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Comparison of the Pulkovo Compilation of Radial Velocities with the RAVE DR1 Catalogue

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Abstract—The Data Release 1 of the Radial-Velocity Experiment (RAVE DR1 1, 24 748 stars) is compared with the May 15, 2006 version of the Pulkovo Compilation of Radial Velocities (PCRV, 35 495 stars). RAVE DR1 includes mostly $9-13^m$ stars, while the PCRV contains brighter stars. Analysis of the "RAVE minus PCRV" radial-velocity differences for 14 common stars has revealed no systematic dependences on any factors, except the effect due to the RAVE radial-velocity zero-point offset known from the RAVE observations. This effect shows up for ten of these stars observed on a single night as a sine wave with an amplitude of 1.5 km s^{-1} in the dependence of the radial-velocity difference on the ordinal number of the optical fiber used and, accordingly, on the star position angle in the field of view of the RAVE instrument. The detection of this dependence confirms a high radial-velocity accuracy in both catalogs: on average, better than 1 km s^{-1} for stars brighter than 10^m (for the RAVE, after applying a correction for the zero-point offset). The RAVE zero-point offset can be corrected for with an accuracy better than 1 km s^{-1} by observing several PCRV stars in each RAVE frame and by analyzing the "RAVE minus PCRV" radial-velocity differences.

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INTRODUCTION

Two major radial-velocity catalogs were published in 2006. Their comparison can improve the accuracy of further radial-velocity observations.

The Pulkovo Compilation of Radial Velocities (PCRV) whose May 15, 2006 release was presented by Gontcharov (2006) contains 35 495 stars brighter than $V = 13^m$ from the Hipparcos catalogue (ESA 1997). The radial velocities of these stars were collected in the PCRV from more than 200 publications, including the major ones: the WEB catalog (Duflot et al. 1995), the catalogue by Barbier-Brossat and Fignon (2000), the Geneva–Copenhagen Survey of the solar neighborhood (below referred to as the GCS) (Nordstrom et al. 2004), and the kinematic survey of K and M giants (Famaey et al. 2005). The observations of standard IAU stars or stars from the compiled work list of secondary standards are used to allow for the zero-point discrepancies between the publications and the list of standards and for significant systematic dependences of the "publication minus list of standards" radial-velocity differences on the radial velocity itself, $B-V$ color index, and equatorial coordinates. Particular attention is given to the analysis of the radial velocities from the four mentioned major publications. The discrepancy between their zero points that was revealed when compared with the list of standards does not exceed 0.5 km s^{-1} and significant systematic dependences, which do not exceed 0.4 km s^{-1} in absolute value, were found only in the GCS. Thus, combining these data into a unified compilation (after applying the appropriate corrections) is quite justifiable.

We used the standard deviation of the "publication minus list of standards" radial-velocity differences after applying a correction for the systematic dependences and zero-point discrepancies to assign weights and to calculate the weighted mean radial velocity of each star and its accuracy. The median accuracy of the weighted mean radial velocity in the PCRV is 0.7 km s^{-1}. The radial velocities of 21 015 stars (59%) have an accuracy better than 1 km s^{-1}. However, unfortunately, the PCRV (like all of the compilations) contain mostly stars whose radial velocities were measured in only one observing program and are given in only one publication: 24 437 stars

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(69%). Therefore, comparing the results of independent radial-velocity measurements with different instruments is of great importance.

One of the major projects in the history of astronomy to measure the radial velocities of stars, the Radial Velocity Experiment (RAVE) (Steinmetz et al. 2006), was started in 2003. By 2011, the spectra of up to one million stars are to be taken and their radial velocities and stellar atmosphere parameters are to be determined. The Data Release 1 (DR1) of the catalog of radial velocities was published in 2006. It includes 24 748 southern-sky stars mostly with magnitudes $9-13^m$, about half of which enter the Tycho-2 catalogue (Høg et al. 2000).

The observations are performed with the spectrograph mounted on the 1.2-m UK Schmidt Telescope at the Anglo-Australian Observatory. The CCD array simultaneously records the spectra of many objects in a 6° field of view. The spectral lines in a narrow infrared spectral range (841–880 nm) around the Ca triplet are measured. The spectra have a mean resolution of $R = 7500$ and the pixel size corresponds, on average, to a velocity of 13 km s^{-1}. Therefore, the radial velocity can be measured theoretically with an accuracy of at least 1.3 km s^{-1} (1/10 pixel) at a high signal-to-noise ratio. It is this scatter that is achieved in the best cases during repeated observations of stars brighter than 10^m at a signal-to-noise ratio larger than 75. The accuracy can theoretically be about 2 km s^{-1} with a mean signal-to-noise ratio of about 30 for the observed stars and will deteriorate greatly at a lower signal-to-noise ratio for $12-13^m$ stars. However, the most important source of errors is the radial-velocity zero-point offset reaching several km s^{-1} in one hour of observations that was revealed by the RAVE team. If this offset is disregarded, then it enters completely into the error of the measured radial velocity and manifests itself when the radial velocities of common PCRV and RAVE stars are compared. Therefore, below we consider the parts of the instrument and the peculiarities of the method for determining the radial velocities in RAVE that can have a bearing on the zero-point offset.

THE RAVE RADIAL-VELOCITY ZERO-POINT OFFSET

In the RAVE instrument, light falls on a plate at the focus of the telescope and is transmitted to the stationary CCD spectrograph by 150 movable optical fibers whose ends are located near this plate. In the parked state, the fiber ends are distributed almost uniformly in the form of a ring along the edge of the focal plate. During measurements, an automatic device alternately displaces the fiber ends from the edge of the field of view to the star images. The displacement line should not deviate from the radial direction by more than 14°. Therefore, each fiber is pointed at objects predominantly in the sector of the field of view nearest to it. It takes about one hour to record the spectra of several tens of stars within the same 6° field of view using most of the fibers together with the flat-field spectra and the comparison spectra from a neon arc before and after the star spectra were recorded. The fibers are used in turn in order of increasing number. Let us call all of the corresponding information recorded by the CCD array for a single 6° field a frame. The radial velocities are determined by the standard cross-correlation method (Tonry and Davis 1979). Since stars of all spectral types and luminosity classes are observed in the RAVE project, the computer spectral "mask" used in the cross-correlation method is formed based on the major libraries of theoretical spectra by Zwitter et al. (2004) and Munari et al. (2005). A total of 22 992 theoretical spectra were used to compile the RAVE DR1 catalogue. As was shown in the description of the RAVE DR1 catalogue, the multistep procedure for choosing the best theoretical spectrum for a specific star ensures a high accuracy of radial-velocity measurements.

The RAVE team found that the emission lines in the comparison spectrum from a neon arc *after* the spectra of stars in the same frame were recorded are shifted along the axes of the spectra relative to their positions *before* the stellar spectra were recorded. Special studies showed a correlation between this shift and the change in the temperature of the instrument, but the ultimate cause of this effect is unclear. This shift results in a systematic radial-velocity zero-point offset reaching 5 km s^{-1} within the same frame. Since the comparison spectrum cannot be recorded more often than two times for the same frame, the RAVE team used the following procedure. The night-sky emission lines recorded in the frame as a background of stellar spectra separately for each optical fiber are used to estimate the zero-point offset when a single frame is recorded. The dependence of the emission-line radial velocity on the ordinal number of the optical fiber obtained in this way is then considered as the zero-point offset, because the fibers within the same frame are used in order of increasing number. This dependence is fitted by a low-degree polynomial and is subtracted from the stellar radial velocities. Each frame has its own polynomial. Figure 1 shows examples of the zero-point corrections as a function of the ordinal number of the optical fiber for three frames on different nights. Unfortunately, the signal-to-noise ratio is low for the night-sky emission lines. Therefore, this method of correcting for the zero-point offset has an accuracy no better than 1 km s^{-1}.

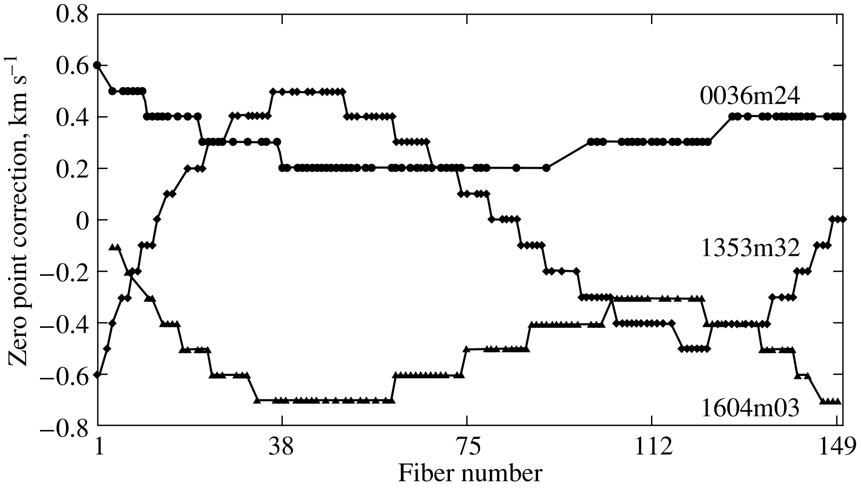

Fig. 1. Examples of the radial-velocity zero-point corrections (in km s^{-1}) determined from night-sky emission lines and applied to the RAVE observations as a function of the ordinal number of the optical fiber in the field of view for several frames on different nights: 0036m24, 1353m32, 1604m03.

COMPARISON OF THE PCRV AND RAVE RADIAL VELOCITIES

Figure 2 shows the distribution of PCRV and RAVE DR1 stars in J magnitude from the 2MASS catalog (we chose the J magnitude, because it is known directly from observations almost for all of the stars under consideration). The catalogues span different magnitude ranges and have only 14 common stars. This is clearly insufficient to fully reveal the systematic errors in the RAVE results, but is quite sufficient to detect the main systematic error in RAVE, the zero-point offset, and, accordingly, to reach the conclusion that regular observations of stars brighter than 10^m with well-known radial velocities are needed in the RAVE project.

The "RAVE minus PCRV" radial-velocity differences for 14 common stars show no significant systematic dependences on magnitude, radial velocity, $B-V$ color index, signal-to-noise ratio, height and width of the peak of the correlation function, focal plate number, and other factors, except the ordinal number of the optical fiber.

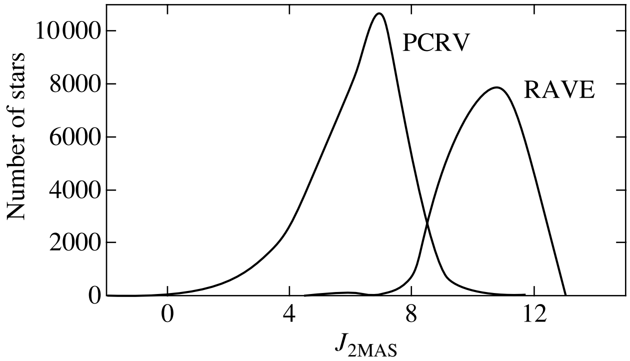

Fig. 2. Distribution of PCRV and RAVE DR1 stars in J magnitude from the 2MASS catalog.

Three of the 14 common stars are scattered in different frames. The "RAVE minus PCRV" radial-velocity differences for them are 0.3, 1.1, and 3.9 km s^{-1}. The first two values agree with the estimated accuracy in the catalogues. The last value was obtained for the faintest of the 14 stars, HIP 67181, with $V = 10^m$, a high radial velocity (408 km s^{-1}, RAVE), a peculiar spectrum, and presumed binarity (Hipparcos DMSA stochastic solution). The remaining 11 stars were observed in two successive frames on August 6, 2003. Table 1 gives parameters of these stars: Hipparcos numbers, approximate coordinates α and δ (J2000) in degrees with fractions, V magnitudes, and $B-V$ color indices from Hipparcos. Table 2 gives data referring to the radial velocities of these stars: Hipparcos numbers, radial-velocity sources (only one for all stars, except HIP 78432, for which two sources were used in the PCRV), radial velocities from the source (for HIP 78432, the mean of two sources), PCRV radial velocities, RAVE DR1 radial velocities, frame designations, signal-to-noise ratios, and the height of the peak of the correlation function in the RAVE observations. Since these frames refer to neighboring regions of the sky and were recorded successively, without any gaps in time, given the correlation between the zero-point offset and the temperature revealed by the RAVE team, a similar zero-point offset can be assumed in these frames. No correction for the zero-point offset was applied in the RAVE DR1 catalogue for these frames. Therefore, the zero-point offset shows up

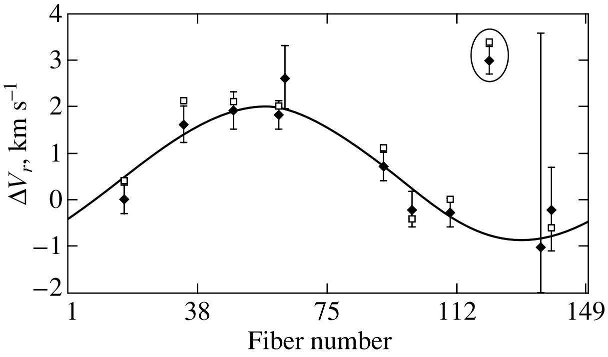

Fig. 3. “RAVE minus PCRV” (diamonds) and “RAVE minus GCS” (squares) radial-velocity differences vs. ordinal number of the optical fiber in the RAVE field of view for 11 stars observed on August 6, 2003. The vertical bars indicate the accuracy from the PCRV. The outlier for the star HIP 79777 is encircled.

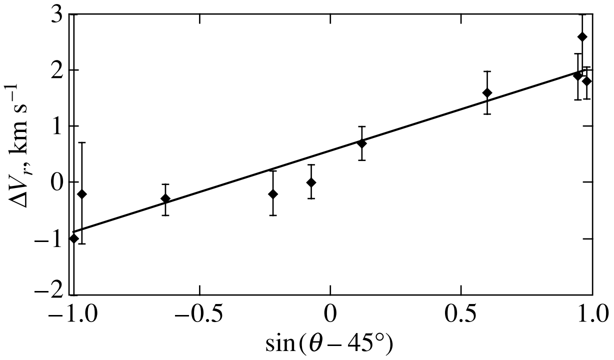

Fig. 4. “RAVE minus PCRV” radial-velocity differences vs. $\sin(\theta - 45°)$, where θ is the position angle of the optical fiber in the field of view (in degrees) for 10 common stars observed on August 6, 2003. The vertical bars indicate the accuracy from the PCRV.

as the dependence of the “RAVE minus PCRV” radial-velocity differences on the ordinal number of the optical fiber. These differences together with the “RAVE minus GCS” differences (in km s^{-1}) are indicated in Fig. 3 as a function of the ordinal number of the optical fiber by the diamonds and squares, respectively. The vertical bars indicate the accuracy of the PCRV radial velocities, which is almost equal to that of the GCS radial velocities. It makes no sense to give the accuracy from the RAVE, because the zero-point offset was disregarded when it was calculated.

The “RAVE minus PCRV” radial-velocity differences for the 10 stars mentioned above (7 in one frame and 3 in the other frame) fall nicely on the $V_{\mathrm{RAVE}} - V_{\mathrm{PCRV}} = 1.50 \sin(\theta - 45°) + 0.58$ km s^{-1} curve, where θ is the position angle of the optical fiber in the field of view (in degrees). The star HIP 79 777 gave an outlier (encircled in Fig. 3), which may result from the smallest height of the peak of the correlation function (0.88) among the 14 stars. The sine wave found resembles the polynomials for other RAVE frames presented in Fig. 1 as examples, but is was drawn much more accurately. Figure 4 shows the correlation between the radial-velocity differences and $\sin(\theta - 45°)$ for 10 stars (without HIP 79 777): the correlation coefficient is 0.94. The correlation coefficient for the GCS radial velocities of eight stars is 0.93 (HIP 79777 also gives an outlier in the “RAVE minus GCS” difference). We see that the GCS radial velocities were included in the PCRV with small corrections. Thus, the authors of RAVE DR1 had sufficient information (the radial velocities of nine GCS stars) to detect the zero-point offset from the “RAVE minus GCS” differences.

If we take the PCRV zero point, then a tentative (due to the small number of stars) conclusion about the necessary mean RAVE radial-velocity zero-point correction, about −0.58 km s^{-1}, can be drawn from the mean “RAVE minus PCRV” radial-velocity difference. This value agrees well with the mean zero-point correction of −0.55 km s^{-1} determined by the RAVE team from night-sky emission lines, which is indicative of a high accuracy of allowance for the zero-point offset *on average*. However, an accurate allowance for the zero-point offset is needed for each frame as well. For example, for the frames in question, allowance for the sine wave found reduces the standard deviation of the radial-velocity differences for these 10 stars from 1.2 to 0.4 km s^{-1}. This is probably the real mean accuracy of the radial velocities for stars brighter than 10^m in the PCRV and RAVE DR1,

Table 1. Parameters of 11 common PCRV and RAVE DR1 stars.

HIP	α, deg	δ, deg	V	$B-V$
78 432	240.18	−47.89	8.7	1.39
78 791	241.27	−48.83	8.3	0.59
79 777	244.22	−49.86	7.6	0.76
79 912	244.67	−51.21	8.7	0.52
83 415	255.75	−43.12	9.5	0.85
84 152	258.07	−43.49	8.5	0.73
84 419	258.88	−42.78	8.5	0.60
84 911	260.30	−41.56	8.7	0.74
85 211	261.18	−45.01	6.7	0.39
85 222	261.21	−41.50	7.8	0.52
85 468	261.98	−42.41	8.4	0.62

Table 2. Radial velocities of 11 common PCRV and RAVE DR1 stars

HIP	Source	V_r, km s^{-1}	V_r(PCRV), km s^{-1}	V_r(RAVE), km s^{-1}	Frame	S/N	Peak
78 432	WEB/DCZ*	−20.9	−20.7	−18.0	1607m49	61	0.97
78 791	GCS	−0.3	−0.1	1.7	1607m49	55	0.96
79 777	GCS	10.8	11.2	14.2	1607m49	117	0.88
79 912	WEB	−6.2	−6.2	−7.2	1607m49	52	0.95
83 415	GCS	−6.8	−6.3	−4.7	1716m42	57	0.94
84 152	GCS	−49.7	−49.3	−49.3	1716m42	75	0.95
84 419	GCS	−2.4	−2.2	−0.3	1716m42	50	0.94
84 911	GCS	−52.5	−52.1	−51.4	1716m42	72	0.95
85 211	GCS	−1.3	−1.7	−1.9	1716m42	147	0.95
85 222	GCS	24.8	24.8	24.5	1716m42	133	0.96
85 468	GCS	−20.7	−20.4	−20.7	1716m42	59	0.94

* DCZ stands for Da Costa and Seitzer (1989).

which is quite achievable after applying an accurate correction for the zero-point offset.

The actually considered effect is a blue and red shift of the spectral lines at the opposite edges of the focal plate (in the frames under consideration, at the "southeastern" and "northwestern" edges). In this case, the zero point may change not just because of the temperature changes, but because these changes compound a certain dependence of the zero point on the position angle in the field of view. A similar effect was found when analyzing the focal scale of the photographic vertical circle (PVC) at the Pulkovo Observatory of the Russian Academy of Sciences) (Gontcharov 1996). Since the focal photographic plate is inclined to the PVC optical axis, the scale changes as $r(at + b \sin\theta)$, where θ is the position angle in the field of view, t is the time, r is the distance from the star to the intersection of the optical axis with the focal plane, and a and b are temperature-dependent coefficients. The RAVE zero-point offsets shown in Fig. 1 can be represented by a similar formula.

Special studies would probably allow the radial-velocity zero-point offset in the RAVE observations to be taken into account more accurately. It may be useful to control the orientation of the focal plate relative to the optical axis. Undoubtedly, observations of radial-velocity standards and/or PCRV stars will be useful. Given the PCRV star density (at least one star with an accurate radial velocity per two square degrees) and their uniform sky distribution, several PCRV stars can be recorded in each frame of the 6° field by different optical fibers at different position angles and the zero-point offset can be taken into account for each frame with an accuracy no worse than the mean accuracy of the PCRV radial velocities, 0.7 km s^{-1}, i.e., much more accurately than is now done using night-sky emission lines, by analyzing the "observations minus PCRV" radial-velocity differences.

CONCLUSIONS

When the two major radial-velocity catalogs are compared, the main systematic error of the RAVE observations, the zero-point offset, manifests itself in the "RAVE minus PCRV" radial-velocity differences. This suggests that the typical accuracy of the radial velocities for stars brighter than 10^m in both catalogues is appreciably better than 1.5 km s^{-1}, the amplitude of the detected systematic effect, and, consequently, it is no worse than the accuracy declared by the authors of both catalogs. The accuracy of the RAVE data can be improved further (probably up to a level of 1 km s^{-1} for several hundred thousand Tycho-2 stars brighter than 11^m) by a careful allowance for the zero-point offset, for example, using regular observations of standard stars or PCRV stars.

Compared to the PCRV, the mean RAVE radial-velocity zero-point correction (−0.58 km s^{-1}) agrees well with the corresponding correction determined by the RAVE team from night-sky emission lines: −0.55 km s^{-1}. This is indicative of a high accuracy of allowance for the zero-point offset in the RAVE results *on average*.

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