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# Test observations that search for metal-poor stars with the Guoshoujing Telescope (LAMOST)

Hai-Ning Li[1,2], Gang Zhao[1], Norbert Christlieb[3], A-Li Luo[1], Jing-Kun Zhao[1], Yong-Heng Zhao[1], Jian-Jun Chen[1] and Zhong-Rui Bai[1]

[1] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; *lhn@nao.cas.cn*; *gzhao@nao.cas.cn*
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany

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**Abstract** Metal-deficient stars are regarded as fossils of the early generation of stars and therefore make crucial observational targets related to stellar astrophysics. They provide fundamental information and insights on properties of the very early stage of the chemical history of the Galaxy and have been investigated for decades. The unique design of the Guoshoujing Telescope (LAMOST), such as its large field and multi-object observational capability, enables it to be an excellent tool for searching for these metal-poor stars in the Milky Way. This work reports the result of test observations which search for metal-poor stars with LAMOST, during which nine candidate metal-poor stars with [Fe/H] $\leq -1.0$ were newly detected based on the low-resolution spectroscopic observations of the LAMOST commissioning data. The sample of stars demonstrates the efficiency of selecting from the input catalog, as well as the ability of LAMOST to enlarge the sample of metal-poor stars in the Milky Way. Furthermore, the sample of stars could be used for future calibrations of the LAMOST stellar parameter pipeline.

**Key words:** Galaxy: stellar content — surveys — stars: Population II

## 1 INTRODUCTION

It is generally recognized that the average metallicity of the Galaxy increases with its age, and therefore studies of metal-poor ([Fe/H] $\leq -1.0$) [1], very metal-poor ([Fe/H] $\leq -2.0$) and extremely metal-poor ([Fe/H] $\leq -3.0$) stars offer us a glimpse at the earliest phase of Galactic history (Beers & Christlieb 2005, and references therein). By studying the chemical composition of metal-poor stars, it is possible to indirectly observe the range of supernovae nucleosynthesis yields of the early Galaxy, and also to ultimately reach the limits that constrain primordial nucleosynthesis expected for certain cosmological models.

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[1] The notation of [A/B]= $\log(N_{\rm A}/N_{\rm B})_{\star} - \log(N_{\rm A}/N_{\rm B})_{\odot}$ is used here, where $N_{\rm A}$ and $N_{\rm B}$ are the number densities of elements A and B respectively.

Various studies in related fields of metal-poor stars have been performed. Detailed abundance analyses have been carried out to identify different classes of abundance patterns of Galactic metal-deficient stars and to explore the nature of the first generation of stars (Ryan et al. 1996; Aoki et al. 2007; Lai et al. 2008; Cohen et al. 2008). Statistical studies on the metallicity distribution function of the Galactic halo (Ryan & Norris 1991; Carollo et al. 2007; Ivezić et al. 2008; Schörck et al. 2009) have gradually revealed the chemical enrichment history of the Galactic halo. Other properties, such as the kinematics of local metal-deficient field stars (Chiba & Beers 2000), the (sub)structure of the Galactic halo (Bell et al. 2008), and the density profile of the Galaxy (Jurić et al. 2008), have also been investigated.

Increasing the sample of metal-poor stars is key to these investigations, and numerous efforts have been made through generations of surveys with that aim. Starting from the first effort by Bond (1970) to carry out systematic searches of metal-poor stars in the Galaxy, the number of discovered very metal-poor and extremely metal-poor star candidates has grown substantially, thanks in large part to the HK survey of Beers et al. (1992) and the more recent Hamburg/ESO survey (HES) of Christlieb et al. (2008). High-resolution follow-ups to these surveys (McWilliam et al. 1995; Norris et al. 1996; Cayrel de Strobel et al. 2001; Norris et al. 2001; François et al. 2003; Cohen et al. 2004; Cayrel et al. 2004; Barklem et al. 2005; Norris et al. 2007; Cohen et al. 2008; Bonifacio et al. 2009) have verified more than 200 extremely metal-poor stars including the discovery of the currently most iron-deficient stars, the hyper-metal-poor (HMP) HE 1327−2326 with [Fe/H] $= -5.4$ (Frebel et al. 2005), and HE 0107−5240 with [Fe/H] $= -5.3$ (Christlieb et al. 2002). With the development of new methods for estimating metallicities and other stellar atmospheric parameters from moderate-resolution spectra, spectroscopic observations from the Sloan Sky Digital Survey (SDSS) (York et al. 2000) are now becoming another potential reservoir of very metal-poor and extremely metal-poor stars. These surveys make it possible to reach deep inside the Galactic halo, and to gather larger and more statistically complete samples for further and deeper investigations; however, current knowledge about the most metal-deficient stars is still limited, and this area of research requires a future, larger spectroscopic survey to enlarge the sample.

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST)[2] project, now called the Guoshoujing Telescope, started its commissioning period in 2009, aiming to test its technical stability and capability to achieve its scientific aims. Its 4 m aperture enables it to obtain the spectra of objects as faint as $20.5^{\rm m}$ with an exposure time of 1.5 h. With a 5° field of view, it provides 4000 optical fibers which enable simultaneous observations of 4000 objects. The special design of LAMOST (Li & Zhao 2009a,b) and its high spectral acquisition rate allow it to carry out spectroscopic surveys related to stellar abundances and Galactic chemical evolution (Zhao et al. 2006), in which searching for metal-poor stars is one important aspect. Furthermore, unlike former surveys that searched for metal-poor stars (e.g., the Hamburg/ESO Survey (HES) or HK survey), with LAMOST, it is possible to directly identify candidate metal-poor stars in the survey mode, and greatly enhance the efficiency of collecting the candidate sample. Therefore, it is quite important that test observations which search for metal-poor stars should be carried out before LAMOST starts conducting its regular survey.

Here we report the test observations from searching for metal-poor stars with LAMOST during LAMOST's commissioning observations in 2009. An introduction to the sample and the related data processing method are presented in Sections 2 and 3, respectively, and a brief summary and discussion are presented in Section 4.

## 2 THE SAMPLE

To make the metal-poor star survey more efficient, it is necessary to optimize the potential candidates to be observed during the LAMOST survey. The preliminary input catalog of the LAMOST metal-

[2] See *http://www.lamost.org/website/* for more detailed information and progress of LAMOST.

poor star survey was compiled from the photometric catalog of stars in SDSS-DR7 (Abazajian et al. 2009). The basic selection criteria are as follows:

1. $g' < 18$ (to avoid too faint objects);
2. $0.1 < (g' - r')_0 < 1.0$ (to mainly include F-, G-, and K-type stars);
3. $-10° < \mathrm{declination} < 70°$ (lower limit refers to LAMOST's observational limit while the upper limit aims to avoid possible vignetting);
4. $20° < |b|$ (to avoid strong extinction);
5. $5\,\mathrm{kpc} < |Z|$ (to enhance the fraction of the halo population, and note that the distance was estimated based on the photometric parallax relation given by Jurić et al. 2008).

Test observations of objects selected from the metal-poor star survey input catalog were carried out by LAMOST during the observations of three commissioning fields including A1775, M67, and ssy05_1 (one in the high Galactic latitude area), in 2009 February, March, and December, including 75 of the sample stars, in one exposure and with the low-resolution mode of $R \sim 1000$. However, due to the fact that some of the objects in our input catalog are relatively faint and that the LAMOST facility is still in the commissioning phase, a considerable fraction of the spectra have rather low S/N ($< 15$) due to the relatively low optical efficiency or problems with the fiber positioning system; hence these objects were excluded from our investigation. This left us with a sample of 19 objects which we investigated further.

## 3 DATA REDUCTION AND ANALYSIS

The raw data were first reduced with the LAMOST 2D pipeline (Luo et al. 2004), then the 1D spectra were obtained through each individual fiber, and the sky background was subtracted, all the while correcting for variations in relative throughput and applying a wavelength calibration. The metallicity values, [Fe/H], along with other stellar parameters, were then estimated from the extracted 1D spectra.

To ensure the determination of the [Fe/H] values of the 19 sample stars with low-resolution spectra obtained by LAMOST, we have carried out several different methods of measurement for a comparison and discussion. It should be noted that for our targets, only LAMOST blue arm spectra were necessary and therefore analyzed and measured.

The first method is an application of an updated version of the methods described by Beers et al. (1999) which included more calibration stars, and thus resulted in better coverage of stellar parameter space, especially for stars with the lowest metallicities. This method obtains [Fe/H] values by making use of the measured KP index, which measures the strength of the Ca II K line and is defined in Beers et al. (1999), and the HP2 index, which measures the strength of the Balmer $H_\delta$ line. This was the same method used in a series of works by HES (e.g., Schörck et al. 2009; Li et al. 2010 in preparation) considering the halo giant star sample or metal-poor turnoff star sample. The metallicity derived with this method is listed in the second column of Table 1.

The second method that we have adopted is the most direct way of computing the stellar parameters, i.e., to compare the observed spectra with synthetic template spectra, which is called a grid. In our case, Kurucz's NEWODF model of stellar atmospheres (Castelli & Kurucz 2003) was used to compute the synthetic spectra of our template grid. The validity of this method depends on the density of the grid and how the grid is produced. Instead of linear interpolations of the model spectrum, parameters are calculated by using smaller and smaller cubes in each step of the iteration so as to improve the interpolation. More details of this method can be found in Luo et al. (2008), and the measured metallicities are listed in Column (3) of Table 1.

The third method used for comparison is Neural Network approach based on the RR (real spectra) regression model (ANNRR) adopted by the SEGUE Stellar Parameter Pipeline, i.e., the SSPP (Lee et al. 2008a,b). This measurement is based on a set of selected stars from the SEGUE plates used in training. The corresponding results are listed in the last column of Table 1.

**Table 1** Comparisons of [Fe/H] Values Measured by Different Methods

| LAMOST ID | [Fe/H] (Beers et al.) | [Fe/H] (Kurucz) | [Fe/H] (ANNRR) |
|---|---|---|---|
| A1775−F1213 | −0.5 | −1.2 | −1.3 |
| A1775−F3211 | −0.8 | −1.1 | −0.8 |
| A1775−G1908 | −0.6 | — | −0.7 |
| A1775−G2808 | −0.3 | −1.2 | −1.3 |
| A1775−H0512 | −1.0 | −1.3 | −1.5 |
| A1775−H1714 | −0.3 | −0.7 | −1.6 |
| M67−G0303 | −0.5 | −1.2 | −1.6 |
| M67−G0310 | −0.5 | −0.8 | −1.8 |
| M67−G1020 | −1.0 | −0.9 | −1.3 |
| M67−G1813 | — | −0.6 | −0.5 |
| M67−G1816 | −0.8 | −1.0 | −0.7 |
| M67−G2407 | −2.7 | −0.1 | −1.0 |
| M67−H0302 | −0.7 | −1.7 | −1.5 |
| M67−H0920 | −0.3 | −1.1 | −1.5 |
| M67−H1725 | −0.4 | −0.2 | −1.5 |
| M67−H2523 | −0.5 | −1.8 | −1.0 |
| ssy05_1−E1613 | −0.2 | −0.9 | −1.0 |
| ssy05_1−H3919 | −0.8 | −0.1 | −0.8 |
| ssy05_1−F1905 | −0.9 | −0.3 | −0.6 |

Notes: LAMOST does not yet have a uniform designation for observed targets, hence we assign an ID for each target with the format of "LAMOST field name"− "corresponding LAMOST fiber unit." Also due to the constraints of the methods (noisy spectra or unclear features, etc.), two spectra failed to get measured by the first two methods.

As shown in Table 1, although the size of the sample is limited, it is still helpful for us to give a rough comparison of the three methods that were tested in our sample of stars. It is clear that different methods derive different values of metallicities, however, for most of the sample stars, metallicities derived by the three methods agree with each other to a certain degree. Specifically, the last two methods (the third and fourth columns in Table 1) show better agreement than the one based on Beers et al. (1999)'s method. We have, therefore, checked the spectra and noticed that for most of the stars having the above discrepancy, the Ca II K line is somehow mixed with other features and hence probably leads to a KP index being higher than the true value (as can be seen from the spectra in Fig. 1), which can directly raise the measured [Fe/H] values in Beers et al. (1999) and make it not as reliable as the other two. Furthermore, although the ANNRR method provides reasonable estimations, it is currently based on a training sample of SEGUE spectra rather than LAMOST spectra (which will only be available when LAMOST has accumulated enough results for this purpose), so we finally decided to adopt the metallicity estimated by the template grid for the following discussion.

After the above step, a visual inspection of the LAMOST spectra was carried out to identify and reject spectra of two objects that were too noisy to provide useful information. This left us an "accepted" sample containing 17 stars (with their spectra shown in Fig. 1). The results of the parameter measurement are listed in Table 2. Note that although they are located in the fields of the well studied open cluster M67 (e.g., Schiavon et al. 2004), after careful identification in terms of the coordinates and magnitudes, some of our targets have proved to be field stars without spectroscopic observations by the SDSS.

## 4 SUMMARY AND DISCUSSION

During LAMOST's commissioning observations, we have obtained low-resolution ($R$ ∼1000) spectra of 19 objects in the input catalog for the LAMOST metal-poor star survey. Except for two objects which were rejected upon visual inspection, stellar parameters were derived for 17 sample stars from

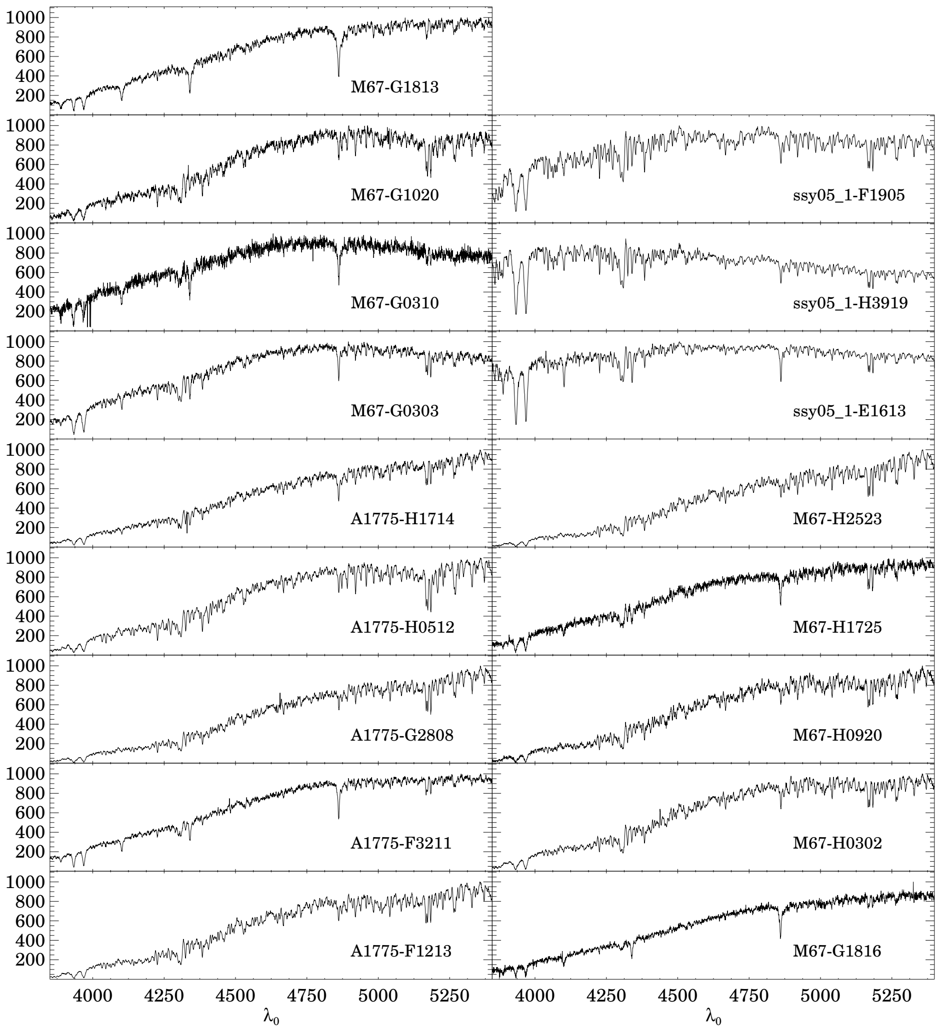


**Fig. 1** LAMOST spectra of the 17 sample stars discussed in the text and Table 2. The ID system is as described in Table 1. Note that only the LAMOST blue arm spectra are shown, and the continuum has not been subtracted.

the LAMOST metal-poor survey's input catalog. The spectra that have been processed for analysis have sufficient S/N, and the results we have adopted are based on popularly used methods in spectral analysis and the results compare well among several different methods. Among the 17 accepted sample stars, 9 of them are newly found to show a metallicity value lower than [Fe/H] $= -1.0$. That is, out of the 19 objects which are selected by our criteria, 9 have [Fe/H] $\leq -1.0$. This fraction clearly suggests that the selection criteria we have adopted to obtain the input catalog for the LAMOST metal-poor star survey are quite efficient.

LAMOST is currently in a rather preliminary phase of operation, and neither the instrumental system of the whole telescope nor the 2D pipeline used for data reduction is performing fully satisfactorily. However, the commissioning data are still able to provide useful scientific information in addition to helping to improve the facility and the software system. In particular, for the targets of the metal-poor star survey, only a few typical spectral features need to be provided. Therefore, it may be more feasible to carry out estimation of $[\mathrm{Fe/H}]$ and identification of candidate metal-poor stars with the currently available LAMOST commissioning spectra, compared with other scientific studies that require more precise or detailed information, e.g., detecting sub-structures in the Galactic halo, identifying hyper-velocity stars or stars with planetary systems. In addition, all major features that are required for such measurement are located in LAMOST's blue arm spectra, hence avoiding the potential problem of combining the blue and red arm spectra. The HES has already proven the possibility and efficiency of using low-resolution spectroscopy and even objective-prism spectra of $R \sim 400$ to successfully identify candidates of metal-poor stars. Moreover, as shown in Table 2, all the spectra of the sample of stars have S/N sufficient for determining metallicities and basic stellar parameters. We hence consider the measurements based on the low-resolution spectra of LAMOST commissioning data to be sufficiently reliable for testing the ability of LAMOST to search for metal-poor stars.

**Table 2** Fundamental Information about the 17 Sample Stars

| LAMOST ID | RA (J2000) (h m s) | Dec (J2000) (° ′ ″) | $g'$ (mag) | $T_{\rm eff}$ (K) | $\log g$ (cm s$^{-2}$) | [Fe/H] (dex) | SDSS objID | S/N |
|---|---|---|---|---|---|---|---|---|
| A1775−F1213 | 13 46 55.2 | +25 41 17 | 14.87 | 4890 | 3.6 | −1.2 | 587739810484060164 | 101 |
| A1775−F3211 | 13 50 36.5 | +27 01 08 | 15.15 | 5950 | 4.4 | −1.1 | 587739706333003845 | 63 |
| A1775−G2808 | 13 51 07.9 | +28 17 05 | 15.32 | 4980 | 4.2 | −1.2 | 587739707943551044 | 82 |
| A1775−H0512 | 13 41 30.0 | +29 39 28 | 14.55 | 5120 | 4.6 | −1.3 | 587739607561404453 | 100 |
| A1775−H1714 | 13 37 59.8 | +28 51 36 | 17.44 | 5690 | 4.1 | −0.7 | 587739707942305841 | 65 |
| M67−G0303 | 08 49 39.8 | +13 46 47 | 15.42 | 5690 | 4.4 | −1.2 | 587742061050855610 | 79 |
| M67−G0310 | 08 47 35.8 | +13 46 51 | 15.60 | 6880 | 0.1 | −0.8 | 587742009510592666 | 38 |
| M67−G1020 | 08 47 44.9 | +13 19 00 | 15.88 | 5380 | 4.9 | −0.9 | 587742060513722566 | 59 |
| M67−G1813 | 08 51 43.9 | +12 50 43 | 15.21 | 6700 | 4.1 | −0.6 | 587744874790322281 | 85 |
| M67−G1816 | 08 50 58.6 | +12 51 57 | 14.95 | 7380 | 4.3 | −1.0 | 587744874790256701 | 62 |
| M67−H0302 | 08 44 06.2 | +13 45 53 | 15.08 | 4970 | 3.9 | −1.7 | 587742061587202080 | 99 |
| M67−H0920 | 08 46 36.0 | +13 21 47 | 15.57 | 5000 | 4.0 | −1.1 | 587742008973590598 | 59 |
| M67−H1725 | 08 46 19.0 | +12 54 31 | 14.97 | 6460 | 4.6 | −0.2 | 587744875326668887 | 47 |
| M67−H2523 | 08 45 25.0 | +12 20 12 | 14.70 | 4670 | 4.2 | −1.8 | 587745244156788837 | 126 |
| ssy05_1−E1613 | 01 37 12.3 | −09 11 45 | 14.83 | 5610 | 4.0 | −0.9 | 587725074989580348 | 35 |
| ssy05_1−H3919 | 20 37 32.4 | +00 00 05 | 15.71 | 6720 | 4.4 | −0.1 | 587726032765059103 | 37 |
| ssy05_1−F1905 | 02 09 07.8 | −09 29 57 | 14.78 | 5270 | 4.4 | −0.3 | 587725074990825537 | 35 |

Notes: Nine out of the 17 sample stars have metallicities [Fe/H] $\leq -1.0$.

We hereby report the test observations in searching for metal-poor stars with LAMOST based on its commissioning data in 2009, discovering nine stars with [Fe/H] $\leq -1.0$ in the process. Although such metallicity is not as metal-deficient as those extremely metal-poor stars located at the "tail" of the metallicity distribution function of the Galactic halo (Karlsson 2006; Salvadori et al. 2007; Prantzos 2008; Schörck et al. 2009), due to their rarity in the Galaxy and the limited size of the test sample, it is still of scientific importance with respect to the LAMOST metal-poor star survey. For example, we plan to obtain high-resolution spectroscopy to verify the stellar parameters of these sample stars, and to carry out future calibrations on the LAMOST stellar parameter pipeline which is crucially important for the future data processing of LAMOST. Despite the limited size of the test sample, it can provide helpful information on the ability of LAMOST to search for metal-poor stars. Among the 19 objects which have been correctly observed by LAMOST, nine of them have an $[\mathrm{Fe/H}]$ value in the range of $-1.0 \sim -2.0$. According to the statistical investigations of Galactic metallicity distributions (e.g., Carollo et al. 2007; Schörck et al. 2009; Li et al. 2010 in preparation), the fraction of very metal-poor stars will be $\sim$1–2 orders of magnitude lower, while extremely metal-poor stars are rarer by an additional factor of about ten. Just for a rough estimation, if LAMOST could successfully observe two million objects of the input catalog from the metal-poor star survey, it will be able to discover several thousand extremely metal-poor stars which will greatly improve the Galactic chemical evolutionary models and possibly lead to the detection of new HMP objects.

This work presents the preliminary result of test observations that search for metal-poor stars with LAMOST based on its commissioning data. It provides supportive evidence about the efficiency of the selection criteria adopted to obtain the input catalog for the LAMOST metal-poor star survey, and also gives insights about the potential of LAMOST to further enlarge the sample of metal-poor, very metal-poor, extremely metal-poor, and even more metal-deficient stars in the Galaxy. Massive photometric and spectroscopic surveys have been or will be designed for exploration of the stellar population and chemical evolution of the Galaxy, which is highlighted by SDSS(SEGUE), LAMOST, RAVE (RAdial Velocity Experiment, Zwitter et al. 2008), HERMES (a High Resolution Multi-object Echelle Spectrograph instrument on the Anglo-Australian Telescope), and APOGEE (Apache POint Galactic Evolution Experiment), etc. In the near future, when LAMOST becomes fully prepared in terms of its facility and pipeline and starts its regular observation, it is quite promising that it will be able to obtain an unprecedentedly large database of metal-poor stars, that will improve our understanding of the formation and chemical evolution of the Galaxy.

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