 0.13. Mean ϖ_{ph} and ϖ_{tr} values for the red contour group are 0.997 and 0.89, respectively.

It should be noted that area No 2, which showed a poor agreement with the Perlmutter et al.'s [42] data in Paper18, does not stand out in the current analysis.

It should be also noted that the cross-matching of Paper18 objects with *Gaia* DR2 catalogue was made correctly. Angular distance on the sky between a Paper18 object and its *Gaia* DR2 counterpart (ρ) does not exceed 1 arcsec, and only for 2 of 72 objects $\rho > 0.3$ arcsec (those two stars were not selected in Paper18 for construction of $A_V(d)$ relation, and consequently, are not shown in Figs. 3 – 5).

Based on the conclusions derived above, our procedure of parameterization of stars will be modified. In particular, the procedure will be extended to sub-dwarf, giant and supergiant stars. Also, at this stage, distant ($\varpi_{ph} < 0.225$ mas) and faint ($g_{SDSS} > 19.^{m}6$) objects will be removed from consideration. We will also reconstruct the procedure to use *Gaia DR2* parallaxes (and future releases, when available), as an input parameter. It is also planed to use data from other multicolor surveys, like WISE (Wide-Field Infrared Survey Explorer), DENIS (Deep Near Infrared Survey of the Southern Sky), etc, and extend this procedure to lower galactic latitudes.

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Author Contributions: The authors made equal contribution to this work; O.M. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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