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Radial Velocity Comparison of *Gaia* DR2 and RAVE DR5 Survey: A Systematic Offset in Radial Velocities among a Group of Highly Accurate Radial Velocity Stars

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Abstract

Here, we report a comparative study of radial velocity (RV) data of two major surveys: *Gaia* Data Release 2 and RAVE Data Release 5. We restricted the sample to stars with relatively accurate RVs ($\sigma_{\mathrm{RV}_{Gaia}} \leqslant 2$ km s^{-1} or $\leqslant$2%, and $\sigma_{\mathrm{RV}_{\mathrm{RAVE}}} \leqslant 2\,\mathrm{km\,s^{-1}}$ or $\leqslant$2%). The difference between RV_{Gaia} and $\mathrm{RV}_{\mathrm{RAVE}}$ for a majority of the sample follows a normal distribution with mean $= 0.28\,\mathrm{km\,s^{-1}}$ and $\sigma = 1.49\,\mathrm{km\,s^{-1}}$. However, we found a very small group of stars ($\approx$0.08% of the total) for which the difference in RVs between the two surveys is significantly larger with an offset of $-104.50\,\mathrm{km\,s^{-1}}$ with $\sigma = 4.92\,\mathrm{km\,s^{-1}}$. Kinematics based on RV_{Gaia} suggest that most of the group members belong to the Galactic thin disk, which agrees with the group's metallicity range of -1.2 to $+0.5$ dex suggesting the offset in RV is probably due to RAVE velocity data for this particular group.

Key words: catalogs – Galaxy: kinematics and dynamics – stars: abundances – stars: kinematics and dynamics – surveys – techniques: radial velocities

1. Introduction

Gaia, an European space telescope mission meant for recording accurate astrometry of more than a billion stars in the Galaxy, began its scientific observations in 2014 July (Gaia Collaboration et al. 2016). Since then, *Gaia* has been scanning the whole sky and observing all the stars within magnitude limits of $2.0 \lesssim G \lesssim 20.7$. The recently released *Gaia* data DR2 (hereafter *Gaia* DR2) provides median radial velocity (RV; over 22 months) of about 7.2 million stars (Gaia Collaboration et al. 2018). The RVs are determined with the Radial Velocity Spectrometer (8450–8720 Å) having spectral resolution of $R \sim 11700$ (RVS; Cropper et al. 2018; Katz et al. 2018). The typical uncertainty in RVs are within $2\,\mathrm{km\,s^{-1}}$. On the other hand, Radial Velocity Experiment (RAVE; 2003–2013), is a ground-based magnitude-limited survey of stars. The selection criteria and the magnitude distribution have been discussed in Steinmetz et al. (2006) and in Lindegren & Dravins (2014), respectively. A spectral region (8410–8750 Å) with effective spectral resolution, $R = \lambda/\Delta\lambda \sim 7500$ was selected to cover the $\mathrm{Ca_{II}}$ triplet, which is similar to *Gaia*'s RVS (Steinmetz et al. 2006). The fifth data release of the RAVE survey (hereafter RAVE DR5) includes RVs of 457,588 unique stars from 520,781 spectra, which have a typical accuracy better than $2\,\mathrm{km\,s^{-1}}$ (Kunder et al. 2017).

RV is a key parameter along with accurate astrometry for computing stars kinematics. While selecting a sample of stars from the publication of *Gaia* DR2 and RAVE DR5, we noticed an offset of about $-104\,\mathrm{km\,s^{-1}}$ in RVs between the two surveys for a tiny group of stars ($\approx$0.08% of the total stars), although the remaining RVs from the two surveys turns out to be in good agreement. Our motive for this article is to highlight the existence of this tiny faulty group and its consequences. We have not attempted to provide solutions for the discrepancy or corrections, rather we looked at different possibilities that might have caused the offset in RVs between the two surveys.

2. Data Sample

For this study, we adopted RV data directly from a catalog of stars which resulted from cross matching of RAVE DR5 and *Gaia* DR2 (rave_DR2_gaia_source.csv available at *Rave survey website* (https://www.rave-survey.org/project/) and added RAVE DR5 table to this using RAVE_OBS_ID (Unique Identifier for RAVE objects, Observation Date, Fieldname, Fibernumber). We took only those stars that are common in the two surveys and for which both the radial velocities ($\mathrm{RV_{RAVE}}$ and RV_{Gaia}) are available. This resulted in 456,316 stars out of the total number of 512,971 stars.

3. Analysis

RV data of all the common stars between the two surveys is shown in Figure 1(a). Though most RV values agree well with each other, there are a number of stars for which differences between the two surveys are quite large, at the central portions in particular (see Figure 1(a)). Both surveys provide RV along with the formal error, σ_{RV}, which are measures of how well the cross-correlation of their spectrum is against the template spectrum. RAVE DR5 also provides the standard deviation (SD; which is not the same as σ_{RV}) and the median absolute deviation (MAD), which provide independent measures of the $\mathrm{RV_{RAVE}}$ uncertainties calculated by re-sampling a spectrum 10 times. For about 2.5% of the RAVE sample, the difference in the RV and RV dispersions when spectrum is re-sampled 10 or 100 times is more than 1σ (for additional details see Kunder et al. 2017). On checking, we found that these stars are the reason for the very large scatter at the central portions as shown in Figure 1(a). Considering the typical accuracy of $\mathrm{RV_{RAVE}}$ in the RAVE survey, which is better than $2\,\mathrm{km\,s^{-1}}$ (Kunder et al. 2017), we excluded all those stars from the sample for which $\mathrm{SD(RV_{RAVE})} > 2\,\mathrm{km\,s^{-1}}$ and $\mathrm{MAD(RV_{RAVE})} > 2\,\mathrm{km\,s^{-1}}$. This resulted in a total of 448,726 stars from RAVE DR5. The resultant data set of RVs from RAVE DR5 is compared in Figure 1(b) with corresponding values of RV_{Gaia} from *Gaia*. The larger scatter that is present in Figure 1(a) is almost absent in Figure 1(b). But one can notice a sharp line parallel to the main

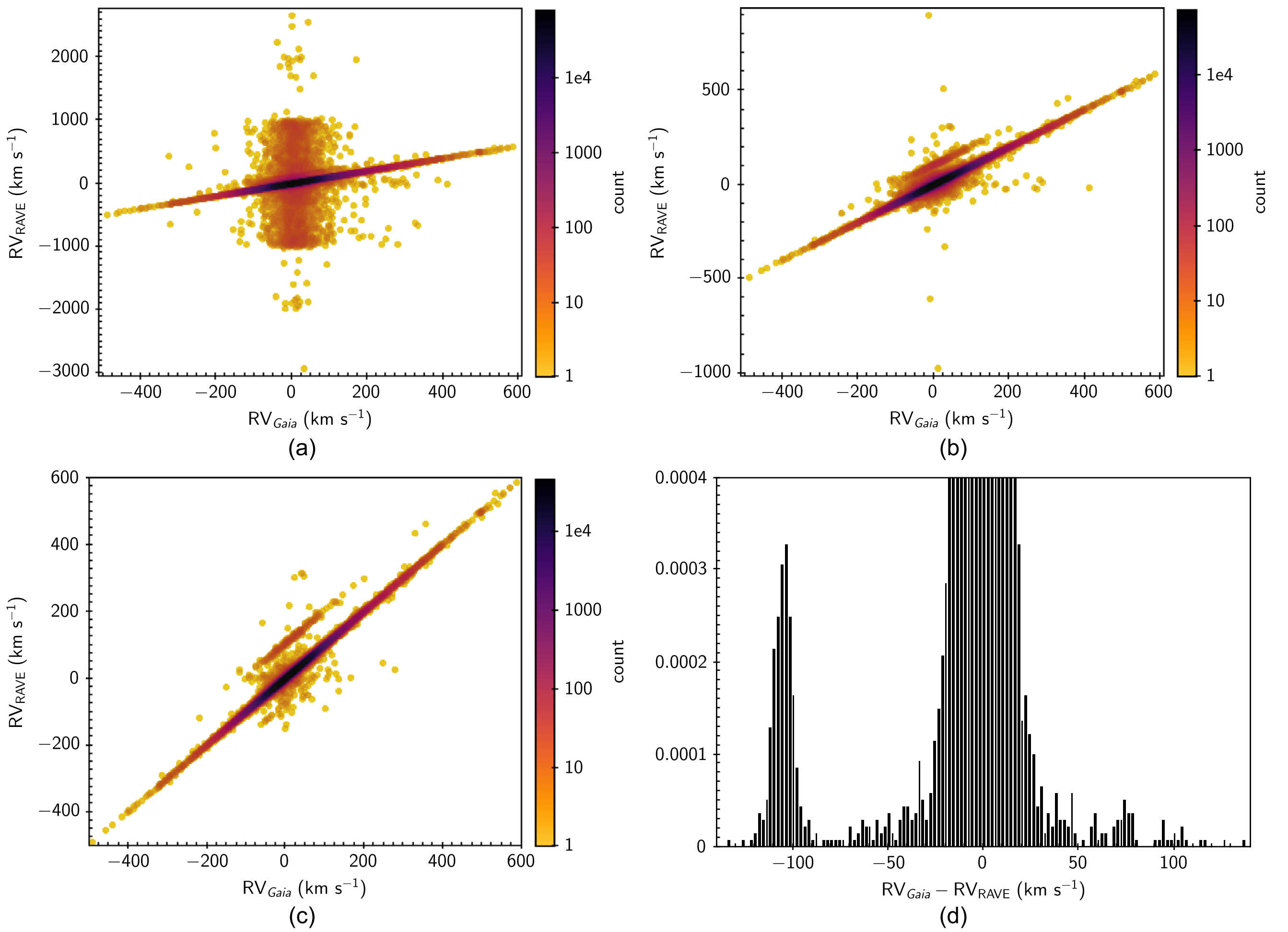

Figure 1. Distribution of RV_{RAVE} and RV_{Gaia} velocities for RAVE DR5 and *Gaia* DR2 cross-matched data with (a) no error limit, (b) $SD(RV_{RAVE}) \leqslant 2\ km\ s^{-1}$, $MAD(RV_{RAVE}) \leqslant 2\ km\ s^{-1}$, (c) $SD(RV_{RAVE}) \leqslant 2\ km\ s^{-1}$, $MAD(RV_{RAVE}) \leqslant 2\ km\ s^{-1}$, and cross-correlation error (σ_{RV}) $\leqslant 2\ km\ s^{-1}$ or 2% in RV_{Gaia} and RV_{RAVE}. (d) A section of normalized histogram of difference in RV_{Gaia} and RV_{RAVE}. Histogram is normalized with respect to maximum count and bin size used is $2\ km\ s^{-1}$.

line of the majority of stars for which RV values in both catalogs are in good agreement.

To further cull out the data with relatively large uncertainties (see Figure 1(b)) and to retain good quality RVs, we chose only those stars from both the surveys that have σ_{RV} values either maximum of $2\ km\ s^{-1}$ (for retaining stars with small RV) or maximum percentage error of 2% (for retaining stars with larger RV) from both the catalogs. These filters yielded a sample of 322,878 stars. Figure 1(c) shows distribution of RV_{Gaia} and RV_{RAVE} velocities. In this figure, the parallel line substructure along with main line (where majority stars are lying) is clearly visible. The distribution of differences in RV_{Gaia} and RV_{RAVE} is shown as normalized histogram (Figure 1(d)).

Based on Figures 1(c) and (d), we divide the entire sample into three groups: (1) Group-01: the majority group consisting of 322,449 stars with a mean difference ($RV_{Gaia} - RV_{RAVE}$) of $0.28\ km\ s^{-1}$ with a spread given by $\sigma = 1.49\ km\ s^{-1}$ (Figure 2), (2) Group-02: a small group consisting of about 272 stars with a large offset between RV_{Gaia} and RV_{RAVE}, the normal distribution for the difference in RV_{Gaia} and RV_{RAVE} velocities is given in Figure 2, which shows that the mean difference between the velocities is $-104.50\ km\ s^{-1}$ with spread given by $\sigma = 4.92\ km\ s^{-1}$, and (3) Group-03: the remaining 156 stars, which lie on either side of the main group distribution.

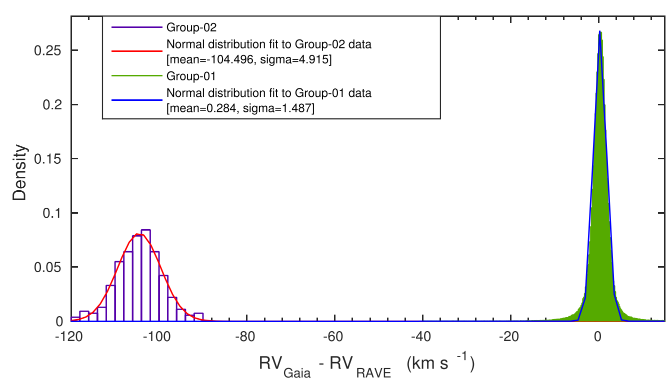

Figure 2. Normalized distribution and corresponding normal distribution fit of difference in velocities for Group-01 and Group-02 stars. Histogram bin size for Group-01 and Group-02 is $0.2\ km\ s^{-1}$ and $2\ km\ s^{-1}$, respectively, which is in agreement with the Freedman-Diaconis rule.

In general, one would expect distribution in differences in high quality RVs between the two surveys similar to the main group (Group-01). However, the large offset of $-104\ km\ s^{-1}$ between the two surveys for the small group (group-02) is surprising. There is a possibility of mistakenly matching fore or

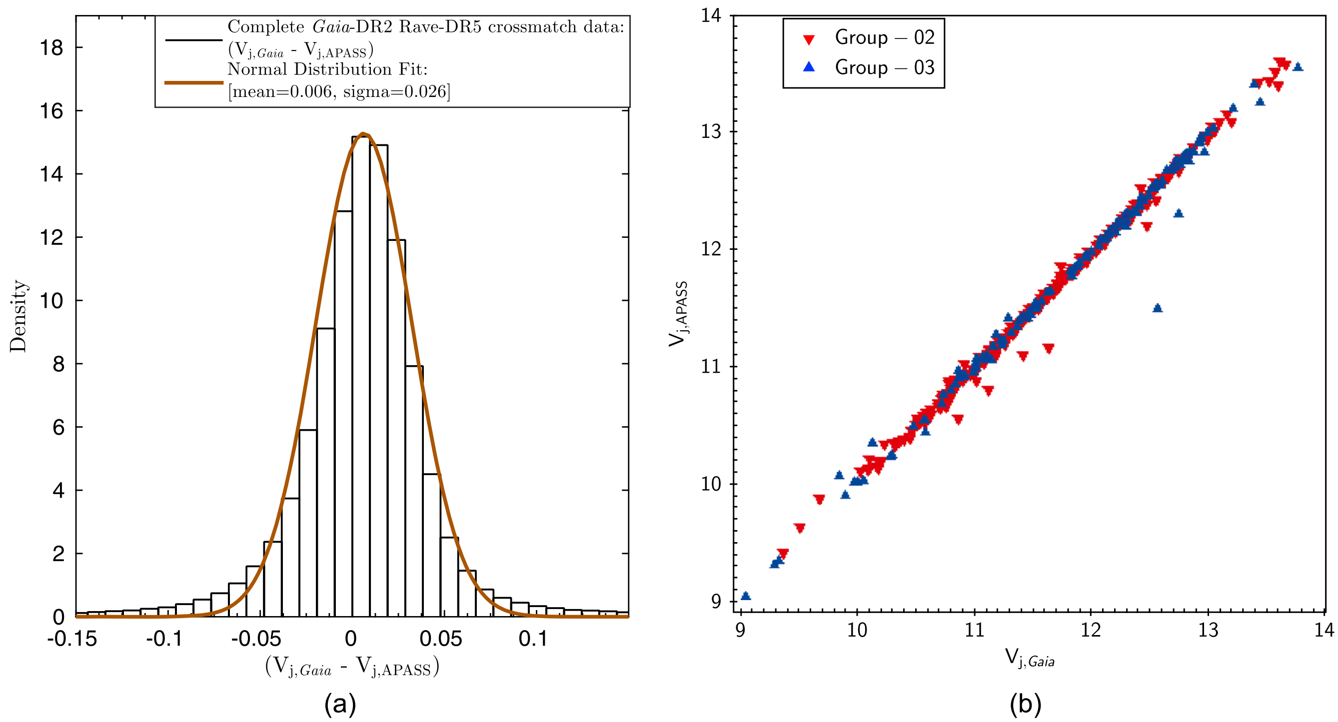

Figure 3. (a) Distribution of difference between $V_{j,Gaia}$ and $V_{j,\mathrm{APASS}}$ for all the *Gaia* DR2 and RAVE DR5 cross-matched stars for which both $V_{j,Gaia}$ and $V_{j,\mathrm{APASS}}$ are available (441,106 stars), and corresponding normal distribution fit. (b) Distribution of $V_{j,\mathrm{APASS}}$ and $V_{j,Gaia}$ for stars belonging to Group-02 (red) and Group-03 (blue). Here, $V_{j,Gaia}$ is calculated from *Gaia*'s G-band magnitudes and $V_{j,\mathrm{APASS}}$ is provided in RAVE DR5.

background stars. For making sure that the V_{rad} values of sample under consideration are in fact of the same stars in the respective surveys, we compared star's magnitudes and positions between the two surveys. To eliminate this possibility, we make sure that the apparent magnitudes of common stars are same or within reasonable limits. But the problem is, the photometric pass-bands used for apparent magnitude measurements are not common in the two surveys. *Gaia* DR2 provides photometric G, G_{BP}, and G_{RP}-band magnitudes in wavelength bands of [330–1050] nm, [330–680] nm, and [630–1050] nm, respectively (see Jordi et al. 2010). RAVE does not have its own measurements, but it has magnitudes collected from various surveys such as *Hipparcos*, TYCHO2, and APASS. Of all, the AAVSO Photometric All-Sky Survey (APASS) Data Release 9 (DR9) is the most comprehensive and precise with two Johnson broad band filters (B and V) and three Sloan filters. The survey is complete from 7 to 17th V-magnitude (hereafter $V_{j,\mathrm{APASS}}$) (see Henden et al. 2015). The cross-match between APASS and RAVE has been discussed in Lindegren & Dravins (2014). To compare $V_{j,\mathrm{APASS}}$ with *Gaia*'s magnitude, both of these need to be put on the same scale. We converted *Gaia*'s G-band photometric magnitudes to Johnson V magnitude (hereafter $V_{j,Gaia}$) using conversion formulas provided by *Gaia* Collaboration (see Evans et al. 2018).

In Figure 3, we plotted the distribution of magnitude difference ($V_{j,Gaia} - V_{j,\mathrm{APASS}}$) for the entire sample of stars for which magnitudes are available in both the surveys. The distribution shows that the magnitudes in both the surveys agree well with a mean difference of 0.006 with $\sigma = 0.026$ (see Figure 3(a)). The magnitude agreement between the two data sets with the exemption of a couple of outliers (Figure 3(b)) validates cross-matching of stars in the two surveys provided by RAVE. This shows that the systematic difference in RV is not an artifact arising from the mismatch of stars between the two surveys. For stars in Group-01 and Group-02, a comparison of the positions of the stars (R.A. and decl.) in the surveys is given in Figures 4(a)–(d), respectively. The difference in position is quite small, except in cases where stars have comparatively large proper motion. Given the different epochs of surveys, such small differences in position are expected.

Of the 272 stars in Group2, there are 51 stars for which RVs are given in RAVE DR5 from more than one spectrum observed at different times. Out of these 51 stars with multiple spectra, on checking RV for the same star from different RAVE observations, we found that 50 stars have at least one spectrum, which gave almost similar values as RV_{Gaia} along with the ones that gave a difference of approximately $-104\ \mathrm{km\ s^{-1}}$. The exception is the star "*Gaia* DR2 5913047541322494080" for which the two listed velocities in RAVE DR5 from two different spectra ("20100803_1726m56_003" and "20100731_1726m56_003") differ from that of RV_{Gaia} by approximately $-107\ \mathrm{km\ s^{-1}}$. Our understanding is that the same reduction methodology was used to derive the RVs from the multiple spectra for the same star, and yet for a small group there seems to be a problem.

4. Discussion

The relatively small spread in RVs in the case of the main group (i.e., Group-01) is probably due to intrinsic errors related to different instrumental set ups and measurement methods. One also cannot rule out the possibility of such differences as a result of measuring intrinsic random motions of stars including low-amplitude pulsations (both radial and non radial) frequently present on giant stars, the spectroscopic binaries, and gravitational redshifts at two different epochs (Lindegren & Dravins 2003). The *Gaia* DR2 data provides median RVs averaged over first 22 months of

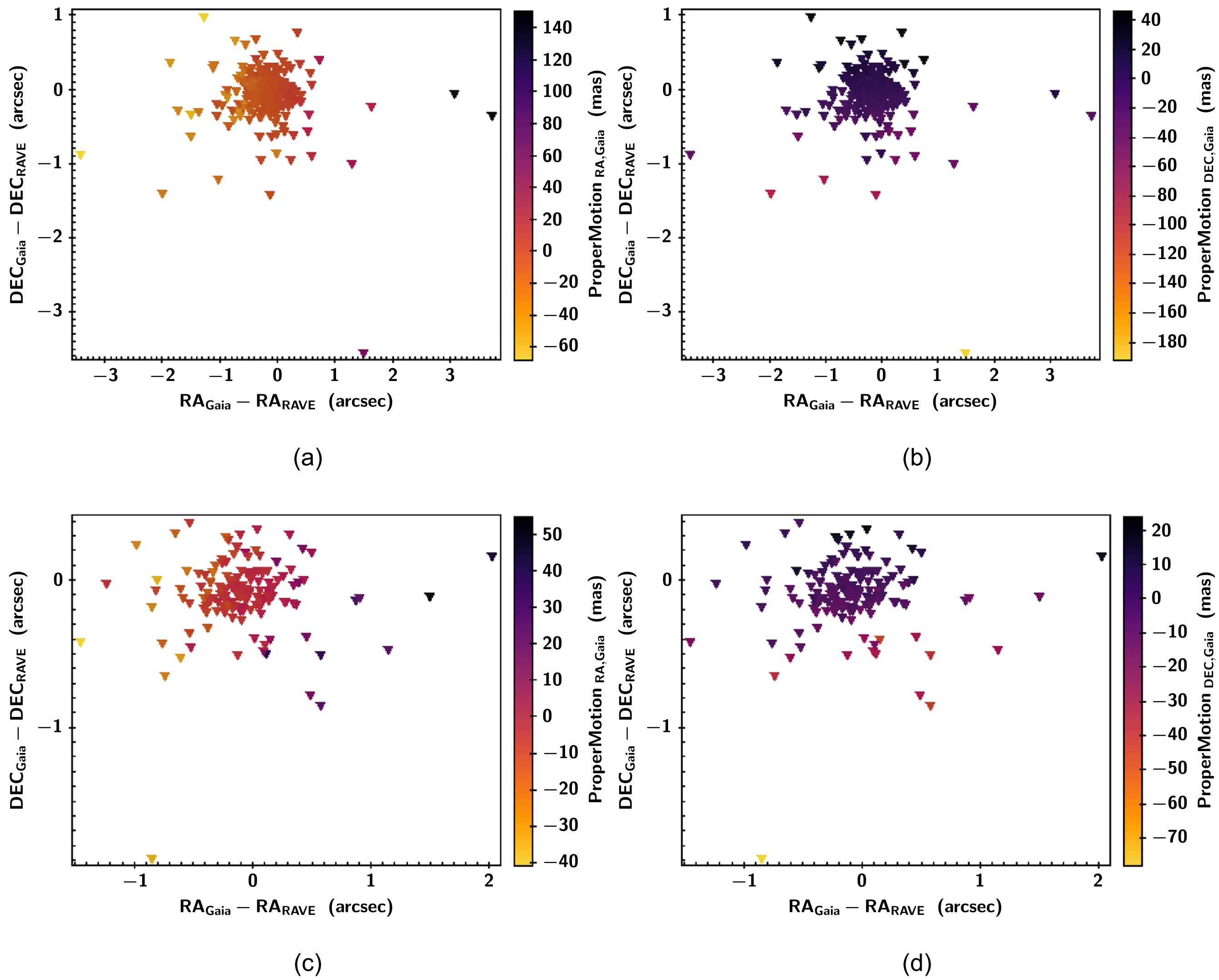

Figure 4. Distribution of difference in position coordinates of Group-02 stars from *Gaia* DR2 and RAVE DR5 catalog when corresponding proper motions (pm) from *Gaia* DR2 along (a) right ascension (R.A.), and (b) declination (decl.) are used as weights. Distribution of difference in position coordinates of Group-03 stars from *Gaia* DR2 and RAVE DR5 catalog when corresponding proper motions (pm) from *Gaia* DR2 along (c) right ascension (R.A.), and (d) declination (decl.) are used as weights.

observations since its launch in 2014 July. On the other hand, RAVE velocities are from the spectra observed from 2003 April to 2013 April. The two surveys measured RVs in a time difference of about 2 to 12 years.

However, it is not clear why such a large offset exists for stars of Group-02 between the two surveys. Though the fraction of faulty stars forms a very small percentage ($\approx$0.08%) of the total sample of highly accurate RV stars considered, it is important to highlight the issue of discrepancy to avoid misleading results. For example, Kinematic velocities (U, V, W) computed using RV values from RAVE DR5 and *Gaia* DR2 for Group-02 stars differ significantly.

Probabilities computed based on the two different sets of kinematics using the recipe given in Reddy et al. (2006) lead to different Galactic components to which stars belong. Stars kinematics based on $\mathrm{RV_{Rave}}$ suggest that most of the stars belong to the thick disk. On the other hand, the kinematics based on RV_{Gaia} values suggest that most of the stars belong to the Galactic thin disk component. This has been illustrated in Figure 5(a) in the form of the Toomre diagram, which represents the relationship between the sum in quadrature of the vertical and RVs (i.e., kinetic energy) and the rotational velocity (i.e., rotational energy) relative to the local standard of rest (Sandage & Fouts 1987). The star's heliocentric velocities (U, V, W) are corrected for the solar motion (using $U_o = 10$, $V_o = 5.3$, $W_o = 7.2$ (km s^{-1}) from Dehnen & Binney 1998) to obtain velocities with respect to local standard of rest (U_{LSR}, V_{LSR}, W_{LSR}). Also, the used kinematic boundaries for the thin disk ($|V_{\mathrm{tot}}| < 80$ km s^{-1}), thick disk ($80 < |V_{\mathrm{tot}}| < 200$ (km s^{-1})), and halo ($|V_{\mathrm{tot}}| > 200$ (km s^{-1})) are in accordance with the results in Reddy et al. (2006).

To understand the source for this discrepancy, we examined star's metallicity ([Fe/H]) provided by RAVE DR5. The distribution shows that the [Fe/H] ranges from −1.2 to +0.5 dex (Figure 5(b)), which is typical of the Galactic disk metallicity range (Reddy et al. 2006). Combined with the available [Fe/H] and kinematics implies that the stars may belong to the Galactic thin disk and the kinematics based on velocities from *Gaia* seems to be consistent with the star's [Fe/H] distribution. Though the thick disk [Fe/H] overlaps with the thin disk metallicities, one would expect most of the stars in the metal-poor side beyond −1.2 dex in case of thick

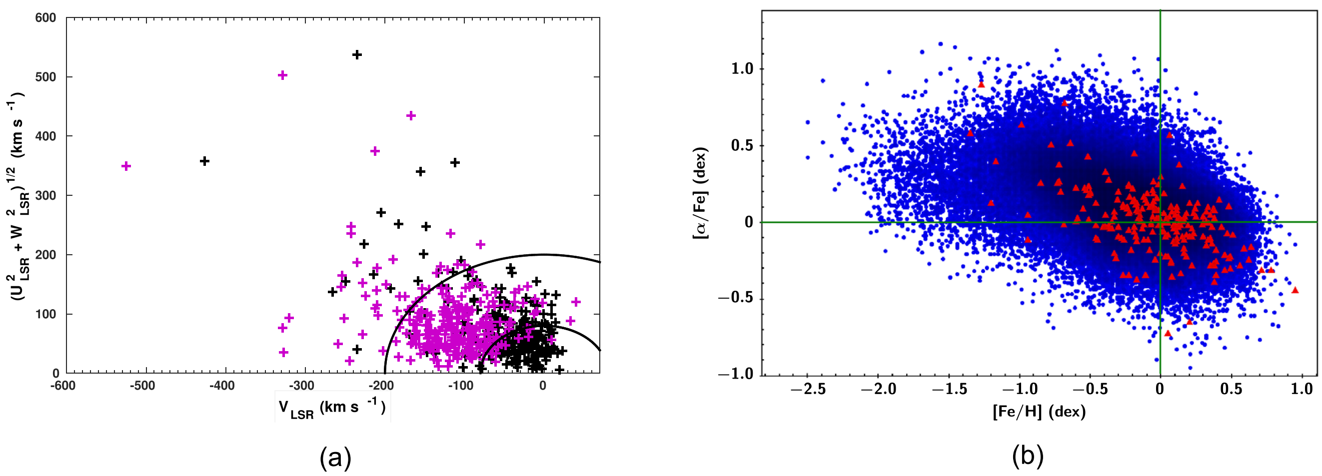

Figure 5. (a) Toomre diagram for stars in Group-02 with kinematics deduced using RV_{Gaia} (black) and RV_{RAVE} (magenta). The two concentric circles delineate constant peculiar velocities ($V_{tot} = (U^2_{LSR} + V^2_{LSR} + W^2_{LSR})^{1/2}$) of 80 and 200 km s^{-1}, and represent kinematic boundary for thin disk ($|V_{tot}| < 80$ km s^{-1}), thick disk ($80 < |V_{tot}| < 200$ (km s^{-1})), and halo ($|V_{tot}| > 200$ (km s^{-1})), which are in accordance with results in Reddy et al. (2006). (b) Distribution of [α/Fe] with respect to [Fe/H] of Group-02 stars (red) with Group-01 in background (blue). Measurements of [α/Fe] are given in RAVE DR5, and out of 272 stars of Group-02, both [α/Fe] and [Fe/H] are available for 227 stars which are plotted here.

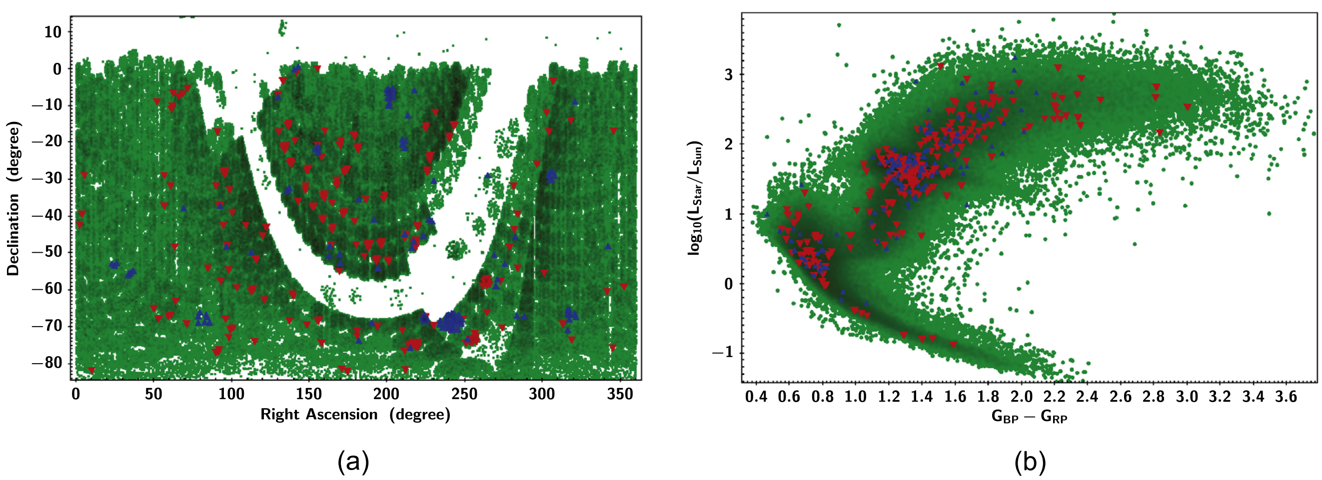

Figure 6. (a) Sky distribution, and (b) Color–Luminosity diagram for stars in our sample. Here green, red, and blue represent Group-01, Group-02, and Group-03 stars, respectively.

Table 1
RV of Three Common Stars from *Gaia*, RAVE, and LAMOST of Group-02

	Object ID		RV (km s^{-1})			σ_{RV} (km s^{-1})		
Gaia DR2	RAVE	LAMOST	*Gaia*	RAVE	LAMOST	*Gaia*	RAVE	LAMOST
5763571271979913472	20060325_0853m01_007	309408135	60.47	164.54	56.7	0.49	0.78	⋯
3831262427493102976	20110422_1013m00_108	230002091	79.43	196.79	84.5	1.05	1.57	⋯
3831274998862303360	20110422_1013m00_107	310212200	21.66	132.48	19.1	1.63	1.48	⋯

disk. Another evidence could be α-process elements for distinguishing thin disk stars from thick disk ones (Reddy et al. 2003). Abundances taken from RAVE survey are plotted against [Fe/H] (Figure 5). Though the majority of stars do show a normal α-process, this does not provide clear separation.

Furthermore, we searched for RV measurements of Group-02 stars among LAMOST and APOGEE spectroscopic surveys. Unfortunately, we found just three stars that are common with LAMOST survey. In Table 1, we have summarized RV values of these three common stars from all the three surveys. The LAMOST values match well with those from the *Gaia* data suggesting that the large offset is probably caused by RAVE data set.

The more intriguing part is the near constant offset of $-104.5\,\mathrm{km\,s^{-1}}$ with a small dispersion. To search for clues for the discrepancy in the RV data, we examined whether these stars were of some particular kind or localized in space. In Figure 6(a), we showed Group-02 and 03 stars superposed with the entire sample as background. Stars are all over the sky without any spatial clustering ruling out the possibility that these stars belong to spatially localized cluster or clusters. We also checked whether these stars are of any particular type. As shown in Figure 6(b), the distribution of stars in the HR-diagram suggest that they are uniformly distributed across the stellar evolutionary phases and have no particular trend with either T_{eff} or log g with respect to the main group.

Another possibility may be the cluster evaporation, in particular the short lived open cluster with loosely bound member stars which may become disrupted and the member stars escape due to encounters with other massive structures in the galaxy like clusters and clouds of gas, and tidal force in the galactic gravitational field as they orbit the galactic center (Shapley 1930; Trumpler 1930; Wielen 1988). Members of such open clusters will be spread along the path traced by it and continue to orbit the galaxy with inherited velocities with certain dispersion (Trumpler 1930). However, this would not explain the offset in difference between the two surveys, but will provide a clue that the members might have belonged to a particular group in the past. A closer scrutiny of the data reveals that these stars are at different distances ranging from 80 pc to 3 Kpc (approximately), and they also do not seem to be kinematically similar as well. Thus, it is unlikely that the offset in difference is due to the stars that belonged to a single group either in the past or present.

5. Conclusion

While comparing RV data from the two major surveys RAVE and *Gaia*, we noticed a significant difference in RV with an offset of $-104.5\,\mathrm{km\,s^{-1}}$ for a small group of 272 stars. While kinematics based on RAVE suggest that most of the stars in the group are of thick disk, velocities from *Gaia* suggest the stars are of thin disk. However, [Fe/H] range of stars in the group from −1.2 to +0.5 dex suggests that most of the stars are in fact from thin disk origin agreeing with *Gaia* velocity data. This is corroborated by LAMOST velocity data for three common stars, in all three surveys, which are in agreement with the *Gaia* values. Though the source of the offset is not clear, our study suggests that the offset is due to the RAVE data set.[1]

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[1] In refereeing, we became aware that the RAVE Consortium, independent of our analysis, has released a list with affected targets (available at https://www.rave-survey.org/project/documentation/dr5/rave_dr5/) that gave issue with a faulty wavelength calibration as the reason for the offset. A corrected wavelength calibration and derived RV will be available for affected targets with the soon-to-be released final RAVE DR6.