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Validation of LAMOST stellar parameters with the PASTEL catalog

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Abstract The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) published its first data release (DR1) in 2013, which is currently the largest dataset of stellar spectra in the world. We combine the PASTEL catalog and SIMBAD radial velocities as a testing standard to validate stellar parameters (effective temperature $T_{\rm eff}$, surface gravity $\log g$, metallicity $[{\rm Fe/H}]$ and radial velocity $V_{\rm r}$) derived from DR1. Through cross-identification of the DR1 catalogs and the PASTEL catalog, we obtain a preliminary sample of 422 stars. After removal of stellar parameter measurements from problematic spectra and applying effective temperature constraints to the sample, we compare the stellar parameters from DR1 with those from PASTEL and SIMBAD to demonstrate that the DR1 results are reliable in restricted ranges of $T_{\rm eff}$. We derive standard deviations of 110 K, 0.19 dex and 0.11 dex for $T_{\rm eff}$, $\log g$ and $[{\rm Fe/H}]$ respectively when $T_{\rm eff} < 8000\,{\rm K}$, and 4.91 $\rm km\,s^{-1}$ for $V_{\rm r}$ when $T_{\rm eff} < 10\,000\,{\rm K}$. Systematic errors are negligible except for those of $V_{\rm r}$. In addition, metallicities in DR1 are systematically higher than those in PASTEL, in the range of PASTEL $[{\rm Fe/H}] < -1.5$.

Key words: stars: fundamental parameters — astronomical data bases: catalogs — astronomical data bases: surveys

1 INTRODUCTION

The formation and evolution of galaxies is one of the key astrophysical subjects at the moment. The Milky Way provides us with a unique example to carry out a detailed and comprehensive study. The study of stars — the fundamental building blocks of galaxies, allows us to map the Galaxy and deepen our understanding of galactic formation and evolution. Recent large stellar spectroscopic surveys such as the RAdial Velocity Experiment (RAVE; Steinmetz 2003), the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009) and the APO Galactic

Evolution Experiment (APOGEE; Allende Prieto et al. 2008) have revolutionized our understanding of the Galaxy, though they all have their advantages and limitations. Sizes of the stellar spectroscopic samples are limited due to Galactic extinction and instrumental limitations. The Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST), a Wang-Su Reflecting Schmidt Telescope located at the Xinglong Station of National Astronomical Observatories, Chinese Academy of Sciences, emerged in response to the pressing need for a more complete spectroscopic sample of the Galaxy (Cui et al. 2012). Its large aperture (effective aperture of 3.6–$4.9\,\mathrm{m}$) and wide field of view (20 square degrees) coexist, benefiting from a special design that allows it to simultaneously obtain 4000 spectra from 3700 to $9100\,\text{Å}$ in a single exposure at resolution $R \sim 1800$.

The LAMOST Experiment for Galactic Understanding and Exploration (LEGUE) survey aims to provide a larger spectroscopic sample than ever before to investigate kinematics and chemical abundances of the Galaxy (Zhao et al. 2012; Deng et al. 2012). This survey consists of three components: the spheroid survey, the Galactic anticenter survey and the disk survey. Each component has its own target selection strategy. The spheroid survey will observe over 2.5 million stars in the North Galactic Cap and the South Galactic Cap selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000). The anticenter survey aims to sample the region $150^\circ < l < 210^\circ$ and $-30^\circ < b < 30^\circ$, with input targets selected from the Xuyi photometric survey (Zhang et al. 2014). The disk survey will cover the low latitude part $-20^\circ < b < 20^\circ$ and will also use the Xuyi photometric survey in conjunction with the third US Naval Observatory CCD Astrograph Catalog (UCAC3; Zacharias et al. 2010) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) to prepare input targets. By the time our study is conducted, LAMOST has produced the largest stellar spectroscopic sample to date, which demonstrates the capability of high efficiency in acquiring spectra provided by the unique design.

After two years of test observations following its national acceptance in 2009, the LAMOST pilot survey began on 2011 October 24 and was completed on 2012 June 24 (Luo et al. 2012). The subsequent regular survey started on 2012 September 28 and finished its first-year mission on 2013 June 15. In 2013 August, the first data release (DR1) of LAMOST became available to the Chinese astronomical community and international colleagues, including spectral products from the pilot survey and the first-year regular survey (Luo et al. 2015). The DR1 consists of 2 204 696 spectra of stars, quasars, galaxies and some other objects, the nature of which could not be established due to the poor quality of their spectra. To extract stellar parameters from such a large amount of spectra, the LAMOST stellar parameter pipeline (LASP) was developed (Wu et al. 2011, 2014). It employs the ULySS software (Koleva et al. 2009) to analyze LAMOST spectra and derives a full set of stellar atmospheric parameters ($T_{\rm eff}, \log g, [\mathrm{Fe/H}]$) and radial velocities through minimizing the χ^2 value between the observed spectrum and a model spectrum generated by an interpolator that is based on the ELODIE library (Prugniel & Soubiran 2001; Prugniel et al. 2007). Some of the radial velocities in DR1 are LASP measurements, and the rest are products of the 1D pipeline (Luo et al. 2012) when LASP measurements are not available. There are 1 944 329 stellar spectra in DR1 catalogs, but only 1 061 918 of these spectra have yielded a full set of stellar atmospheric parameters and radial velocities due to quality control. Only late A or FGK type stars with g-band signal-to-noise ratio $\mathrm{S/N} \geq 15$ or $\mathrm{S/N} \geq 6$ for bright and dark nights respectively are allowed to be input into LASP (Wu et al. 2014).

The reliability of these spectral products has to be investigated before any further applications are made. The PASTEL catalog provides a good testing standard. It is a catalog of stellar atmospheric parameters for tens of thousands of stars compiled by surveying bibliographies in the main astronomical journals and the CDS database. Determination of most stellar parameters in the catalog is based on analysis of high-resolution and high-$\mathrm{S/N}$ spectra, though some recent precise $T_{\rm eff}$ measurements that are not based on high-resolution spectra are also included (Soubiran et al. 2010). The majority of stars in the catalog are FGK stars. 90% of the stars in the catalog have V magnitude brighter than $9.75\,\mathrm{mag}$. Internal errors of their parameters are 1.1%, $0.10\,\mathrm{dex}$ and $0.06\,\mathrm{dex}$ for T_{eff}, $\log g$ and $[\mathrm{Fe/H}]$, respectively. In addition, the catalog provides information such as the equatorial coordinates and B, V, J, H, K magnitudes retrieved from the SIMBAD database (Wenger et al. 2000), on which our cross-identification of common targets is based.

We first perform a coarse cross-identification of the DR1 catalogs and the PASTEL catalog and then gradually refine the sample. Detailed information about the validation sample resulted from the cross-identification and the subsequent refinements will be given in Section 2. Subsequently, we compare the stellar parameters from the DR1 catalogs with those from the PASTEL catalog and the SIMBAD database. Results of the comparison are shown and discussed in Section 3. Finally, we summarize our work in Section 4.

2 THE SAMPLE FOR VALIDATION

2.1 Cross-identification

In order to compare stellar parameters from DR1 and PASTEL, we first identify common objects in the DR1 catalogs and the PASTEL catalog. The PASTEL catalog is regularly updated. The version that we use is 17-May-2013, and consists of 52 045 entries of 26 657 individual stars. Due to the offsets in positions of the bright stars observed with LAMOST, we expand the search radius to 10 arcsec. We carefully check the common entries given by the loose position criteria according to the consistency of the photometry data in the DR1 catalogs and the PASTEL catalog and images of targets from the SIMBAD database. After removal of false positives, we obtain a raw sample of 422 stars.

2.2 Stellar Parameters in the Sample

Stellar atmospheric parameters and radial velocities of more than 300 stars in the sample are available for stellar types A, F, G and K in catalogs that are part of DR1. Only radial velocity measurements are available in the DR1 catalogs for the remaining stars. A total of 420 stars in the sample have T_{eff} measurements in the PASTEL catalog, while $\log g$ and $[\mathrm{Fe/H}]$ are only available for about 150 stars in the sample. That causes a deficiency in testing standards for DR1 $\log g$ and $[\mathrm{Fe/H}]$ measurements. We also retrieve radial velocities for 323 stars in the sample from the SIMBAD database for further analysis.

For some PASTEL stars that have multiple measurements, we remove the very old (published before 1990) measurements that deviate from the more recent ones, and we average the remaining measurements as adopted values. Thus, each star in the comparison sample has a unique testing standard. For DR1 stars we retain every entry when multiple measurements are available in the catalogs. We notice that some of the DR1 stellar parameters show great deviation from their testing standards through a tentative comparison. We select these potential outliers with the criteria

$$|T_{\mathrm{eff}}(\mathrm{DR1}) - T_{\mathrm{eff}}(\mathrm{PASTEL})| \geq 1000\,\mathrm{K}\,,$$

$$|\log g(\mathrm{DR1}) - \log g(\mathrm{PASTEL})| \geq 0.5\,\mathrm{dex},$$

$$|[\mathrm{Fe/H}](\mathrm{DR1}) - [\mathrm{Fe/H}](\mathrm{PASTEL})| \geq 0.5\,\mathrm{dex}\,,$$

or

$$|V_{\mathrm{r}}(\mathrm{DR1}) - V_{\mathrm{r}}(\mathrm{SIMBAD})| \geq 20\,\mathrm{km\,s^{-1}}$$

for further inspection. We retrieve DR1 spectra of these potential outliers for careful examination and find some of these spectra were obtained under poor observation conditions, which might have caused problems in determination of the stellar parameters. Spectra with low $\mathrm{S/N}$ (i.e. $\mathrm{S/N} < 7$) yield poor estimates of stellar parameters. Some spectra with bad pixel masks leave little information

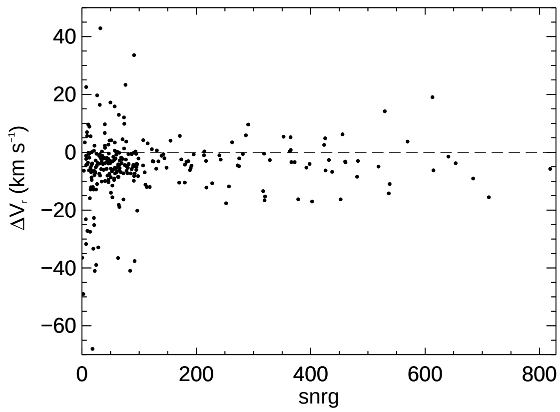

Fig. 1 Precisions of DR1 $V_{\rm r}$ as compared with those from the SIMBAD database depend on the g-band $\rm S/N$, where $\Delta V_{\rm r}$ is defined to be $V_{\rm r}(\rm DR1) - V_{\rm r}(\rm SIMBAD)$, and $snrg$ is the g-band $\rm S/N$ extracted from the DR1 catalogs.

for stellar parameter measurements, therefore the results from these broken spectra are not reliable. In addition to the quality of spectra, we examine the validity of cross-identification of these potential outliers. We find that some stars residing in binaries or star clusters are prone to effects from the problem of fiber mispointing. In consideration of position offset ($\sim 4'' - 9''$) during a LAMOST observation, these stellar parameters may belong to another star in a crowded field, which is responsible for the dramatic deviation in the stellar parameters. We also find a few mistakes in the PASTEL catalog by checking the original bibliographies. The catalog has mismatches between stellar parameters of KIC 5524720 and those of TYC 3125-2594-1, between stellar parameters of TYC 2667-624-1 and those of TYC 2267-624-1, and between stellar parameters of SAO 201781 and those of HD 201781.

Before we remove all these outliers, it is necessary to investigate how the $\rm S/N$ affects precisions of DR1 stellar parameters. We remove all outliers mentioned above except for the low-$\rm S/N$ ones. The fact that the majority of the sample are bright stars results in a lack of low-$\rm S/N$ statistics that are required to investigate the dependence of parameter precisions on the $\rm S/N$, which is obvious in Figure 1. 85% of the DR1 measurements have g-band $\rm S/N \geq 20$, for those whose $V_{\rm r}$ testing standards are available in the SIMBAD database. It is unrealistic to draw conclusions about which $\rm S/N$ range our following comparison results will hold. However, we expect that for a sample with lower $\rm S/N$, derived precisions of DR1 measurements will be poorer. Finally, we remove the remaining low-$\rm S/N$ ($\rm S/N < 7$) outliers as well.

Discarding problematic spectral products excludes impacts from other factors, and highlights how precisions vary for stars with different spectral types. We group the DR1 measurements into three effective temperature bins: $T_{\rm eff} < 8000\,\rm K$, $8000\,\rm K \leq T_{\rm eff} < 10\,000\,\rm K$ and $T_{\rm eff} \geq 10\,000\,\rm K$. In order to avoid ambiguity, we use different grouping strategies for different bins; we group the DR1 measurements into the $T_{\rm eff} < 8000\,\rm K$ bin only when both their corresponding PASTEL effective temperatures and the DR1 effective temperatures satisfy $T_{\rm eff} < 8000\,\rm K$; for the other two bins, we accept measurements when their corresponding PASTEL effective temperatures or the DR1 effective temperatures fall within the temperature ranges. Since there are only a handful of measurements in the two high temperature bins, we manually examine each of them and find that there is no duplicate occurrence in these two bins. We find that most DR1 stellar atmospheric parameters of stars hotter than $8000\,\rm K$ show a great deviation from the testing standards (see Fig. 2). The $V_{\rm r}$ measurements

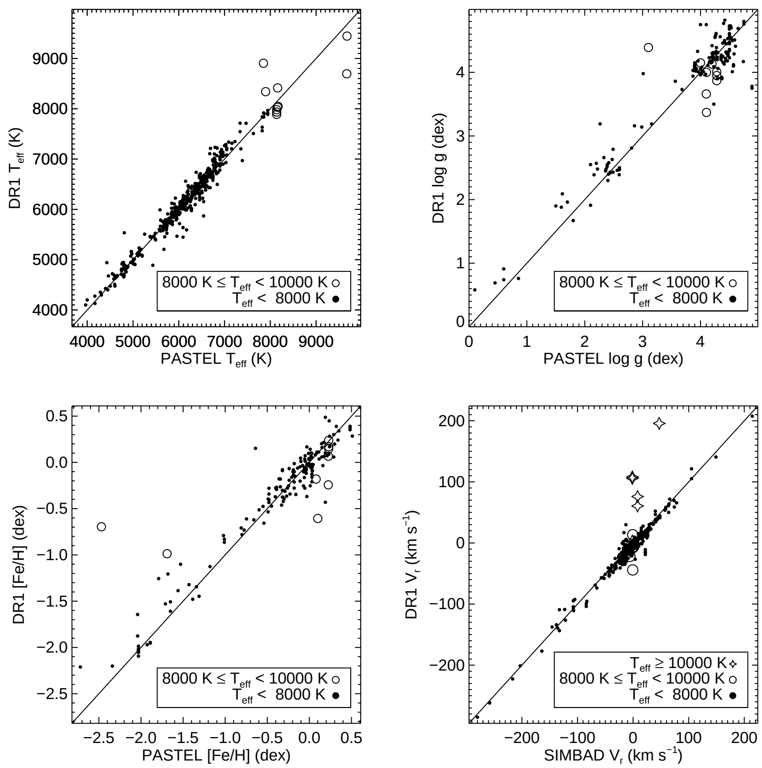

Fig. 2 Tentative comparison of stellar parameters from DR1 with those from PASTEL and SIMBAD after discarding problematic measurements. Filled circles indicate measurements in the $T_{\rm eff} < 8000\,{\rm K}$ bin, open circles represent measurements in the $8000\,{\rm K} \leq T_{\rm eff} < 10\,000\,{\rm K}$ bin and open stars are for measurements in the $T_{\rm eff} \geq 10\,000\,{\rm K}$ bin.

in the $8000\,{\rm K} \leq T_{\rm eff} < 10\,000\,{\rm K}$ bin still show moderate accuracy as compared to the SIMBAD radial velocities. Finally, we confine our sample to an effective temperature range of $T_{\rm eff} < 8000\,{\rm K}$ for validation of $T_{\rm eff}$, $\log g$, [Fe/H], and another effective temperature range of $T_{\rm eff} < 10\,000\,{\rm K}$ for validation of $V_{\rm r}$, where $T_{\rm eff}$ here stands for the effective temperature of both DR1 and PASTEL.

2.3 Internal Scatter of the DR1 Stellar Parameters

Now that we have obtained a clean sample, the next step is to combine the multiple measurements in the DR1 catalogs for individual stars which have corresponding testing standards available in the PASTEL catalog and in the SIMBAD database. When a star was observed more than once, we remove relatively low-S/N measurements that show significant offsets from the others, and then adopt the mean value of the remaining measurements. Note that there were only a few low-S/N measurements left after we removed those outliers in Section 2.2. We retrieve 176 multiple $T_{\rm eff}$ measurements for 73 stars, 48 multiple $\log g$ measurements for 19 stars, 48 multiple [Fe/H] measurements for 19 stars and 178 multiple $V_{\rm r}$ measurements for 73 stars to validate our choice of their "mean" values. The DR1 internal scatters of multiple measurements are shown in Figure 3 by taking the adopted stellar parameters as fiducials. The internal errors as measured using standard deviations of Gaussian

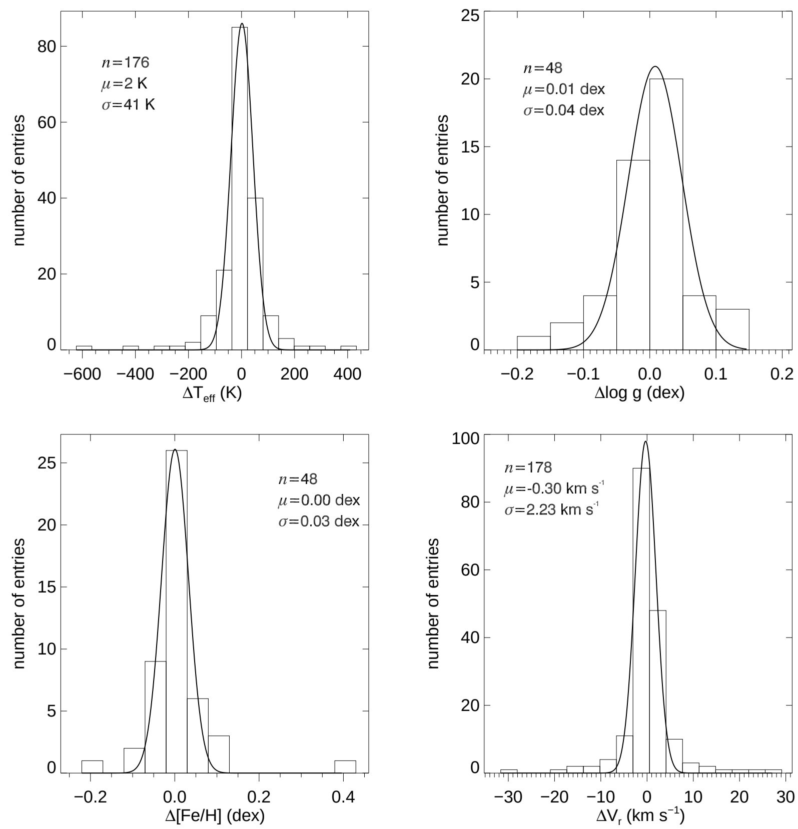

Fig. 3 Internal scatter associated with multiple measurements of stellar parameters derived from DR1. Internal scatter is defined by $\Delta P = P_{\rm mul} - P_{\rm adop}$, where P is one of the four stellar parameters, "mul" stands for multiple measurements in DR1 and "adop" represents the adopted "mean" value of the multiple measurements. In all panels, n is the number of multiple measurements, μ is the mean of the Gaussian fit and σ is the standard deviation of the Gaussian fit.

fits are $41\,{\rm K}$, $0.04\,{\rm dex}$, $0.03\,{\rm dex}$ and $2.23\,{\rm km\,s^{-1}}$, for $T_{\rm eff}$, $\log g$, $[{\rm Fe/H}]$ and $V_{\rm r}$, respectively. Our adopted stellar parameters appear to be reasonable "mean" values of multiple measurements since there are only a few measurements that show a great deviation from the adopted value.

3 VALIDATION OF STELLAR PARAMETERS

After removal of spectral products from poor quality spectra and misidentified entries, we applied different temperature constraints to the sample, because the DR1 $V_{\rm r}$ measurements have a good enough accuracy over the high temperature range. Eventually, after combining multiple DR1 measurements, we derived a clean and well-established sample of 306 stars for $T_{\rm eff}$ comparison, 121 stars for $\log g$ comparison, 121 stars for $[{\rm Fe/H}]$ comparison and 277 stars for $V_{\rm r}$ comparison.

Figure 4 displays, from top to bottom, the comparison results of $T_{\rm eff}$, $\log g$, $[{\rm Fe/H}]$ and $V_{\rm r}$, respectively. Systematic errors and standard deviations listed in Table 1 are calculated through Gaussian fits.

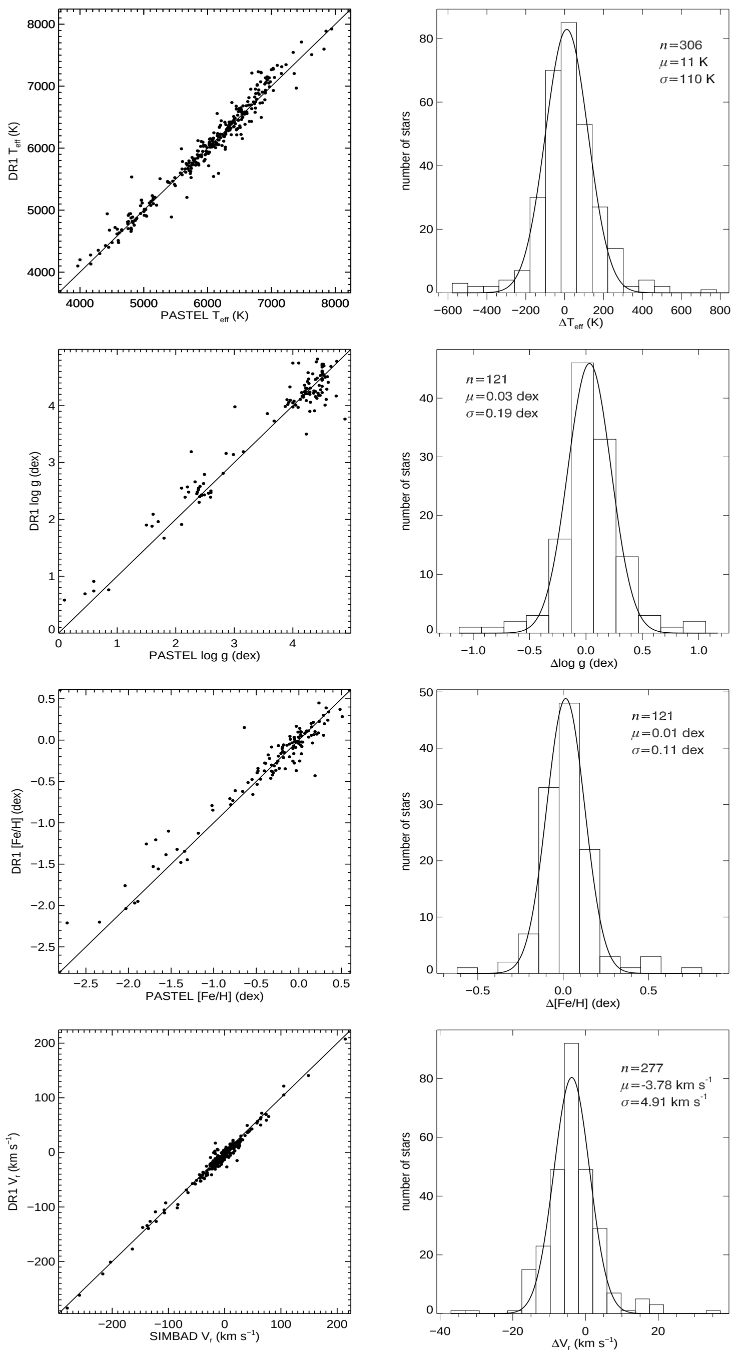

Fig. 4 Comparison of stellar parameters from DR1 with those from the PASTEL catalog and the SIMBAD database for individual stars in the clean sample. The offsets of the stellar parameters are defined as $\Delta P = P(\mathrm{DR1}) - P(\mathrm{PASTEL/SIMBAD})$, where P is one of the four stellar parameters. In the four panels of the right column, n is the number of stars, μ is the mean of the Gaussian fit and σ is the standard deviation of the Gaussian fit.

Table 1 Precisions of the DR1 Stellar Parameters for Individual Stars

	$T_{\rm eff}$	$\log g$	[Fe/H]	$V_{\rm r}$
Number of stars	306	121	121	277
Systematic error	11 K	0.03 dex	0.01 dex	$-3.78\,{\rm km\,s^{-1}}$
Standard deviation	110 K	0.19 dex	0.11 dex	$4.91\,{\rm km\,s^{-1}}$

Systematic errors of stellar parameters are negligible except for that of $V_{\rm r}$. Since radial velocities in the SIMBAD database are collected from different literatures, systematic biases of these measurements are expected to be canceled out. Thus, a systematic error of $-3.78\,{\rm km\,s^{-1}}$ should be taken into account when $V_{\rm r}$ is used. We also find that DR1 metallicities of metal-poor stars (i.e. PASTEL $[{\rm Fe/H}] < -1.5\,{\rm dex}$) are systematically higher than metallicities obtained from high-resolution spectral analysis; statistical analysis of 12 stars in this region gives an overestimation of $0.23\,{\rm dex}$. Stellar parameters from DR7 of SDSS also show similar behavior (Xu et al. 2013). One should exercise caution when using these derived metallicities. Metallic lines for these metal-poor stars are so weak that spectral noise could dominate over these spectral regions. We speculate that such an overestimation might somehow be caused by the significant spectral noise.

Lee et al. (2008) showed that in an effective temperature range of $4500\,{\rm K} \leq T_{\rm eff} \leq 7500\,{\rm K}$, precisions of stellar atmospheric parameters derived by the SEGUE Stellar Parameter Pipeline (SSPP; Beers & Lee 2012) are $141\,{\rm K}$, $0.23\,{\rm dex}$ and $0.23\,{\rm dex}$ for $T_{\rm eff}$, $\log g$ and $[{\rm Fe/H}]$, respectively, based on a comparison with analysis of high-resolution spectra. These statistics are comparable to the standard deviations listed in Table 1. These similarities are not surprising because both SEGUE and LEGUE are medium-resolution spectroscopy surveys, and in addition their techniques used to derive stellar parameters share some similarities such as template matching methods. DR1 has achieved similar precisions but provided a much larger dataset compared with SEGUE.

4 SUMMARY

We perform cross-identification of the DR1 catalogs and the PASTEL catalog. We set a search radius of 10 arcsec to avoid missing the bright stars with position offset. We then remove false positives and obtain a preliminary sample of 422 stars. With this sample we make a tentative comparison and select some potential outliers for further inspection. Finally, we discard results from problematic spectra, risky cross-identifications and a few misidentifications in the PASTEL catalog itself. We obtain an effective temperature range $T_{\rm eff} < 8000\,{\rm K}$ for validation of $T_{\rm eff}$, $\log g$ and $[{\rm Fe/H}]$, and another effective temperature range $T_{\rm eff} < 10\,000\,{\rm K}$ for validation of $V_{\rm r}$, because we do not expect that the DR1 measurements have equally good precisions in all effective temperature ranges. We derive standard deviations of 110 K, 0.19 dex and 0.11 dex for $T_{\rm eff}$, $\log g$ and $[{\rm Fe/H}]$ respectively when $T_{\rm eff} < 8000\,{\rm K}$, and 4.91 ${\rm km\,s^{-1}}$ for $V_{\rm r}$ when $T_{\rm eff} < 10\,000\,{\rm K}$. The DR1 stellar parameters show no systematic offsets except for $V_{\rm r}$ but have overestimates of $[{\rm Fe/H}]$ at the low metallicity tail. We are looking forward to more observations of PASTEL stars by LAMOST in the future, which will provide us with a larger sample to evaluate the accuracy of LAMOST stellar parameters.

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