Catalog of secondary RV standards from the RAVE survey

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Abstract

RAdial Velocity Experiment (RAVE) measured radial velocities (RVs) of nearly half-a-million stars with $9 \lesssim V \lesssim 13$ in the Southern hemisphere using the UK Schmidt telescope at the Australian astronomical observatory. Here we present a catalog of RVs and a comprehensive estimate of their errors for stars which showed a constant radial velocity (within 1.5 km s^{-1}) during multiple observations. The catalog contains information on 10,277 such stars. Quality and especially quantity of these measurements does not satisfy a standard astronomical definition to call them radial velocity standards, but these stars can still be used as an extensive set of secondary standards which are useful for validation of the RVS instrument. The catalog builds on an upgrade from the previous version (GAIA-C6-TN-LU-TZ-2) which contained less stars and reported only formal errors on RV, which do not take into account systematic effects. The new version is also cleaned from spurious spectra using a morphological classification scheme.

Document History

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Contents

1 Introduction

1.1 Objectives

Measurements of radial velocities with the Gaia RVS are producing a self-calibrating body of data. The instrument is producing excellent results which clearly show that the self-calibration is working well. But, as with any instrument, it is important to have a set of complementary RV measurements for verification purposes. This then allows to study several effects, which are still being worked on, and include subtraction of scattered light, influence of overlapping background spectra, and issues related to selection of sub-optimal templates for RV derivation. All these effects are well understood for bright stars, but their study for the majority of targets which are faint and so yield spectra with low values of S/N continues to be an important topic.

Compilation of lists of radial velocity standards is a difficult task. Stars can have their radial velocity intrinsically variable for several reasons which occur on very different timescales. Binarity can affect radial velocities on timescales from minutes to years and on velocity ranges up to several hundred km s^{-1} for short orbital periods. But it is much more frequent to encounter a binary with a long period which involves radial velocities on a level of just a few km s^{-1}. Such systems are difficult to recognise unless one we are having an extensive set of RV measurements spanning several years at our disposal. On the other hand pulsations and rotating spotty stars tend to show variability on timescales of days. These are easier to recognise, as these phenomena are also limited to confined regions of the HR diagram. Finally, stellar outbursts can be aperiodic and occur on very long recurrence times. As a result it is difficult to claim that RV velocity of a certain star is constant; such statements can be only probabilistic and on limited timescales.

Here we adopt a simplistic approach by supplying an extensive list of *candidates* for RV standards. This simply means that a given star was observed more than once and that its measured RV was consistent with a constant value for all observations. As already said this does not mean that the star could not have a drifting or shifting RV in future. But, statistically speaking, this does not seem very probable. So the list is useful for statistical verification of radial velocities derived from observations with the RVS instrument.

The list is compiled from measurements of the RAVE (RAdial Velocity Experiment) survey which measured radial velocities of nearly half-a-million stars with $9 \lesssim V \lesssim 13$ in the Southern hemisphere. Most stars were observed just once, but a significant number has two observations or more. RAVE observed in the same spectral domain as RVS and at a similar resolving power ($R \sim 7500$) which makes use of these data particularly relevant. Reliability of each individual measurement in RAVE is expected to be better than single observations by the RVS because RAVE achieves a relatively high SNR ~ 40 for a typical spectrum. But, as said, the number of repeated observations is limited, so RAVE results are prone to errors due to long term trends, including the fact that many of the observed stars are members of binary systems. The survey has been described in detail in the data release papers (Steinmetz et al. 2006, Zwitter et al. 2008, Siebert et al. 2011, Kordopatis et al. 2013). Here we extract data from the forthcoming DR5 data release (Kunder et al. 2016). We also include results from the re-run of morphological spectral classification as described in Matijevič et al. (2012).

The results we are presenting here are tailored to the needs of the RVS. In particular we choose only stars with reliable RV measurements and with non-peculiar spectral type that show a constant RV on two or more separate observations. We also combine multiple RV measurements into a weighted average, and provide a comprehensive error estimate which attempts to include both formal and systematic errors.

To summarise, the objectives are to provide a sizeable body of relatively reliable external secondary RV standards to be used for verification control of the RVS data reductions.

1.2 Definitions

1.2.1 2MASSiD identifier (2MASSID)

2MASSID identifier - a unique name given to each observed object. The identifier is quoted also by SIMBAD using a ”2MASS J” prefix. Its format is HHMMSSss+DDMMSSs, starting with right ascension given in hours (HH), minutes (MM), seconds (SS), and their hundredths (ss), followed by the sign of declination (+ or -), followed by declination degrees (DD), arc-minutes (MM), arc-seconds (SS), and their tenths (s).

1.2.2 RAVEID identifier (RAVEID)

RAVEID identifier - a unique name given to each observed object. The identifier is quoted also by SIMBAD using a ”RAVE” prefix.

1.2.3 Right ascension of the target ($RAdeg$)

Right ascension of the object in degrees, epoch 2000.0 and equinox J2000.0, taken from 2MASS and ucac4 catalogs.

1.2.4 Declination of the target ($DEdeg$)

Declination of the object in degrees, epoch 2000.0 and equinox J2000.0, taken from 2MASS and ucac4 catalogs.

1.2.5 Galactic longitude of the target ($Glon$)

Galactic longitude in degrees calculated from $RAdeg$ and $DEdeg$.

1.2.6 Galactic latitude of the target ($Glat$)

Galactic latitude in degrees calculated from $RAdeg$ and $DEdeg$.

1.2.7 Heliocentric radial velocity ($HRVaverage$)

Heliocentric radial velocity in km s^{-1}. Its calculation for the case of multiple observations is explained below.

1.2.8 Estimated error on heliocentric radial velocity ($HRVsigma$)

Estimated error on heliocentric radial velocity in km s^{-1}. Its calculation is explained below.

1.2.9 Number of observations ($measurements$)

Number of separate observations of a given target that were used for calculations of $HRVaverage$ and $HRVsigma$. See text.

1.3 Acronyms

A list of used acronyms:

Acronym	Description
2MASS	Two Micron All Sky Survey
CU	Coordination Unit (in DPAC)
DPAC	Data Processing and Analysis COnsortium
DU	Development Unit (in DPAC)
RAVE	Radial Velocity Experiment
RV	Radial velocity
SNR	Signal-to-Noise Ratio
TN	Technical Note

2 Selection of spectra in the sample

Initial selection is similar to the one described in GAIA-C6-TN-LU-TZ-4. So we repeat the relevant description with relevant modifications. Results of RAVE reductions give the following numbers which are relevant in calculation of final radial velocities ($HRVaverage$) and their estimated errors ($HRVsigma$):

1. HRV, measurement of heliocentric radial velocity for each spectrum, in km s^{-1}, estimated from a parabolic fit to the correlation peak between the observed normalised spectrum and its best matching synthetic template.
2. $eHRV$, formal error on measurement of heliocentric radial velocity for each spectrum, in km s^{-1}, estimated from the width of the correlation peak between the observed normalised spectrum and its best matching synthetic template.
3. $ZeroPointRV$, a zero-point correction, in km s^{-1}, that was applied to the spectrum before calculating its radial velocity. Reasons for this correction are discussed in DR papers, and its influence on derived radial velocities is discussed in Matijevič et al. (2011).
4. STN, estimate of the S/N ratio per pixel, as given by the SPARV pipeline (Siebert et al. 2011).
5. $flag1$, $flag2$, $flag3$, ..., 20 most relevant morphological classification flags for the spectra, each flag is a single character. They are described in detail in Matijevič et al. (2012). Morphological classification has been re-run on the present dataset.

The goal of the present catalog is to include only trustworthy and multiple measurements, which can be used for verification purposes. So we select only spectra which satisfy the following criteria:

1. $STN > 20$,
2. $eHRV < 5$ km s^{-1},
3. the first three morphological classification $flag1$, $flag2$, and $flag3$ have the value 'n' which denotes a 'normal', i.e. a non-peculiar star.

Altogether 334,084 different stars satisfy these criteria. This can be compared to 522,123 spectra of 458,771 different stars that were observed overall.

$HRVaverage$ was calculated as a simple average value of RV measurements in individual spectra of a given object which satisfy the selection criteria mentioned above. We decided to avoid a more sophisticated scheme that would include weighting by individual values of STN for the following reasons. RAVE spectra are generally not limited by shot noise. At the low STN end ($STN < 20$), which is anyway excluded from our sample, the errors on RV are dominated by limited knowledge of the parameters of the best matching synthetic template and by uncertainties related to interference fringe subtraction and fibre cross-talk. On the other hand very high STN spectra ($STN > 60$) have their RV accuracy limited by a limited quality of normalisation and interference fringe subtraction. So we are left with a modest range of $20 < STN < 60$ where STN weighting cannot influence the results very much. So we kept a simple average as the preferred value.

Estimation of the representative error on radial velocity, $HRVsigma$, is more complicated. It should take into account three separate effects:

1. formal error of RV measurement from each spectrum ($eHRV$),
2. shift of the zero point that was applied to each spectrum ($ZeroPointRV$),
3. dispersion of measurements in cases where a given object was observed more than once.

The final RV error estimate $HRVsigma$ was obtained from the expressions:

$$(eHRVaverage)^2 = \frac{1}{N}\sum_i^N [(eHRV_i)^2 + (\frac{ZeroPointRV_i}{2})^2] \tag{1}$$

$$(HRVsigma)^2 = (eHRVaverage)^2 + \frac{1}{N}\sum_i^N (HRV_i - HRVaverage)^2 \tag{2}$$

Here N is the number of measurements of the object which passed the selection criteria explained above. Equation (1) estimates the total error of each RV measurement as a sum (in squares) of the formal error of measurement and the applied zero point shift. The later is weighted in with a factor of 0.5, which follows the justification in Matijevič et al. (2011). Note that this zero point term is usually not important, as the zero point corrections are very small. But in a few cases of large zero point shifts it helps to avoid a too-optimistic overall error estimate. Equation (2) adds in square total errors of each measurement and dispersion of individual measurements.

Finaly we need to include additional criteria used to define secondary RV standards. These are:

1. $HRVsigma < 1.5$ km s^{-1}, and
2. $N \geq 2$.

So only stars with at least 2 measurements and with an overall estimate of the RV error smaller than 1.5 km $s^{-1}$are included. The final catalog contains data on 10,277 secondary RV standards.

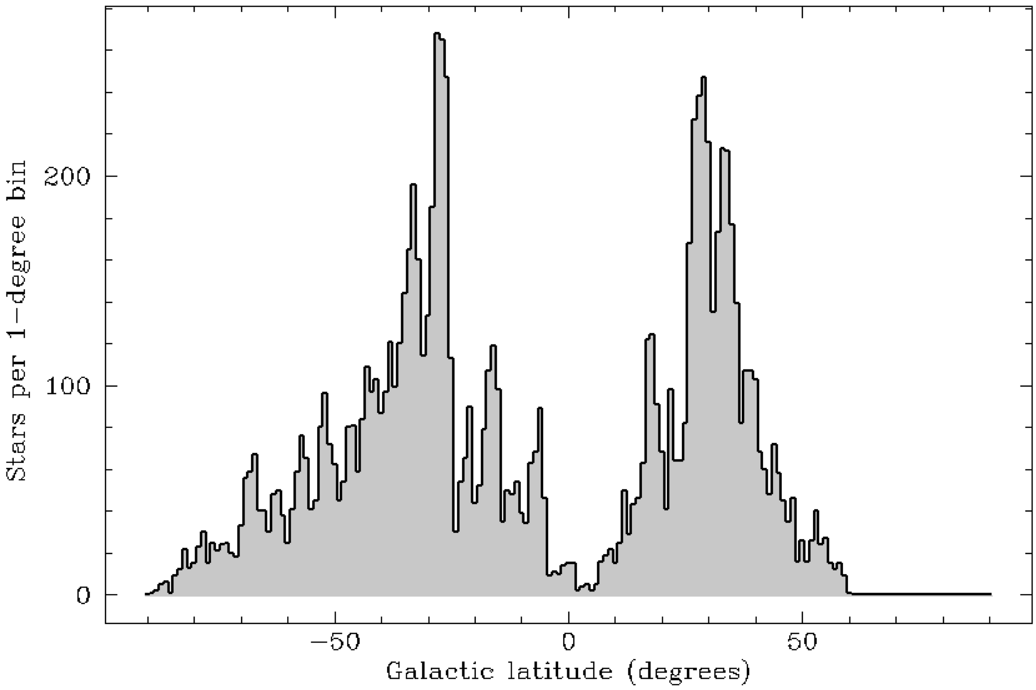

FIGURE 1: Histogram of Galactic latitudes of stars in the catalog. Note the asymmetry with respect to the Galactic plane which is due to the fact that RAVE is a Southern sky survey. Zig-zag appearance of the histogram is caused by distribution of survey fields: these fields with a diameter of 6.7 degrees are arranged in steps of Galactic latitude.

3 Retrieval and contents of the catalog

Csv file with the catalog can be retrieved from the first author on request. The catalog contains the following columns (defined above):

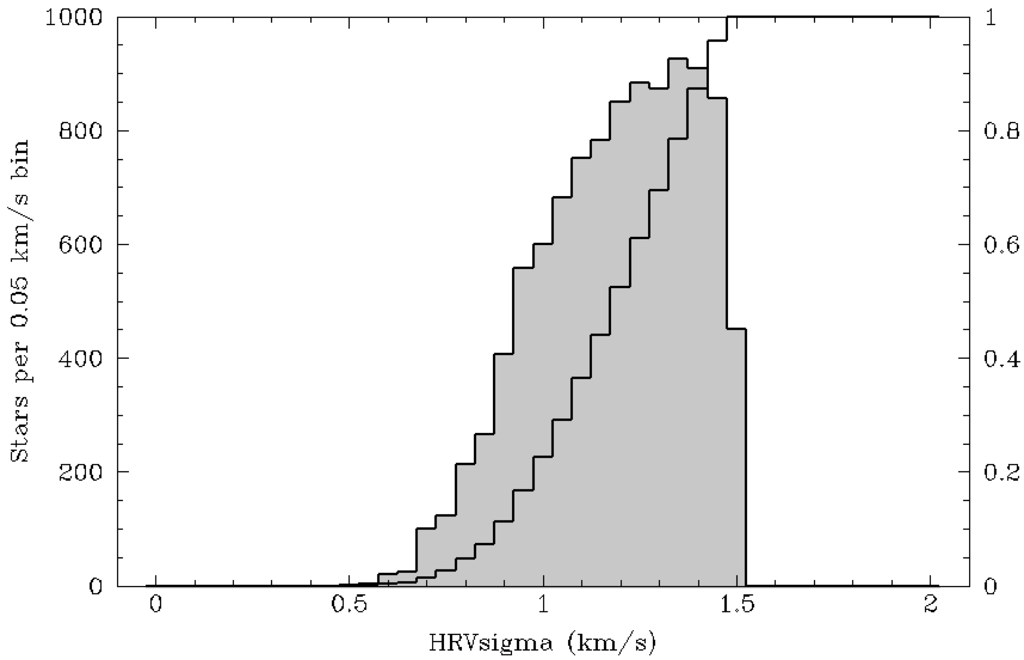

FIGURE 2: Histogram and a cumulative distribution of estimated uncertainties ($HRVsigma$) for stars in the final catalog.

column	acronym	units	type	description
1	2MASSID		string	2MASSid identifier
2	RAVEID		string	RAVEid identifier
3	RAdeg	degrees	float	Right ascension of the object
4	DEdeg	degrees	float	Declination of the object
5	Glon	degrees	float	Galactic longitude of the object
6	Glat	degrees	float	Galactic latitude of the object
7	HRVaverage	km s^{-1}	float	Estimated radial velocity of the object
8	HRVsigma	km s^{-1}	float	Estimated error on radial velocity of the object
9	measurements		integer	Number of measurements used for calculation of items 7 & 8.

4 Characterisation of the catalog

Figure 1 shows the distribution of stars in the catalog as a function of Galactic latitude. RAVE is a Southern sky survey, so most of the stars are in the Southern celestial and so also Galactic hemisphere. Figure 2 shows that the estimated errors of radial velocities for the stars in the catalog are mostly between 1 and 1.5 km s^{-1}.

RAVE collected repeated observations only for a moderate number of stars. Table 2 reports the

TABLE 2: Number of stars in the catalog of secondary RV standards with a given number of observations.

Number of observations	Number of stars
1	0
2	8458
3	535
4	389
5	540
6	242
7	54
8	20
9	17
10	17
11	2
12	3

number of stars with 1..12 observations. which are included in the present catalog of secondary RV standards.

Kordopatis, G., Gilmore, G., Steinmetz, M., et al. 2013, AJ, 146, 134
Matijevič, G., Zwitter, T., Bienaymé, O., et al. 2011, AJ, 141, 200
Matijevič, G., Zwitter, T., Bienaymé, O., et al. 2012, ApJS, 200, 14
Siebert, A., Williams, M.E.K., Siviero, A., et al. 2011, AJ, 141, 187
Steinmetz, M., Zwitter, T., Siebert, A., et al. 2006, AJ, 132, 1645
Zwitter, T., Siebert, A., Munari, U., et al. 2008, AJ, 136, 421