Data Collection	<GAIAESO/batch_16100>
Release Number	<4.1>
Data Provider	<G.Gilmore, S.Randich>
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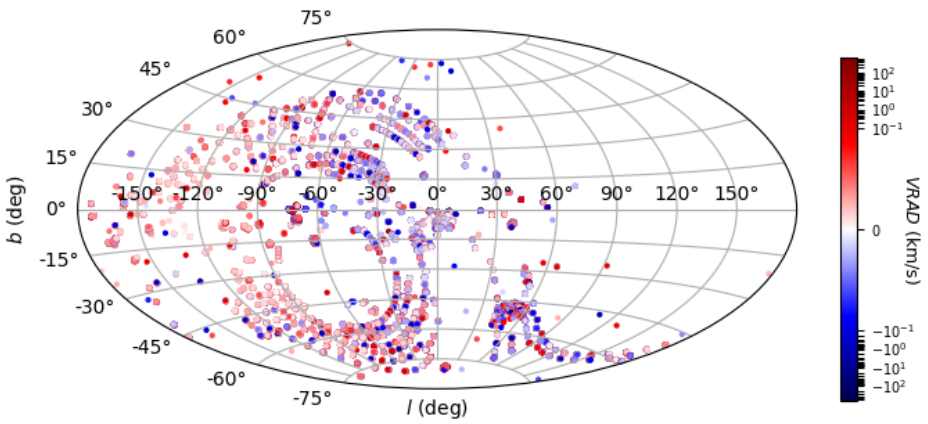
Introduction

Gaia-ESO is a large public spectroscopic survey[1] carried out with FLAMES on the VLT between 2012 and 2018. The Survey targeted $\geq 10^5$ stars (in total 115,000 were observed) to systematically cover all major components of the Milky Way, from halo to star-forming regions in order to provide the first homogeneous overview of the distributions of kinematics and elemental abundances. These measurements by themselves have the power to revolutionise knowledge of Galactic and stellar evolution: when combined with *Gaia* astrometry the survey will quantify the formation history and evolution of young, mature and ancient Galactic populations. With well-defined samples, Gaia-ESO has surveyed the bulge, thick and thin discs and halo components, and open star clusters of all ages and masses. The UVES and Giraffe spectra allow us to quantify individual elemental abundances in each star; yield precise radial velocities for a 4-D kinematic phase-space; map kinematic gradients and abundance - phase-space structure throughout the Galaxy; follow the formation, evolution and, dissolution of open clusters as they populate the disc, and provide a legacy dataset that adds enormous value to the *Gaia* mission and on-going ESO imaging surveys. Joined exploitation of Gaia-ESO spectroscopy and Gaia astrometry has successfully started and 169 papers with "Gaia-ESO" in the title have been published, earning to date 4164 citations. 315 papers have been published with “Gaia-ESO” in the abstract, the other 146 being analyses external to the Gaia-ESO team. All Survey spectra have been processed and analysed, with the final homogenisation of advanced products complete. Overall, the Survey has met and delivered its top-level aims. In this data release we deliver the catalogue of radial velocities for the spectra already released in DR4. The next and final release will deliver the complete final catalogue of results, including stellar atmospheric parameters and chemical abundances, along with the small subset of spectra yet to be released (as detailed in the release description accompanying DR4).

Overview of Observations

The Gaia-ESO Survey (GES)[2] observations relevant to this catalogue are described in the release document accompanying DR4. The sky distribution of the targets is shown in Figure 1 along with their radial velocities which are delivered in this release, DR4.1.



[1] . ESO programmes 188.B-3002, 193.B-0936 described in 2012Msngr.147...25G

[2] . ESO programme 188.B-3002(A,B,C,D,E,F,G,H,I,J,K,L,M,N,O,P,Q,R,S,T,U,V,W)

Figure 1: Distribution of targets in Galactic coordinates, with the colour scale indicating the radial velocity (*VRAD*).

For reference, the summary of GES field type descriptors used for the observations, and in the catalogue contained in this release, is repeated below in Table 1.

Table 1: The list of GES_TYPE header keywords used within the Survey to denote the observation and field types, and their definitions. GES_TYPE is also included as a column in the radial velocity catalogue.

GES_TYPE prefix	**Observation type**
GE	Observed by GES
AR	ESO archive observation (processed by GES reduction pipelines)
GES_TYPE[3]	**Field type**
*_MW	Milky Way programme field
*_MW_BL	Milky Way programme field: bulge field
*_CL	Open Cluster programme field
*_SD_BM	Standard field[4]: FGKM benchmark stars
*_SD_BC	Standard field: Cool benchmark stars
*_SD_BW	Standard field: Warm benchmark stars
*_SD_CR	Standard field: CoRoT field
*_SD_K2	Standard field: Kepler (K2) field (C3)
*_SD_GC	Standard field: globular cluster
*_SD_MC	Standard field: miscellaneous[5]
*_SD_OC	Standard field: calibrating open clusters
*_SD_PC	Standard field: peculiar star templates
*_SD_RV	Standard field: radial velocity standards
*_SD_TL	Standard field: telluric standards

Release Content

The present data release consists of a catalogue containing radial velocities for all objects for which spectra were released in DR4, where available, and subject to minor selection criteria described below..

1. THE CATALOGUE

Radial velocities are released here for 97% of the objects for which spectra were released in DR4. The catalogue contains rows only for those objects which have a recommended VRAD available, therefore a small fraction of objects for which spectra were released in DR4 will not have a

[3] In the following list, '*' denotes either of the strings 'GE' or 'AR', which complete the GES_TYPE keyword.

[4] Standard fields are observed/extracted from the ESO archive for calibration purposes

[5] Stars which no longer meet the definition criteria of their original classification (e.g. BM) and which may otherwise contaminate the selection functions of the observing programmes have been reclassified as miscellaneous.

corresponding row in the catalogue. See Table 3 for a description of the columns of the radial velocity catalogue delivered in this release.

The quality thresholds for inclusion of radial velocities are discussed below. When a star has been observed with more than one instrumental setup and/or with multiple exposures, and more than one spectrum is available per star (i.e., HR10 and HR21, or HR15N and UVES580), only one recommended radial velocity (one row of data) is written to the catalogue, in accordance with the radial velocity homogenisation rules.

Release Notes

Data Reduction and Calibration

The data processing for the GES spectra has been described in the release description accompanying DR4. The instrumental pipeline determination of radial velocities is described below. Radial velocities for hot stars are determined during the stellar parametrization phase by Working Group 13 (WG13; Blomme et al. 2021).

Radial Velocity Pipeline: GIRAFFE
All spectra are iteratively matched against a range of templates to identify the most suitable object-specific templates, thus determining the output radial velocity, and its probability distribution function. Errors are estimated from the curvature of the chi-square surface around the minimum and then empirically corrected to reflect the systematic error floor limit, different for each instrument setup, as further described in Koposov et al. (2011; ApJ,736,146).

Radial Velocity Pipeline: UVES
Radial velocities (RVs) are derived by cross-correlating each spectrum with a grid of synthetic template spectra. The grid is composed of 36 spectra convolved at the FLAMES-UVES spectral resolution. It covers seven effective temperatures ($T_{\rm eff}$ = 3100, 4000, 5000, 6000, 7000, 8000 K), three surface gravities (log(g) = 2.5, 4.0, 5.0), and two values of metallicity ([Fe/H] = 0.0, −1.0). Each spectrum is cross-correlated with all the spectra of the grid, using the IRAF task FXCOR masking the Balmer lines (Hα and Hβ) and regions of the spectra with strong telluric lines. To derive the RV, the cross-correlation function (CCF) with the highest peak is selected and the peak is fitted with a Gaussian function to derive its centroid. This procedure fails for very early-type stars with an effective temperature above the highest temperature of our grid, which are characterised by the presence of no, or very few, absorption lines other than the Balmer lines. Radial velocities for these stars are instead determined by the hot star Working Group, WG13.

To estimate the precision of the RVs, we used the same approach proposed for GIRAFFE by Jackson et al. (2015, A&A, 580, A75) and used for the HR15N set up. We assume that the error on the RVs is the sum in quadrature of two components: the first depends on the properties of the star and the spectra (e.g. VSINi and SNR), while the second depends only on the setup and is associated with the uncertainties on the zero point of the wavelength calibration. We used spectra from multiple exposures of the same stars within an Observing Block to estimate the parameters that allow us to calculate the first component, and spectra of stars with repeated observations in different OBs to estimate the error associated to the wavelength calibration.

After iDR4 (the internal Gaia-ESO release upon which the DR3 catalogue is based), we started to correct the zero point of wavelength calibration using the emission lines from the sky spectrum. After the introduction of this correction, the median error on UVES pipeline RVs is 0.32 km s^{-1}.

Thanks to the observations of radial velocity standard stars, the radial velocities for all of the instrumental setups observed could be shifted to a common zero point as described in the Data Quality section below.

Data Quality

The quality aspects for the GES spectra from which the radial velocities were determined are described in the release description accompanying DR4.

Quality control: Radial Velocity Catalogue

Radial velocities

Radial velocities per object spectrum are determined during the spectral processing, as described above. Quality Control on UVES pipeline radial velocities is performed by the reduction team itself, while the group at Keele University performs QC on the GIRAFFE radial velocities by looking at the nightly spectra. As discussed in Jackson et al. (2015, A&A, 580, A75) and Sacco et al. (2014), for most of the spectra the major source of error is the uncertainty on the zero point of the wavelength calibration. This component was reduced for the the GIRAFFE observations by collecting arc lamp spectrum simultaneously to each OB, but given the limited number of fibres available for UVES (6 to 8 depending on the setup), we decided not to take the simultaneous arc-lamp and perform a standard wavelength calibration using the arc-lamp taken in daytime.

Radial velocities are generally of the expected quality. For GIRAFFE, Jackson et al. (2015) have analysed the achieved precision as a function of SNR, stellar parameters, and vsini; the analysis has shown that the maximum achieved precision is of the order of 0.25 km s^{-1}, matching the initial goal. A lower precision is achieved with UVES (0.32 km s^{-1}), due to the lack of simultaneous calibration exposures.

The range of instrumental setups with which a star is observed, and hence the number of available spectra with associated radial velocities, varies per star. Calibrators, for example, have typically been observed with a broader range of instrumental configurations and will thus have a relatively greater number of radial velocity determinations than a typical field star. Additionally, particular analysis nodes and Working Groups deliver revised estimates of the radial velocities for their targets of interest that they determine during their specialised analysis for the parametrization of these spectra. Thus, as with most of the quantities derived from the spectral analysis, multiple radial velocity results are available per object and these need to be homogenised to produce a single recommended radial velocity per object.

As part of the homogenisation by GES Working Group 15 of the available radial velocities for each star, described in Hourihane et al. (2021, to be submitted) different instrumental setups were compared, and offsets were applied to bring the radial velocities onto a scale with a common zeropoint. The radial velocities from the HR10 setup were used to establish the zeropoint of the radial velocity scale due to their good agreement with the literature values of the Gaia Radial Velocity Standards (Soubiran et al. 2018; see Figure 6), which were observed by GES. Figure 2 shows an example of the cross-match between different instrumental setups and the offset found and applied during homogenisation.

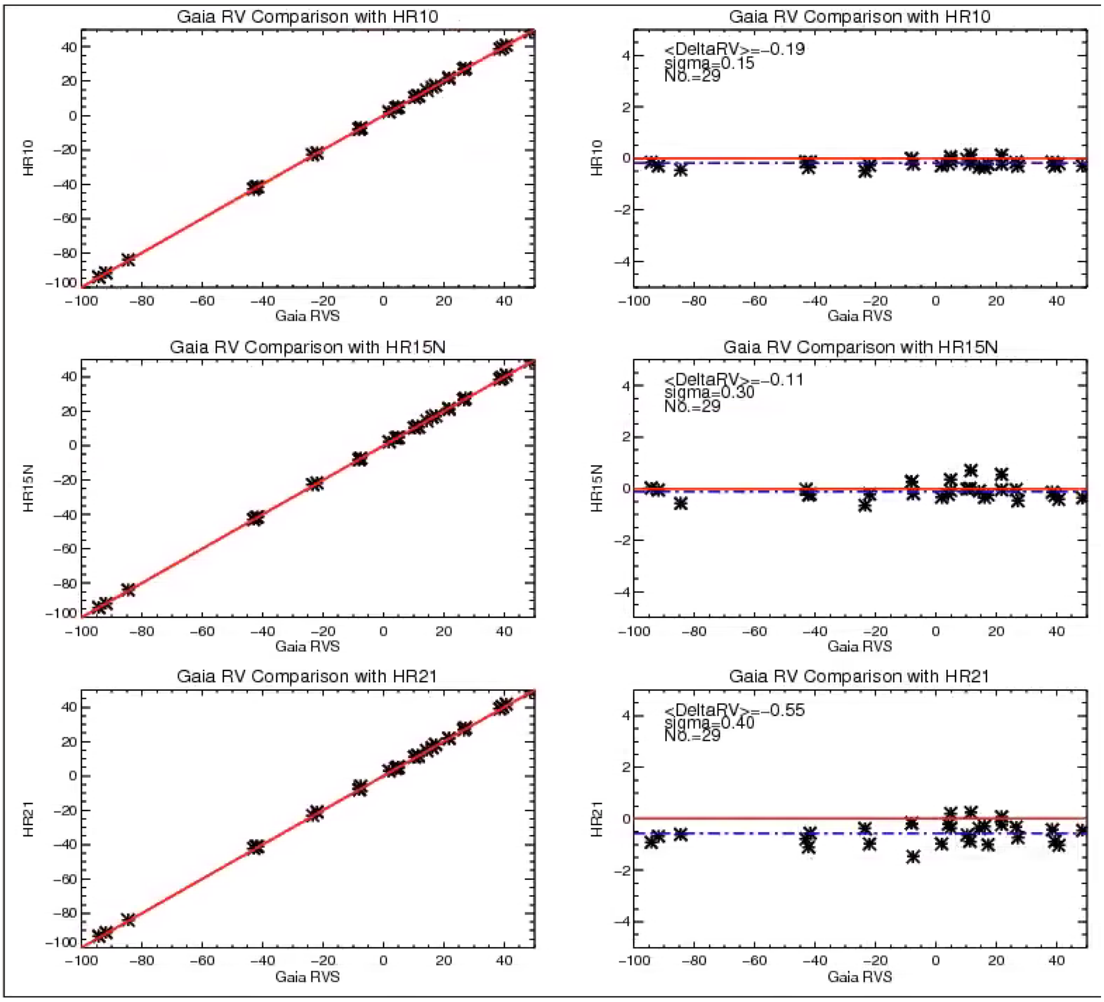


Figure 2: Comparison of radial velocities determined for the Gaia Radial Velocity Standards by the GES pipeline for various Giraffe instrumental setups with the reference values for the same stars from Soubiran et al. (2018).

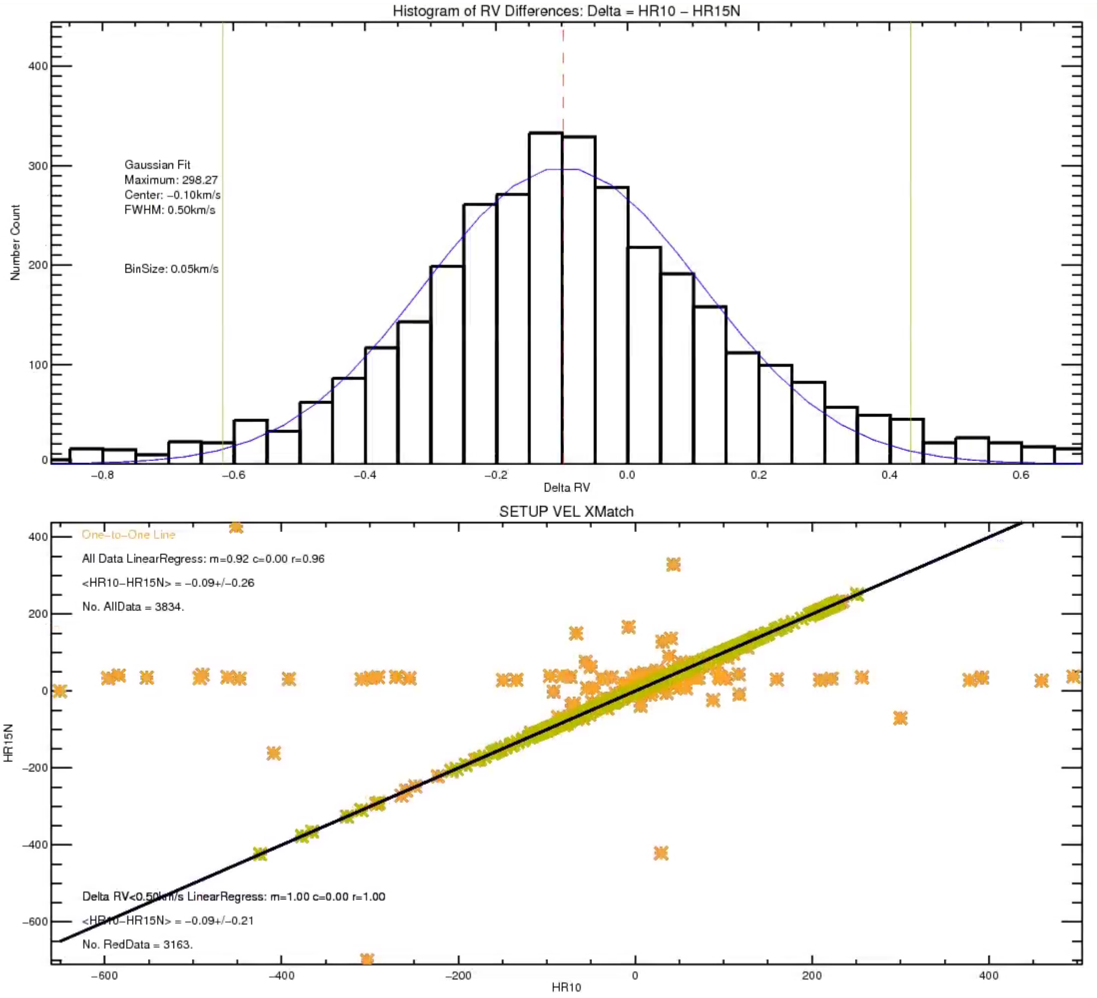


Figure 3: A comparison of the GES radial velocity pipeline results for the stars in common between the Giraffe HR15N and HR10 instrumental setups. The agreement is very good, with the offset between the two scales determined to be -0.09±0.26 km s^{-1}.

In this release (DR4.1), a catalogue is delivered which contains radial velocities for 97% of the targets (OBJECTs) for which spectra were delivered in DR4. The quality criteria applied for selection of radial velocities and spectra are listed below. Note that the abbreviation 'RV' has been used for pipeline radial velocities, but the recommended radial velocity delivered in the catalogue after homogenisation is denoted as 'VRAD'. The VRAD (radial velocity) and E_VRAD (uncertainty on VRAD) distributions for the Cluster and Milky Way samples delivered in this release are shown in Figure 4.

E_VRAD

The radial velocity precision being achieved for the majority of survey targets is well within the required 1 km s^{-1} (see Figure 4). Indeed it reaches below to 0.3 km s^{-1} (our requirement) for cool stars in clusters (see Figure 5 and Jackson et al. 2015). Similarly, very good precision is obtained for UVES (see Sacco et al. 2014).

Quality Criteria:

The radial velocities included in this data release satisfy the following criteria:

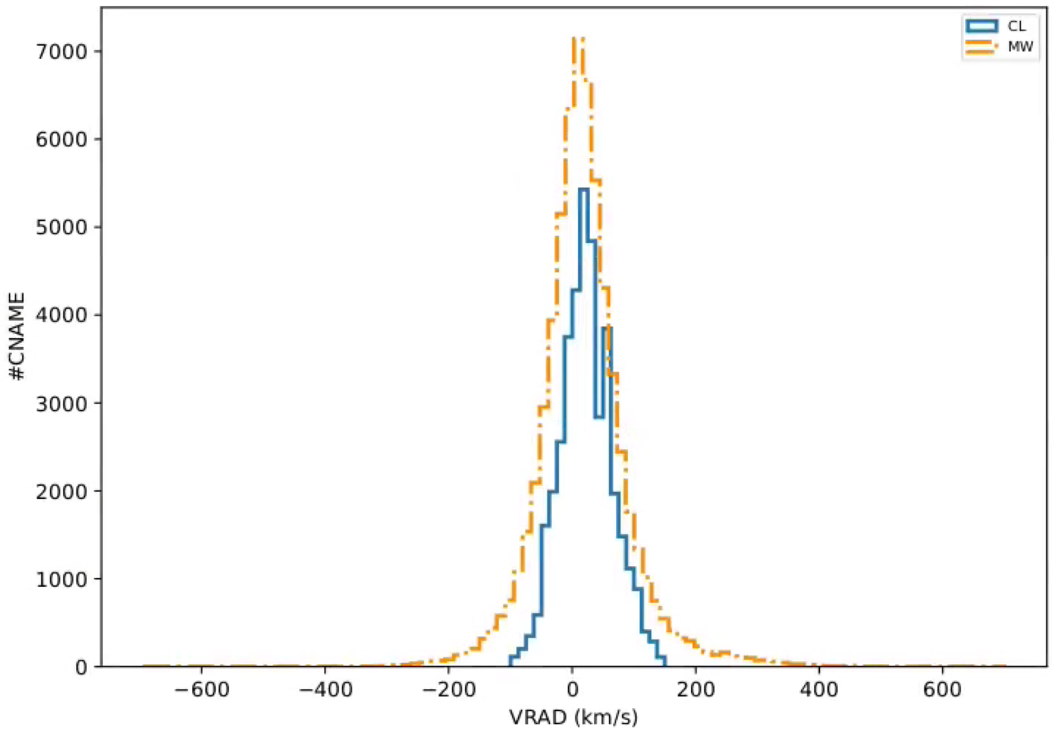
1. The error E_VRAD must have been determined
2. For the clusters: -100 km s^{-1} < VRAD < 150 km s^{-1}
3. For the clusters: The error (E_VRAD) must be below 6 km s^{-1}
4. For the MW and the rest of the sample (includes standard fields): the error (E_VRAD) must be below 20 km s^{-1}

The upper E_VRAD threshold for the clusters has increased from 2 km s^{-1} in the previous DR3 catalogue release to 6 km s^{-1} in this release, DR4.1.

The criteria for inclusion of spectra in the previous DR4 release are repeated here:

1. One best spectrum per object and per instrumental setup, observed and/or processed as part of the Gaia-ESO Survey[6];
2. Spectra are not characterized by obvious reduction issues: spectra suffering from such defects were deprecated during the final analysis cycle.
3. Spectra have all undergone an internal cycle of analysis (the GES iDR6), even if the resulting parameters are not yet released because the work on the final catalogue is ongoing.
4. The pipeline-determined signal-to-noise ratio is not less than two for all the spectra included in DR4 (SNR>=2).
5. UVES spectra have matching upper and lower CCD spectra available. (This prevents those cases where one of the upper/lower pair of spectra gets thrown out for low SNR and the other spectrum of the pair is also low-SNR but above the SNR threshold.)

In DR3 the spectra were subject to stricter SNR constraints (SNR>20 or 30 for most spectra) whereas in DR4, the lower SNR threshold of 2 allows a much larger sample of radial velocities to be delivered here - for 110762 objects, more than four times the DR3 sample. Due to the addition of a large sample of low-SNR spectra, the dispersion of E_VRAD has increased and an upper E_VRAD threshold of 20 km s^{-1} has been introduced for the rest of the sample, apart from the clusters. This threshold still allows delivery of radial velocities for 97% of the objects in the sample.



[6] Includes relevant ESO archival spectra selected for complementarity to science or calibration goals of the Survey and processed as part of the Gaia-ESO Survey but does not include archival spectra observed with instruments other than Giraffe or UVES or spectra observed for internal validation.

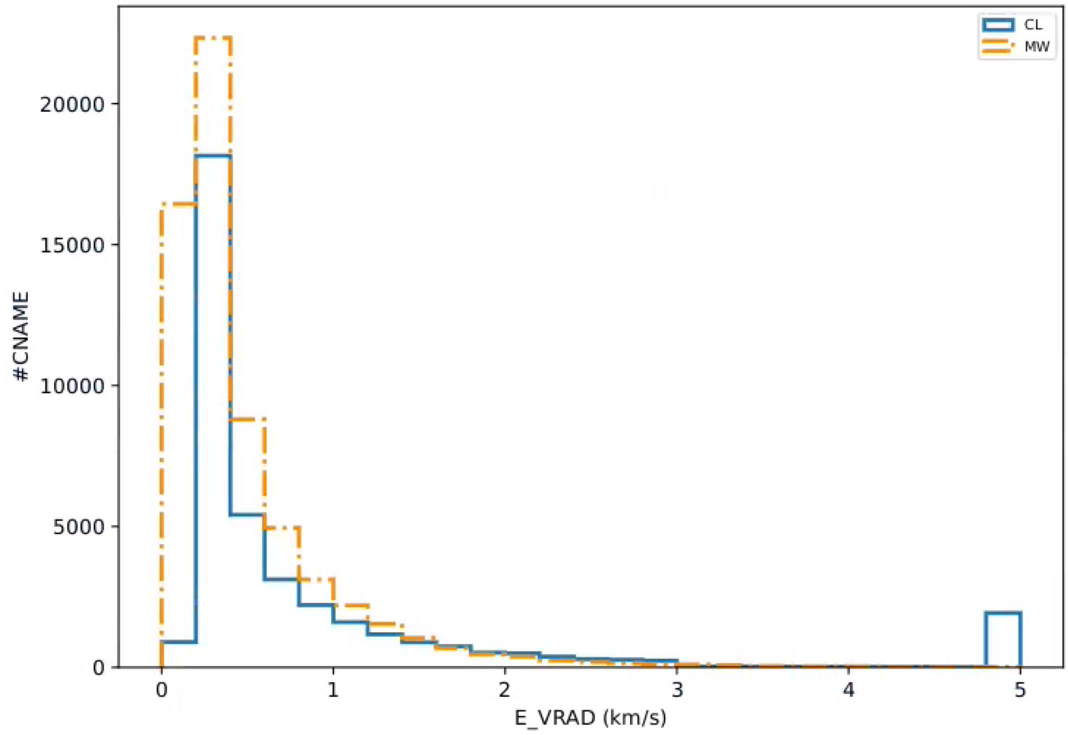


Figure 4: The distributions of radial velocities and uncertainties on the radial velocities included in this release (DR4.1) for the Cluster and Milky Way samples. Note that the bump in E_VRAD at 5 km s^{-1} comes from the hot stars for which radial velocities are more difficult to measure precisely.

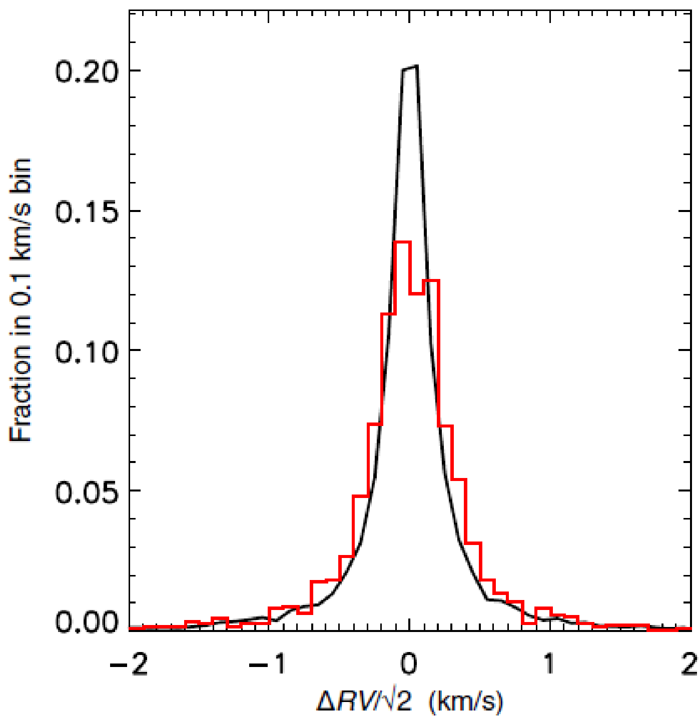


Figure 5: Comparison of the probability density of the observed precision in RV using long (different OBs) and short term (same OB) repeats in the setup HR15N. The black line shows results for short-term repeats (i.e. pairs of observations within the same OB). The red histogram shows results for long-term repeats (i.e. spectra of the same targets but taken from different Obs where individual targets are allocated to different fibres). (Jackson et al. 2015)

Signal-to-Noise Ratio (SNR)
A Signal-to-Noise Ratio ('SNR') column has been included in the catalogue. The SNR gives an indication of the quality of the spectrum from which the radial velocity was determined. The SNR is determined for both UVES and GIRAFFE spectra as part of the pipeline processing. The method is reliable for the majority of the spectra but is liable to fail in a small percentage of cases, for example in the case of peculiar stars. In the catalogue we report the SNR associated with the provenance spectrum for the radial velocity reported. We applied a lower SNR threshold of 2 for the spectra released in DR4 and the associated radial velocities included in DR4.1 to remove obviously unreliable results. Where the VRAD has been determined from a combination of UVES spectra with upper and lower spectra observed simultaneously, the SNR values of the provenance spectra for VRAD have been added in quadrature. Where the VRAD is sourced from the WG13 analysis, which considers a combination of GIRAFFE and UVES spectra, the median SNR of the spectra considered is reported.

Radial Velocity Flags
A new quality flag on the radial velocity has been included. VRAD_FLAG (default value of -1) is raised (value of 1) where inconsistency is detected in the radial velocities determined from spectra of different instrumental setups at the following level: the standard deviation of VRAD measured for different setups is more than 5 times higher than the quoted error. VRAD_FLAG is raised for fewer than 3% of the objects. The number of spectra considered in the determination of VRAD_FLAG is reported in NF_VRAD_FLAG (a value of -1 is returned for NF_VRAD_FLAG where VRAD_FLAG is not calculated, for example where only one radial velocity value from one spectrum is available).

Object identifiers (OBJECT/IDR6NAME)
The ESO 'OBJECT' spectral header keyword corresponds to the 'CNAME' keyword used within the GES project. The DR4 header keyword 'IDR6NAME' denoting the original GES iDR6 CNAME has been propagated to the catalogue for traceability, as a number of object names (CNAMEs) were merged (across setups and in GES vs archival observations) after the beginning of iDR6.

GES_FLD, GES_TYPE and SETUP
These columns, described below and in Table 1, contain additional useful metadata pertaining to the radial velocity provenance spectra.

Known issues

There are no known issues with the data products contained in this release.

Previous Releases

The previous release was DR4 which contains the spectra upon which the current catalogue products are based. The previous catalogue release was DR3. The changes in the present release are as follows:

1. A catalogue of radial velocities is delivered (see Table 3). The number of columns in the catalogue is fewer than in the previous catalogue release (DR3) because the remainder of the advanced products (including stellar atmospheric parameters and chemical abundances) will be released in a subsequent final catalogue release; however, the radial velocity sample is much more extensive than in previous catalogues, with velocities now available for more than 110,000 stars.
2. A new radial velocity quality flag has been introduced (VRAD_FLAG) compared to the previous catalogue released in DR3.
3. The radial velocity offsets used in the homogenisation are now reported in VRAD_OFFSET.
4. Spectra withheld from DR4 for consistency issues with object identifiers in previous releases will now be released in a subsequent release with the final catalogue.

Data Format

Files Types

The catalogue file provided for this release is in the format as specified in version 6 of the *ESO Science Data Products Standard*. The catalogue consists of a FITS file with a primary header unit containing no data and two binary FITS table extensions containing the catalogue data and the provenance file information.

The catalogue column GES_TYPE specifies the type of the Gaia-ESO Survey field (values are listed in Table 1 in the **Overview of Observations** Section). GES_TYPE is intended to provide useful supplementary information on the field for the user.

Catalogue Columns

The catalogue comprises fourteen columns with 110,762 rows of data. Only objects for which spectra were released in DR4 and which have a recommended radial velocity available (97% of the objects in DR4) are included in the catalogue. The columns are described in Table 3.

Table 3: Column names, data format, description and units contained within the Gaia-ESO Survey DR4.1 Radial Velocity Catalogue.

Column	**Data Format**	**Description**	**Units**
OBJECT	16A	GES object name from coordinates, corresponds to OBJECT in header of FITS spectrum	
GES_FLD	12A	GES field name from CASU	
OBNAME	32A	GES object name from OB	
GES_TYPE	26A	GES Classification Designation of Target Programmes for provenance spectra	
SETUP	49A	Grating setups used for radial velocity analysis	
RA	D	Object Right Ascension	deg
DECLINATION	D	Object Declination	deg
SNR	D	Object Signal-to-Noise Ratio in VRAD provenance spectrum	
VRAD	D	Object Radial Velocity	km s^{-1}
E_VRAD	D	Uncertainty on VRAD	km s^{-1}
VRAD_FLAG	I	Quality flag indicating the inter-setup VRAD consistency, raised where inconsistency is detected (default value: -1. Value set to 1 if flag is raised)[7]	
NF_VRAD_FLAG	I	Number of spectra used in VRAD_FLAG determination[8]. A value of -1 indicates VRAD_FLAG has not been calculated.[9]	
VRAD_OFFSET	D	The instrumental setup-dependent offset applied during VRAD homogenisation.	km s^{-1}
IDR6NAME	16A	Original iDR6 GES object name from coordinates	

[7] The VRAD_FLAG was raised (value = 1) if the standard deviation of VRAD measured for different setups is more than 5 times higher than the quoted error.

[8] Note that while the provenance spectra for the reported VRAD values have been included in DR4, not all of the spectra considered when determining the standard deviation of VRAD values may be included in the release as these spectra included internal validation spectra.

[9] For example, where only one spectrum was available.

Acknowledgements

Please use the following statement in your articles when using these data:
Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 188.B-3002.