ON THE METALLICITIES OF *KEPLER* STARS

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ABSTRACT

We use 12,000 stars from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) spectroscopic survey data to show that the metallicities of *Kepler* field stars as given in the Kepler Input Catalog (KIC) systematically underestimate both the true metallicity and the dynamic range of the *Kepler* sample. Specifically, to the first order approximation, we find

$$[\mathrm{Fe/H}]_{\mathrm{KIC}} = -0.20 + 0.43[\mathrm{Fe/H}]_{\mathrm{LAMOST}},$$

with a scatter of ∼0.25 dex, due almost entirely to errors in KIC. This relation is most secure for $-0.3 <$ $[\mathrm{Fe/H}]_{\mathrm{LAMOST}} < +0.4$ where we have >200 comparison stars per 0.1 dex bin and good consistency is shown between metallicities determined by LAMOST and high-resolution spectra. It remains approximately valid in a slightly broader range. When the relation is inverted, the error in true metallicity as derived from KIC is (0.25 dex)/0.43–0.6 dex. We thereby quantitatively confirm the cautionary note by Brown et al. that KIC estimates of [Fe/H] should not be used by "anyone with a particular interest in stellar metallicities". Fortunately, many more LAMOST spectroscopic metallicities will be available in the near future.

Key words: planetary systems – stars: abundances

Online-only material: color figure

1. INTRODUCTION

Of the several thousand planetary candidates found by *Kepler*, only a few hundred have high-resolution spectra of their hosts. The number of "control sample" stars (without known planets) with such spectra is much smaller. Hence, large-sample statistical studies generally must rely on the Kepler Input Catalog (KIC; Brown et al. 2011). It is well known that the KIC was not designed for this purpose, and KIC metallicities are known to be particularly problematic. Brown et al. (2011) cautioned that "anyone with a particular interest in stellar metallicities should not use the KIC for their estimates of log(*Z*)." Using stellar parameters determined from 34 high-resolution spectra of *Kepler* target stars, they found that KIC metallicities were ∼0.17 dex smaller and there were indications of significant systematics. However, the faintness of *Kepler* stars has meant that high-resolution spectra are expensive in telescope resources.

An alternate approach is to obtain medium resolution spectra, which are generally adequate for estimating basic stellar parameters, i.e., effective temperature T_{eff}, gravity $\log g$, and metallicity [Fe/H]. Medium resolution spectrographs have the advantage that they can be easily multiplexed. For example, the Sloan Digital Sky Survey (SDSS) in its various incarnations has characterized of the order of 6×10^5 stars using an $R \sim 2000$ multi-object optical spectrograph (Aihara et al. 2011; Ahn et al. 2013). Unfortunately, SDSS did not target the *Kepler* field with

its optical spectrograph, although SDSS-III has begun observing brighter *Kepler* stars with its high-resolution APOGEE infrared multi-object spectrograph.

Because of the high science value of planetary hosts, exceptional efforts have nevertheless been made to obtain spectra. Buchhave et al. (2012) obtained high-resolution spectra for 152 hosts, and Everett et al. (2013) obtained $R \sim 3000$ optical spectra for 268 hosts. However, because these samples are still relatively small, and more importantly because the stellar parameters of the underlying population (with and without planets) is poorly characterized, it is difficult to do statistical studies of planet frequency as a function of stellar parameters.

Therefore, large statistical studies have been compelled to make use of KIC parameters. For example, Wang & Fischer (2013) used KIC metallicities as a proxy for spectroscopic metallicities to estimate the relative planet frequency for high-versus-low metallicity stars in several planet-radius bins. Other statistical works using KIC metallicities include Schlaufman & Laughlin (2011), Dodson-Robinson (2012), and Dawson & Murray-Clay (2013).

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, also known as Goushoujing Telescope) is an ideal instrument to explore the ∼115 $\deg^2$ *Kepler* field with spectroscopy. LAMOST is a Schmidt telescope with a ∼4 m effective aperture and 4000 fibers that can be deployed a 5° diameter field of view. Here we use data from Data Release 1 (DR1) and Data Release 2 (DR2) from LAMOST (Zhao et al. 2012; Cui et al. 2012; Luo et al. 2012) with $R \sim 1800$ to

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evaluate the relation between KIC metallicities and those determined from spectroscopy. We show that in the mean, there is fairly tight relation, but that the slope of this relation is quite shallow (0.43). Thus although the scatter of KIC metallicities around the true ones is modest (0.25 dex), if one is compelled to infer the true metallicity from the KIC value, the error is much larger: $0.25/0.43 \sim 0.58$ dex. Hence, we quantitatively confirmed the warning issued by Brown et al. (2011) that KIC metallicities must be used with extreme caution.

LAMOST DR1 and DR2 reports stellar parameters for ∼17,000 *Kepler* stars with no preference for known planet hosts as part of the "LAMOST-*Kepler* project" to observe all target stars in the *Kepler* field (De Cat et al. 2014). The LAMOST samples should eventually enable solid statistical investigations that are able to accurately characterize both the "numerators" (targets hosting planets) and the "denominators" of various subsamples. We ourselves are working on analyses regarding dependence of planet frequency on metallicities and various other host properties. However, our purpose here is to apply DR1 and DR2 Season 1 to a much more limited question: quantifying the systematics of KIC metallicities.

2. LAMOST *KEPLER* SAMPLE

We query the LAMOST DR1 and DR2 AFGK-type stars catalog[10] for *Kepler* stars, but not those that were specifically targeted because they had planets. We find 16,959 stars with KIC identifications, of which 317, or about 1.9%, host planetary candidates. This is statistically indistinguishable from the *Kepler* catalog as a whole, which has 2716 candidate hosts out of ∼150,000 stars, or 1.8%. We eliminate those with LAMOST $\log g < 3.5$ in order to focus on dwarf stars. We also eliminate stars that lack KIC metallicities. This leaves a sample of 12,400 stars. Of these, 64 stars lie outside the range $-0.85 < $ [Fe/H] $ < +0.65$. At these extremes, there are fewer than 20 stars per 0.1 dex bin, which would lead to poor statistical precision. We therefore also eliminate these 64 stars.

The $T_{\rm eff}$, $\log g$, and [Fe/H] in the catalog are determined by the LAMOST Stellar Parameter pipeline. This pipeline has been built upon the algorithm in Wu et al. (2011) analysing the commissioning LAMOST data, but it has been significantly improved since then, in particular taking considerable care in handling problems associated with relative flux calibration of the LAMOST spectra, which was found to be a main source of systematics shown in the commissioning data analysed by Wu et al. (2011) before (A. Luo 2014, private communication). In Section 4, we find that the [Fe/H] measurements from the LAMOST DR1 and DR2 catalog have a high degree of consistency with those determined from high-resolution spectroscopy in the literature.

3. COMPARISON OF LAMOST TO KIC METALLICITIES

Figure 1 shows a comparison of LAMOST to KIC metallicities in 0.1 dex bins of LAMOST metallicity. The outer error bars show the standard deviation and the inner ones show the standard error of the mean. We make a linear fit to all the data (the solid line) to gain an understanding of the relation between KIC and LAMOST metallicities to the first-order approximation. The second and third highest metallicity bin and the three lowest metallicity bins appear to differ noticeably from the trend. The reason for this is unclear. It could be a relatively large statistical
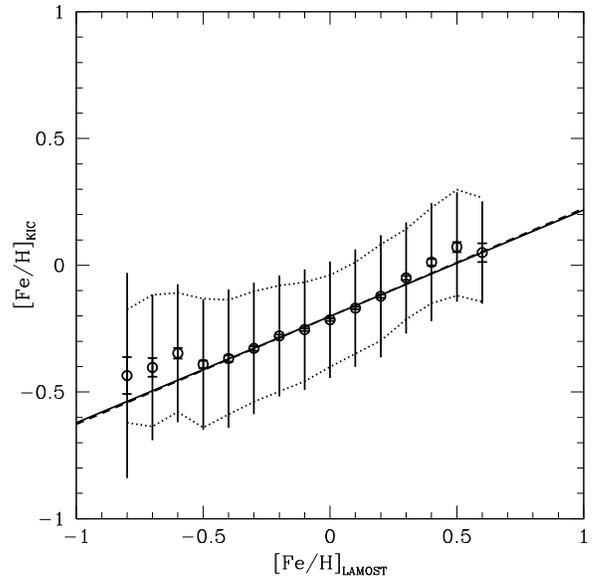
Figure 1. *Kepler* star metallicities as determined by KIC as a function of LAMOST spectroscopic metallicity. Outer error bars show standard deviations and inner error bars show standard errors of the mean. Dotted lines enclose the central 68.3% of the distribution. Solid line is fit to all the data, while dashed line removes the bins <200 stars. The remaining bins also coincide with the parameter regime where calibrations of LAMOST [Fe/H] with high-resolution spectroscopic [Fe/H] determinations are available ($-0.4 \lesssim$ [Fe/H]$_{\rm LAMOST} \lesssim$ +0.4). They are essentially the same. The zero-point and slope are both detected at high significance, -0.203 ± 0.002 and 0.434 ± 0.011, respectively.

fluctuation or it could be that either the KIC and/or LAMOST determinations actually change their trends. After all, the three highest and lowest metallicity bins only contain 6% of stars in the sample, and stars with [Fe/H] $\lesssim -0.4$ or [Fe/H] $\gtrsim +0.5$ also belong to the regime of the parameter space where we do not have external calibrations with high-resolution spectra (see discussions in Section 4). To be conservative, we remove these bins, each of which has fewer than 200 stars. The dashed line shows the fit to the remaining data. Both the mean offset and slope are detected at very high significance,

$$\begin{aligned}[\text{Fe/H}]_{\rm KIC} = (-0.203 \ \pm \ 0.002) \\ + (0.434 \ \pm \ 0.011)[\text{Fe/H}]_{\rm LAMOST}.\end{aligned} \quad (1)$$

The scatter in the individual bins is about 0.25 dex. We conclude that not only are the KIC metallicities too low, their dynamic range is substantially compressed relative to the metallicity range of the underlying stars. If the above linear relation is inverted to find true metallicity from KIC [Fe/H], the observed scatter is ∼0.6 dex = 0.25 dex/0.43. We caution that the linear fit given here is to understand the systematics of KIC metallicities. Given the large scatter, this relation should not be used to "correct" the KIC metallicity.

Figure 2 shows the metallicity distributions of the overlapping LAMOST/KIC sample as determined by each catalog. Note that the mean LAMOST [Fe/H] is close to solar while the mean KIC [Fe/H] is about -0.2 dex. The LAMOST [Fe/H] distribution is similar to that found in the solar neighborhood according to the recently revised stellar parameters of the Geneva–Copenhagen Survey (Casagrande et al. 2011). Casagrande et al. (2011) raised [Fe/H] zero point by about 0.1 dex compared to the previous study (Nordström et al. 2004). KIC adopted a Bayesian [Fe/H] prior peaked at -0.1 dex (Brown et al. 2011), similar to the distribution from Nordström et al. (2004).
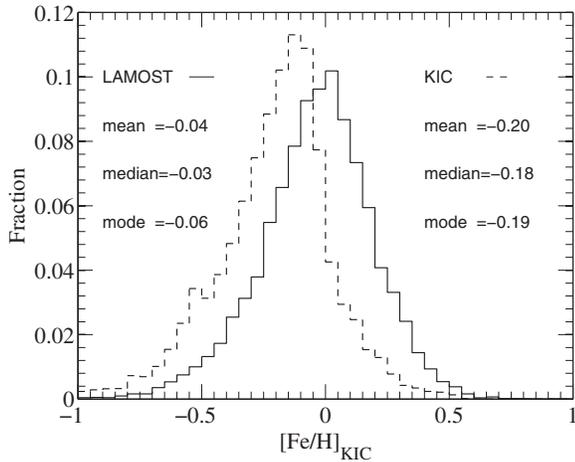
Figure 2. Metallicity distribution of the sample. Solid: LAMOST [Fe/H]; dashed: KIC [Fe/H]. The mean, median, and mode of each distribution are displayed.

4. COMPARISON OF LAMOST TO HIGH-RESOLUTION SPECTROSCOPIC METALLICITIES

Buchhave et al. (2012) presented the largest homogeneous high-resolution spectroscopy sample of *Kepler* stars. They introduced a new stellar parameter classification (SPC) technique that reports an average abundance [M/H] of the elements producing absorption lines between 5050 Å and 5360 Å. In order to compare the SPC [M/H] to LAMOST [Fe/H], we make use of the study by Torres et al. (2012), who systematically examined SPC-determined [M/H] with [Fe/H] as measured from the widely used Spectroscopy Made Easy (SME) package (Valenti & Piskunov 1996) and the spectral synthesis code MOOG (Sneden 1973).

The upper panel of Figure 3 shows the [M/H] by SPC and [Fe/H] by SME of 44 common stars and by MOOG of 36 common stars observed with high-resolution spectra from Torres et al. (2012) in filled red circles and green circles, respectively. They have mean differences of 0.020 ± 0.015 dex and -0.049 ± 0.019 dex, respectively, but their difference shows noticeable trends in difference fashions as a function of metallicity. These trends have amplitudes at about 0.1 dex, indicating systematics among these methods at this level, and the sources of these systematics are unknown (Torres et al. 2012). The overlap between LAMOST [Fe/H] and SPC [M/H] from Buchhave et al. (2012) is shown in filled blue circles. The 47 common stars also have a very small mean difference of -0.006 ± 0.015 dex. The standard error of the difference is 0.10 dex, at essentially the same level of systematics exhibited in the comparison of three different methods. The middle and lower panels of Figure 3 show the difference between LAMOST [Fe/H] and SPC [M/H] as a function of effective temperature ($T_{\rm eff}$) and surface gravity ($\log(g)$), and the difference show no noticeable trend over the available $T_{\rm eff}$ and $\log(g)$ ranges.

The above comparison demonstrates that [Fe/H] measurements from the LAMOST pipeline are in good agreement with those using high-resolution spectroscopy over a wide range of metallicity from ~ -0.3 dex to $\sim +0.4$ dex. However, it would certainly be desirable to make more systematical comparisons, especially for low-metallicity stars. We also note that the overlapping stars between LAMOST and Buchhave et al. (2012) have $5000\,{\rm K} \lesssim T_{\rm eff} \lesssim 6500\,{\rm K}$, which corresponds to the $T_{\rm eff}$ range for the majority of the LAMOST sample. The stars used in the Torres et al. (2012) sample to cross-calibrate SPC, SME
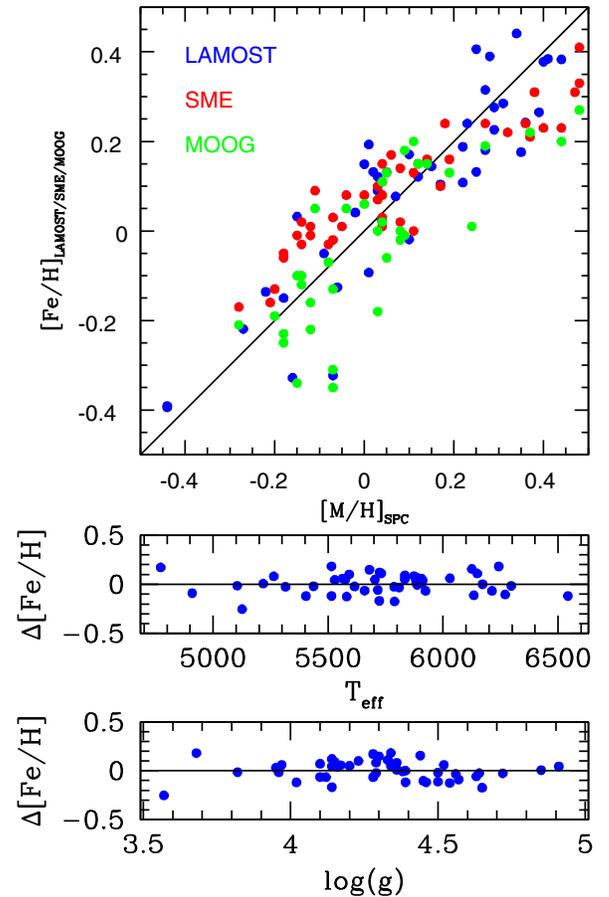

Figure 3. Comparison of [Fe/H] as determined by LAMOST (blue), the SME technique (red), or the MOOG technique (green) with [M/H] as determined by the SPC technique (Buchhave et al. 2012). The LAMOST/SPC comparison is based on 47 *Kepler* stars in common, while the SPC/SME and SPC/MOOG comparisons are based on 44 and 36 high-resolution stars, respectively, from Torres et al. (2012). All three comparisons show small mean offset (LAMOST/SPC: -0.006 ± 0.015 dex; SME/SPC: 0.020 ± 0.015 dex; MOOG/SPC: -0.049 ± 0.019 dex). SME/SPC and MOOG/SPC comparisons show trends in different fashions at amplitudes of ~ 0.1 dex, indicating systematics in these methods at this level with unknown sources (Torres et al. 2012). The standard deviation of the difference between LAMOST and SPC is 0.10 dex, suggesting that LAMOST [Fe/H] determinations are reliable at the level that present high-resolution spectroscopic methods are most secure. The middle and lower panels plot the LAMOST/SPC difference as a function of $T_{\rm eff}$ and $\log(g)$, showing no noticeable trends.

(A color version of this figure is available in the online journal.)

and MOOG are in the range of $4600\,{\rm K} < T_{\rm eff} < 6900\,{\rm K}$ and $-0.3 < {\rm Fe/H} < +0.5$, which covers the parameter space of overlapping LAMOST and Buchhave et al. (2012) stars. We caution that the reliability of the LAMOST metallicity for stars with $T_{\rm eff}$ outside this range shall be examined with other high-resolution spectroscopic data. Comprehensive calibrations of LAMOST stellar parameters using a large, homogeneous high-resolution spectroscopic sample covering a broader range of parameters are underway.

5. CONCLUSION

In our view, LAMOST metallicities should be used in place of KIC metallicities whenever they are available (and if there are no high-resolution spectra available).

Extreme caution is indicated when KIC metallicities are the only ones available. In particular, if Equation (1) is inverted to try to derive real metallicities from KIC metallicities, the observed

scatter in the individual bins (0.25 dex) must be divided by 0.43 to obtain the final error, i.e., 0.6 dex.

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