Properties of Radial Velocities Measurement Based on LAMOST-II Medium-resolution Spectroscopic Observations

R. Wang, A.-L. Luo, J.-J. Chen, Z.-R. Bai, L. Chen, X.-F. Chen, S.-B. Dong, B. Du, J.-N. Fu, Z.-W. Han, J.-L. Hou, Y.-H. Hou, W. Hou, D.-K. Jiang, X. Kong, L.-F. Li, C. Liu, J.-M. Liu, L. Qin, J.-R. Shi, H. Tian, H. Wu, C.-J. Wu, J.-W. Xie, H.-T. Zhang, S. Zhang, G. Zhao, Y.-H. Zhao, J. Zhong, W.-K. Zong, and F. Zuo

1 Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
2 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
3 Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People’s Republic of China
4 Key Laboratory for the Structure and Evolution of Celestial Objects, Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, People’s Republic of China
5 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China
6 Department of Astronomy, Beijing Normal University, Beijing 100875, People’s Republic of China
7 Nanjing Institute of Astronomical Optics, & Technology, National Astronomical Observatories, Chinese Academy of Sciences, Nanjing 210042, People’s Republic of China
8 School of Astronomy and Space Science, Nanjing University, Nanjing 210093, People’s Republic of China
9 Key Laboratory of Modern Astronomy and Astrophysics in Ministry of Education, Nanjing University, Nanjing 210093, People’s Republic of China

Received 2019 May 12; revised 2019 August 12; accepted 2019 August 13; published 2019 October 1

Abstract

The radial velocity (RV) is a basic physical quantity that can be determined through the Doppler shift of the spectrum of a star. The precision of the RV measurement depends on the resolution of the spectrum we used and the accuracy of wavelength calibration. In this work, radial velocities of the Large Sky Area Multi-Object Fibre Spectroscopic Telescope-II (LAMOST-II) medium-resolution (R ~ 7500) spectra are measured for 1,594,956 spectra (each spectrum has two wavebands) through matching with templates. A set of RV standard stars are used to recalibrate the zero point of the measurement, and some reference sets with RVs derived from medium-/high-resolution observations are used to evaluate the accuracy of the measurement. By comparing with reference sets, the accuracy of our measurement can get 0.0277 km s⁻¹ with respect to radial velocities of standard stars. The intrinsic precision is estimated with the multiple observations of single stars, which can be achieved to 1.36 km s⁻¹, 1.08 km s⁻¹, and 0.91 km s⁻¹ for the spectra at signal-to-noise levels of 10, 20, and 50, respectively.

Key words: binaries; spectroscopic – methods: data analysis – techniques: spectroscopic

1. Introduction

The radial velocity (RV) is a basic and key physical quantity in the kinematic and dynamic study of our Galaxy. RVs of stars can be derived from the Doppler shifts of their spectra. Many spectroscopic sky surveys have released large samples of RVs—for example, the Sloan Digital Sky Survey (SDSS)/Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009), SDSS/Apache Point Observatory (APOGEE; Holtzman et al. 2015, 2018; Majewski et al. 2017), Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST)/LAMOST Experiment for Galactic Understanding and Exploration (LEGUE; Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012; Luo et al. 2015), RAdial Velocity Experiment (RAVE; Steinmetz et al. 2006; Kunder et al. 2017), Gaia-ESO Survey (Gilmore et al. 2012), Gaia-Radial Velocity Spectrometer (RVS; Katz et al. 2004; Cropper et al. 2018), High Efficiency and Resolution Multi Element Spectrograph (HERMES)-Galactic Archaeology with HERMES (GALAH; De Silva et al. 2015), etc. These big samples of RVs were obtained through spectra with different resolving power, which provides astronomers useful tools for dissecting and understanding the structure of the Milky Way.

A large sample with consistently measured RVs is a key underpinning for much research work; for example, Geller et al. (2015) use RVs to determine membership of a stellar cluster. Besides, researchers analyzed the RV variations to constrain the stellar pulsation model (Britavskiy et al. 2018) and to determine the properties of the eclipsing binary stars (Helminiak et al. 2019; Martin et al. 2019).

LAMOST started a medium-resolution survey (MRS; L. Chao et al. 2019, in preparation) after its first 5 yr low-resolution survey (Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012; Luo et al. 2015). The new MRS is driven by several scientific motivations (Galactic archeology, time-domain astronomy, star formation, etc.; see details in L. Chao et al. 2019, in preparation). Although contemporary and future space-based projects (such as Gaia, Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014), etc.) will provide new scientific prospect, LAMOST MRS also develops the corresponding observation plan in the Gaia field, TESS field, and Kepler field (Liu et al. 2019) for producing valuable information from medium-resolution spectra, including radial velocities and stellar parameters (L. Chao et al. 2019, in preparation).

The performance of RV measurement is the basis to realize the science goal of the LAMOST MRS survey. The precision of RV measurements from stellar spectra is limited by many aspects, such as spectral resolution, wavelength calibration, spectral type, spectral range, and the measurement methods (Bouchy et al. 2001). In this work, we try to make use of the whole LAMOST MRS spectral information to measure RVs for all type of stars. Also, the MRS spectra of stars with repeat
observations are used to estimate intrinsic precision of the RV measurement for MRS spectra, while some standard stars are used to derive the accuracy of the RV measurement. The paper is organized as follows. LAMOST-II medium-resolution spectroscopic observation and data reduction are described in Section 2. The methods for the determination of RV are presented in Section 3. Calibration and validation results are highlighted in Section 4. Finally, we summarize this work in Section 5.

2. Data

2.1. Observations

LAMOST is a telescope possessing an effective aperture of 4 meters and 5° fields of view, which is located at the Xinglong Observatory, Hebei Province, China. The light of 4000 stellar objects that are simultaneously observed is transmitted to 16 spectrometers through 4000 fibers and then recorded by 32 4K X 4K charge-coupled device (CCD) cameras. The LAMOST spectrograph has two resolving modes: the low-resolution mode of \( R = 1800 \) and the medium-resolution mode of \( R = 7500 \). After the phase one (LAMOST-I) low-resolution survey from 2011 October 24 to 2017 June 16 (Luo et al. 2015), a period of test observation of the MRS for LAMOST phase two (LAMOST-II) began on the 2017 September 1. Until 2018 December 31, 1,597,675 spectra of 281,515 stars from the MRS test observation have been collected, and each spectrum consists of two wavelength bands, i.e., a blue band (4900–5400 Å) and a red band (6300–6800 Å). According to wavelength ranges and the size of the CCD, each pixel width is 0.12 Å (500 Å/4096 pixels). The “footprints” of LAMOST-II MRS test observations are shown in Figure 1. The distribution of the corresponding \( G_{\text{RVS}} \) magnitude adopted from the Gaia DR2 photometer catalog and the distribution of the signal-to-noise ratio (S/N) of the test observations are respectively shown in Figure 2. Hereafter, S/N is defined as an average value in a wavelength band and indicates the S/N per pixel.

2.2. Data Reduction

The MRS spectra are extracted from raw data (CCD images) with the LAMOST reduction pipeline, which is the same processing as that of low-resolution spectra (Luo et al. 2015). The dispersion curves derived from Th–Ar and Sc lamps are used for the wavelength calibration of MRS spectra, which is different from using Cd–Hg and Ar–Ne lamps to carry out wavelength calibration for low-resolution spectra. Appropriate barycentric corrections were applied during the wavelength calibration process. The flux of each spectrum is rectified for both blue and red bands, which means the continua are normalized to “one.” To eliminate the effect of strong emission lines during the calculation of RV, we especially mask the normalized flux higher than 10% of the continuum. For the spectra with S/Ns higher than 10, basic stellar parameters have been calculated using the LAMOST Stellar Parameter pipeline (Wu et al. 2011; Luo et al. 2015). An example of MRS spectra with two wavebands of a star is shown in Figure 3, which include both before and after the continua were normalized.

3. Methods

The basic idea of an RV measurement is to pick out the largest peak from a group of correlation functions, which are calculated between an observed spectrum and each synthetic template of the 2194 Kurucz spectra (Castelli & Kurucz 2004). This full template fitting uses all pixels in all spectral lines rather than a few line centers to reduce the error of wavelength calibration caused by the uncertainty of the dispersion function of gratings. The stellar parameter coverage of the synthetic template grids is shown in Table 1. Both the MRS spectra and synthetic spectra are continuum-normalized using the same method as Lee et al. (2008).

It takes three steps to find the best-fit template and the corresponding Doppler shift for an observed MRS spectrum. The details are presented as follows:

### Table 1

| Variable  | Range          | Step Size |
|-----------|----------------|-----------|
| \( T_{\text{eff}} \) (K) | 3500 ~ 10,000  | 250       |
| \( \log g \) (dex) | 0.0 ~ +5.0 | 0.5       |
| [Fe/H] (dex) | \(-2.5 ~ +0.5\) | 0.5       |

Note. Besides the seven [Fe/H] values in the list, there are two additional values of \(-4.0\) and \(+0.2\) dex.
1. First, an observed spectrum is matched with all synthetic spectra of the grid that shifted with a coarse RV step of 40 km s$^{-1}$ from $-600$ km s$^{-1}$ to 600 km s$^{-1}$. After this step, the rough RV of a spectrum has been decided.

2. Second, the observed spectrum is matched with all synthetic spectra of the grid that shifted with a fine RV step of 1 km s$^{-1}$ in $\pm 60$ km s$^{-1}$ around the optimal solution RV obtained in the above procedure. Then, a Gaussian fitting is done with 10 points around the peak of the correlation function to determine the final RV estimation.

3. For each spectrum, the blue and red wavebands are processed independently, and two RVs (RV$_{\text{blue}}$ and RV$_{\text{red}}$) are obtained. Then when the limit of S/N > 10 is applied to both blue and red wavebands of all spectra, 1,594,956 out of 1,597,675 spectra (each has two single bands) are left. The additional cut is applied to remove the spectra with a large difference between RV$_{\text{blue}}$ and RV$_{\text{red}}$. Figure 4 shows the difference of RVs between blue and red, and we can see that the 1$\sigma$ difference is 9.44 km s$^{-1}$. We use |RV$_{\text{blue}}$ − RV$_{\text{red}}$| > 25 km s$^{-1}$ (close to 3$\sigma$ difference) to carry out the cutting. Finally, 1,531,586 spectra (3,063,172 spectra if a single band is regarded as an individual spectrum) are left.

The first two steps are very computationally intensive for millions of spectra, so we employ the distributed parallel computing platform Spark (Zaharia et al. 2016) to deal with the challenge of this arduous computing task. The total time consuming the RV two-step calculation for LAMOST MRS 3,195,350 single-band spectra is about 10 days using a computing cluster consisting of 15 PCs.

4. Results

4.1. RV Zero-point Calibration

The wavelength of LAMOST MRS spectra is calibrated using Th–Ar and Sc arc lamps, which may shift with time from spanning a long time baseline. A time sequence study with multi-observations is one of the main goals of the MRS, which requires the RV zero point (RVZP) to be fixed using some RV standard stars (RV-STDs). To guarantee the stability of the RVZP, the RV-STDs we plan to use should be proved that their RVs vary within a level of 100 m s$^{-1}$. Many works provided RV-STDs from different survey projects, such as Crifo et al. (2010) who established a list of 1420 RV-STDs candidates, Soubiran et al. (2013, 2018) who compiled an RV-STDs catalog of 4813 stars for Gaia mission, and Huang et al. (2018, hereafter HY18) who presented a catalog of 18,080 RV-STDs selected from APOGEE data.

We pick out 983 RV-STDs from HY18 that have 7820 LAMOST MRS spectra covering all spectrographs and exposures. We compare the RV differences between the observed MRS spectra and the corresponding RV-STDs. Figure 5 shows the overall RV offsets and dispersions for MRS RVs compared with RV-STDs. The RVZP offset of the spectra with Sc lamp-based wavelength calibration is about $-5.99$ km s$^{-1}$ for the blue waveband and $-4.18$ km s$^{-1}$ for the red waveband. The RVZP offset based on Th–Ar lamp is, however, $+0.25$ km s$^{-1}$ and $-0.09$ km s$^{-1}$ for the blue and red wavebands, respectively.

Considering the different situation for individual spectrographs, the RVZPs for each spectrograph with both Sc and Th–Ar lamp-based wavelength calibration is individually calculated and shown in Figure 6. We can see that the RVZPs vary slightly with different spectrographs (“spid” in the figures indicates the ID of the spectrograph). Before 2018 October 19, the Sc lamp is adapted to carry out the wavelength calibration for LAMOST MRS test observation spectra, while the Th–Ar lamp dominates later. In fact, there is no essential difference between using these two lamps, so the wavelength calibration of MRS spectra will be executed by only using the Th–Ar lamp for future observations.

Applying the RVZPs obtained from 7820 spectra of 983 RV-STDs to each exposure, spectrograph, and band, the RVs of all 1,594,956 two-band spectra are recalibrated to remove the offsets. Figure 7 shows the difference between recalibrated RVs of 7820 spectra and RVs from HY18 RV-STDs. We plan to release both the RVs from two wavebands for all spectra before and after the RVZPs correction in the formal data release for different purpose of use. For example, RVs before the correction of RVZPs can be used to shift a spectrum to the rest-frame while the calibrated RVs can be used in study kinematics. Here, we recommend the recalibrated RV of the
blue part because of higher precision and remind readers that using the RV of the red part should be taken cautiously in case of strong Hα emission in the absorption, referring to the “Flagred = 1” in the catalog.

4.2. Parameters of the Best Template

To integrally understand the precision of RV measurement for the LAMOST MRS, the spectral class of targets selected for the MRS test survey should have the same parameter span as the formal MRS survey. The stellar parameter distribution of the best matching templates used to determine RVs is shown in Figure 8. The effective temperature ranges from 3500 to 10,000 K with two peaks at 5000 and 6250 K. The surface gravities mainly concentrate around the value of 4.5 dex corresponding dwarfs, and a large part is also distributed between 2.5 and 3.5 dex corresponding giants and subgiants. The peak of metallicities ([Fe/H]) is −0.5 dex, and the number of stars fell sharply as [Fe/H] was less than −1.0 dex and greater than 0 dex. This distribution of stellar parameters almost covers all kinds of stars for the future formal MRS survey.

4.3. RV Accuracy

To ensure the reliability and accuracy of the RVs of LAMOST MRS spectra, we employ some reference sets with RVs derived from medium-/high-resolution observations for comparison and validation. To obtain reliable results, we only select LAMOST spectra with both S/Nblue ≥ 10 and S/Nred ≥ 10 for comparison. The reference sets we employed are as follows:

1. The HY18 RV-STD catalog. We crossmatch the LAMOST MRS RV catalog with HY18 RV-STD and get 1106 common stars corresponding to 8336 LAMOST spectra.
2. The Gaia RV-STD catalog (Soubiran et al. 2018). We crossmatch the LAMOST MRS RV catalog with Gaia RV-STD and get 52 common stars corresponding to 326 LAMOST spectra.
3. The Apache Point Observatory for Galactic Evolution Experiment DR14 (APOGEE; Holtzman et al. 2015; Majewski et al. 2017). APOGEE is a spectroscopic survey with a median to high resolution of 22,500 in the near-infrared spectral range (λ = 15700–17500 Å).
APOGEE DR14 (DR14; Holtzman et al. 2018) has collected ∼277,000 spectra, predominantly for giant stars. The complete APOGEE DR14 sample has 13,003 stars in common with the LAMOST MRS RV catalog. We neglect the stars flagged by APOGEE as having large RV errors and finally a total of 89,741 spectra with repeated observations are left.

4. RAVE DR5 (Steinmetz et al. 2006; Zwitter et al. 2008; Siebert et al. 2011; Kordopatis et al. 2013; Kunder et al. 2017). RAVE is a spectroscopic survey with a same median resolution of $R = 7500$ as the LAMOST medium resolution, covering the Ca II infrared (IR) triplet region ($\lambda = 8410–8795$ Å) and aims to measure RVs and stellar atmospheric parameters of one million stars using the 1.2 m UK Schmidt Telescope of the Anglo-Australian Observatory. RAVE DR5 (Kunder et al. 2017) has presented 520,781 spectra of 457,588 unique stars. RAVE DR5 has 893 stars, corresponding to 6,449 spectra, in common with the LAMOST MRS RV catalog after the exclusion of outliers.

5. The Gaia-RVS DR2 (Katz et al. 2004; Cropper et al. 2018). Gaia-RVS on the European Space Agency’s Gaia mission is an integral-field spectrograph with a resolving power of 11,500 covering the infrared wavelength range within 8450–8720 Å. Gaia DR2 (Gaia Collaboration et al. 2018; Sartoretti et al. 2018; Katz et al. 2019) published the first RVS measurements, which contain RVs for 7,224,631 stars. The Gaia-RVS RVs catalog has 152,734 stars in common with the LAMOST MRS RV catalog corresponding to 868,663 spectra.

For each case, we use the common star subsets for comparison. The RV residuals derived from the comparison of LAMOST MRS spectra with the reference data sets are shown in Table 2. LAMOST MRS shows a small offset of 0.0277 and −0.2797 km s$^{-1}$ with respect to two RV standard stars catalogs: HY18 RV-STD and Gaia RV-STD. It shows a nearly constant offset with respect to Gaia RV stars. For S/Ns higher than 100, the accuracy shows unexpected fluctuations because the number of spectra
decreases rapidly. The lack of sufficient common star samples led to the residuals of RV of LAMOST and Gaia RV-STD that are not stable as others. Both the LAMOST MRS RV estimation and the reference sets contribute to the error bar in Figure 9. Most of the error of RV residuals decrease with S/N increasing. The RV differences between LAMOST and RAVE are larger than APOGEE and Gaia because the resolution of RAVE spectra is less than APOGEE’s and Gaia-RVS’s.

Figure 10 shows the accuracy varies as a function of G\textsubscript{RVS}. The RV residuals stay at a very low level for stars with G\textsubscript{RVS} of 9, even to 15 mag, except the RV residuals between LAMOST and RAVE become upturned at the G\textsubscript{RVS} bright end. According to the other reference sets, the reason for “upturning” probably comes from the inaccuracy of RAVE RV estimation. Besides, LAMOST RVs exhibit an inconsistency with the RVs of Gaia RV-STD when G\textsubscript{RVS} is at 11 mag and when the median RV residuals reach about 0.9 km s\(^{-1}\) at G\textsubscript{RVS} = 11 mag for the blue part.

Figure 11 shows the accuracy varies as a function of the color index \(b_{p} - r_{p}\) employed from the Gaia DR2 photometric catalog. LAMOST MRS RVs are very consistent with the reference catalogs for the stars with \(b_{p} - r_{p}\) higher than 0.5 mag. It needs to be pointed out that RAVE RVs are inconsistent with LAMOST RVs and other RV reference sets in many situations, such as stars with \(b_{p} - r_{p}\) around 0.5 and 2.0 mag.

### 4.4. RV Precision

The precision of RVs is estimated based on the RV measurements of multiple observations in different epochs for the same stars. Figure 12 shows the distribution of the number of repeated observations with measurable RVs. The statistical estimator used to access the precision is:

\[
\epsilon = \sqrt{\frac{N}{N-1} \sum_{i=0}^{N} (R_{i} - \overline{R}_V)^2},
\]

where \(N\) is the number of repeated observations and \(\overline{R}_V\) is the mean value of \(R_{i}\).

The main factor affecting the precision of an RV measurement of a spectrum is its S/N. Figure 13 shows the precision of RVs as a function of S/N for the LAMOST MRS spectra with S/N \(\geq 10\). In Figure 13, the top panel displays RVs measured by the blue parts of the spectra (RV\textsubscript{blue}), the middle panel is the RV\textsubscript{red} derived from the red part, and the bottom is the mean values of RV\textsubscript{blue} and RV\textsubscript{red}. The precision improves as the S/N increases. For spectra of the blue parts with S/N\textsubscript{blue} equal to 10, the precision is 1.36 km s\(^{-1}\) and improves to less than 1.0 km s\(^{-1}\) when S/N\textsubscript{blue} increases to higher than 30. The precision of RV\textsubscript{blue} is better than RV\textsubscript{red} not only because there are more absorption lines in the blue part of the most type of spectra than that in the red part but also because the lines in the blue part are sharper.

### 4.5. An RV Catalog for the LAMOST MRS Test Survey

We provide an RV catalog for the LAMOST MRS test survey containing 1,594,956 spectra. The information in the catalog
includes: Gaia identifier (Gaia_source_id), the identifier for corresponding star (starid), LAMOST spectral identifier medid, observation information (obsdate, spid, and lamp), right ascension (R.A.), declination (decl.), S/N of the spectra, RVs without RVZP correction (RVblue and RVred), corresponding RV errors (ERVblue and ERVred), RVs with RVZP corrected (RVblue,cali and RVred,cali), correlation coefficient between the observation and the best-fit template (corr), effective temperature ($T_{\text{eff}}$), surface gravity (log g) and metallicities ([Fe/H]) of the best-fit template, the quality flag for accessing RVs, the corresponding Gaia photometric magnitude ($G_{\text{RVS}}$), and the color index ($bp-rp$). A description of columns of the LAMOST RV catalog is shown in Table 3. The full catalog can be accessed online at the China-VO PaperData repository (Wang & Luo 2019).
5. Summary

The test observation for the LAMOST MRS ($R = 7500$) began on 2017 September 1, and a total of 1,594,956 spectra (each has two bands) of stars with $S/N$ higher than 10 was collected until 2017 December 31. We measure RVs for the data set by cross-correlation method and corrected the zero point of the RVs based on a set of standard stars (RV-STD). Then, we evaluate the properties of RVs of LAMOST spectra by comparing with five reference sets: HY18 RV-STD, Gaia RV-STD, APOGEE DR14, RAVE DR5, and GAIA DR2. The RVs of the LAMOST MRS test survey performed well; the accuracy is 0.03 km s$^{-1}$ compared to HY18 RV-STD and 0.28 km s$^{-1}$ compared to Gaia RV-STD. The precision of the measurement can be obtained through repeat observation and is mainly dominated by the $S/N$—for example, the RV precision is from 1.36 to 0.91 km s$^{-1}$ as the $S/N$ levels from 10 to 50.

We provide an RV catalog that is available online at the China-VO PaperData repository (Wang & Luo 2019).

Table 3

| Col. | Name                        | Description                                                                 |
|------|-----------------------------|----------------------------------------------------------------------------|
| 1    | `Gaia_source_id`            | `Gaia` source id by crossmatching `Gaia` DR2                                |
| 2    | starid                      | ID for corresponding star based on the R.A. and decl., with the form of LAMOST Jdddmms ssddmms |
| 3    | medid                       | LAMOST spectral ID, with the form of Date-PlateID-SpectrographID-FiberID-MJM-PiplineVersion |
| 4    | medid_blue                  | LAMOST spectral ID for the blue part                                         |
| 5    | medid_red                   | LAMOST spectral ID for the red part                                          |
| 6    | obsdate                     | Date of the observation                                                      |
| 7    | spid                        | Spectrograph ID                                                             |
| 8    | lamp                        | Lamp used for wavelength calibration                                        |
| 9    | R.A.                        | R.A. of J2000 (°)                                                           |
| 10   | Decl.                       | Decl. of J2000 (°)                                                          |
| 11   | $S/N_{blue}$                | Signal-to-noise ratio of the blue part                                       |
| 12   | $S/N_{red}$                 | Signal-to-noise ratio of the red part                                        |
| 13   | RV$_{blue}$                 | RV measured from the blue part without zero-point correction (km s$^{-1}$)   |
| 14   | ERV$_{blue}$                | Error of RV measured from the blue part (km s$^{-1}$)                       |
| 15   | RV$_{red}$                  | RV measured from the red part without zero-point correction (km s$^{-1}$)    |
| 16   | ERV$_{red}$                 | Error of RV measured from the red part (km s$^{-1}$)                        |
| 17   | RV$_{blue,cali}$            | RV with zero-point corrected for the blue part (km s$^{-1}$)                |
| 18   | RV$_{red,cali}$             | RV with zero-point corrected for the red part (km s$^{-1}$)                 |
| 19   | corr$_{blue}$               | Correlation coefficient between the blue part and the best-fit template     |
| 20   | corr$_{red}$                | Correlation coefficient between the red part and the best-fit template      |
| 21   | $T_{eff}_{blue}$            | Effective temperature of the best-fit template of the blue part (K)         |
| 22   | log $g_{blue}$              | Surface gravity of the best-fit template of the blue part (dex)             |
| 23   | [Fe/H]$_{blue}$             | [Fe/H] of the best-fit template of the blue part (dex)                       |
| 24   | $T_{eff}_{red}$             | Effective temperature of the best-fit template of the red part (K)          |
| 25   | log $g_{red}$               | Surface gravity of the best-fit template of the red part (dex)              |
| 26   | [Fe/H]$_{red}$              | [Fe/H] of the best-fit template of the red part (dex)                       |
| 27   | Flag$_{blue}$               | Quality flag for accessing RV derived from the blue part, 0 for good, else 1 for bad |
| 28   | Flag$_{red}$                | Quality flag for accessing RV derived from the blue part, 0 for good, else 1 for bad |
| 29   | G$_{rh}$                    | $G$ magnitude employed from `Gaia` DR2 photometric catalog. (mag)            |
| 30   | bp–rp                       | bp–rp color index employed from `Gaia` DR2 photometric catalog. (mag)        |

Note. The full catalog can be accessed online at the China-VO PaperData repository (Wang & Luo 2019).
formal MRS, we will put enough RV-STDs in the input catalog of LAMOST MRS observations to correct the zero point for each spectrometer in each exposure.

This work is supported by the National Key Basic Research Program of China (grant No. 2014CB845700), the National Natural Science Foundation of China (grant No. 11390371), and China Scholarship Council, Key Research Program of Frontier Sciences, CAS (grant No. QYZDY-SSW-SLH007). The Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by National Astronomical Observatories, Chinese Academy of Sciences.

Software: Numpy (Oliphant 2006), Scipy (Jones et al. 2001), Matplotlib (Hunter 2007), Pandas (McKinney 2011), Astropy (Astropy Collaboration et al. 2013), Spark (Zaharia et al. 2016).

**ORCID iDs**

A.-L. Luo @ https://orcid.org/0000-0001-7865-2648

**References**

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33

Bouchy, F., Pepe, F., & Queloz, D. 2001, A&A, 374, 733

Britavskiy, N., Pancino, E., Tsybinb, V., Romano, D., & Fossati, L. 2018, MNRAS, 474, 3344

Castelli, F., & Kurucz, R. L. 2004, A&A, 419, 725

Cifio, F., Jasni&szlig;ewicz, G., Souihir, C., et al. 2010, A&A, 524, A10

Cropper, M., Katz, D., Sartoretti, P., et al. 2018, A&A, 616, A5

Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 1197

Deng, L.-C., Newberg, H. J., Liu, C., et al. 2012, RAA, 12, 735

De Silva, G. M., Freeman, K. C., Bland-Hawthorn, J., et al. 2015, MNRAS, 449, 2604

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1

Geller, A. M., Latham, D. W., & Mathieu, R. D. 2015, AJ, 150, 97

Gilmore, G., Randich, S., Asplund, M., et al. 2012, Msgr, 147, 25

Helminiak, K. G., Tokovinin, A., Niemczura, E., et al. 2019, A&A, 622, 114

Holtzman, J. A., Hasselquist, S., Shetrone, M., et al. 2018, AJ, 156, 125

Holtzman, J. A., Shetrone, M., Johnson, J. A., et al. 2015, AJ, 150, 148

Huang, Y., Liu, X.-W., Chen, B.-Q., et al. 2018, AJ, 156, 90

Hunter, J. 2007, CSE, 9, 90

Jones, E., Oliphant, T., Peterson, P., et al. 2001, SciPy: Open Source Scientific Tools for Python v1.2.0, http://www.scipy.org/

Katz, D., Munari, U., Cropper, M., et al. 2004, MNRAS, 354, 1223

Katz, D., Sartoretti, P., Cropper, M., et al. 2019, A&A, 622, A205

Kordopatis, G., Gilmore, G., Steinmetz, M., et al. 2013, AJ, 146, 134

Kunder, A., Kordopatis, G., Steinmetz, M., et al. 2017, AJ, 153, 75

Lee, Y. S., Beers, T. C., Sivarani, T., et al. 2008, AJ, 136, 2022

Liu, N., Fu, J.-N., Zong, W., et al. 2019, RAA, 19, 75

Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2015, RAA, 15, 1095

Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2017, AJ, 154, 94

Martin, D. V., Triaud, A. H. M. J., Udry, S., et al. 2019, A&A, 624, 68

McKinney, W. 2011, pandas: powerful Python data analysis toolkit v0.24.0, http://pandas.sourceforge.net/

Oliphant, T. 2006, CSE, 9, 10

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2014, Proc. SPIE, 9143, 914320

Sartoretti, P., Katz, D., Cropper, M., et al. 2018, A&A, 616, A6

Siebert, A., Williams, M. E. K., Siviero, A., et al. 2011, AJ, 141, 187

Souihir, C., Jasni&szlig;ewicz, G., Chemin, L., et al. 2013, A&A, 552, A64

Souihir, C., Jasni&szlig;ewicz, G., Chemin, L., et al. 2018, A&A, 616, A7

Steinmetz, M., Zwitter, T., Siebert, A., et al. 2006, AJ, 132, 1645

Wang, R., & Luo, A. 2019, LAMOST Medium Resolution Survey Radial Velocity Catalog v1.0, China-VO, doi:10.12149/101088

Wu, Y., Luo, A.-L., Li, H.-N., et al. 2011, RAA, 11, 924

Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377

Zaharia, M., Xinn, R. S., Wendell, P., et al. 2016, Commun. ACM, 59, 56

Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P., & Deng, L.-C. 2012, RAA, 12, 723

Zwitter, T., Siebert, A., Munari, U., et al. 2008, AJ, 136, 421

---

**Figure 13.** Precision of RV derived from repeated observations as a function of the S/N. The top panel shows the precision for the RV derived from the blue part (RV\textsubscript{blue}), the middle panel shows the precision for the red part (RV\textsubscript{red}), and the bottom shows the mean value of RV\textsubscript{blue} and RV\textsubscript{red}. The error bar step of the S/N is 10.