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Infrared colours and inferred masses of metal-poor giant stars in the *Kepler* field

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ABSTRACT
Intrinsically luminous giant stars in the Milky Way are the only potential volume-complete tracers of the distant disk, bulge, and halo. The chemical abundances of metal-poor giants also reflect the compositions of the earliest star-forming regions, providing the initial conditions for the chemical evolution of the Galaxy. However, the intrinsic rarity of metal-poor giants combined with the difficulty of efficiently identifying them with broad-band optical photometry has made it difficult to exploit them for studies of the Milky Way. One long-standing problem is that photometric selections for giant and/or metal-poor stars frequently include a large fraction of metal-rich dwarf contaminants. We re-derive a giant star photometric selection using existing public g-band and narrow-band DDO_{51} photometry obtained in the *Kepler* field. Our selection is simple and yields a contamination rate of main-sequence stars of $\lesssim$1% and a completeness of about 80 % for giant stars with $T_{\rm eff} \lesssim 5250\,{\rm K}$ – subject to the selection function of the spectroscopic surveys used to estimate these rates, and the magnitude range considered ($11 \lesssim g \lesssim 15$). While the DDO_{51} filter is known to be sensitive to stellar surface gravity, we further show that the mid-infrared colours of DDO_{51}-selected giants are strongly correlated with spectroscopic metallicity. This extends the infrared metal-poor selection developed by Schlaufman & Casey, demonstrating that the principal contaminants in their selection can be efficiently removed by the photometric separation of dwarfs and giants. This implies that any similarly efficient dwarf/giant discriminant (e.g., *Gaia* parallaxes) can be used in conjunction with *WISE* colours to select samples of giant stars with high completeness and low contamination. We employ our photometric selection to identify three metal-poor giant candidates in the *Kepler* field with global asteroseismic parameters and find that masses inferred for these three stars using standard asteroseismic scaling relations are systematically over-estimated by 20–175%. Taken at face value, this small sample size implies that standard asteroseismic scaling relations over-predict stellar masses for metal-poor giant stars.

Key words: stars: abundances, fundamental parameters; photometry: infrared; asteroseismology: masses, scaling relations

1 INTRODUCTION

Red giant stars are effective tracers of the disk, bulge, and halo of the Milky Way. They are especially important for penetrating the most extincted regions of the bulge (e.g., Rich 1990; Rich et al. 2007; Casey & Schlaufman 2015). In short, they allow for a thorough and relatively unbiased examination of all major components of the Milky Way and its satellite systems. Given their importance for tracing the structure and evolution of the Milky Way, an efficient photometric selection for giant stars has been long-standing goal of Galactic astronomers.

Geisler (1984) presented what has become the most influential photometric dwarf/giant separation. Geisler's clas-

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sification of the narrow-band Washington (Canterna 1976) DDO_{51} filter demonstrated that the $g-DDO_{51}$ colour was significantly different for FGK-type dwarfs and giants. The colour separation is the result of strong stellar absorption features that appear in the spectra of FGK-type stars near the central wavelength of the DDO_{51} filter. Specifically, the Mg I triplet near 517 nm is one of the strongest spectral features in late-type stars, with dwarfs showing extended wings induced by pressure broadening. In addition to the Mg I triplet lines contributing $\log g$ sensitivity to the DDO_{51} filter, several bands of the MgH $A^2\Pi - X^2\Sigma$ structure are present in this narrow wavelength range. Despite a small secondary dependence on metallicity (Paltoglou & Bell 1994; Majewski et al. 2000), these features are much weaker in giants than dwarfs at the same effective temperature. Although the g-band filter is broader than the narrow DDO_{51} filter by more than 100 nm, both responses curves peak near the same central wavelength. For these reasons, the $g-DDO_{51}$ colour provides outstanding photometric sensitivity in surface gravity in late-type stars. For comparison, metal-rich main-sequence stars overlap with very metal-poor giant stars in the $c_{1.0}$–$(b-y)_0$ plane of Strömgren photometry, and giant/dwarf separation using Strömgren photometry is extremely sensitive to reddening (Árnadóttir et al. 2010). Thus, the $g-DDO_{51}$ colour is among the most promising for distinguishing giant stars, particularly metal-poor giant stars, from main-sequence stars.

While the DDO_{51} filter is known for its ability to distinguish dwarfs from giants, it has not seen extensive use in large-scale studies of Milky Way (though see Majewski et al. 2000; Morrison et al. 2001; Helmi et al. 2003; Muñoz et al. 2005; Saha et al. 2010; Janesh et al. 2016; Slater et al. 2016; Blanton et al. 2017). Most galactic studies seeking to assemble a clean (i.e., relatively uncontaminated) sample of giant stars have focused on later-type M stars. In constructing the standard $JHKLM$ system, Bessell & Brett (1988) showed that dwarfs and giants bifurcated in infrared colours at spectral types later than M. This feature allows for a clean sample of either cool M dwarfs or giants to be easily constructed without the need for narrow-band photometry. Given that M giants are more luminous than FGK type stars, many studies have produced inferences about Milky Way structure through uncontaminated samples of M giants (e.g., see Sheffield et al. 2014; Koposov et al. 2015; Li et al. 2016).

While it is tempting to assert that M giants selected from public infrared photometry are sufficient tracers of the Milky Way, it is well understood that M giants preferentially trace metal-rich stellar populations. For this reason, most of the structure in the Milky Way's metal-poor halo will not appear in even the cleanest M-giant sample. This can result in biased inferences, leaving the largest component of the Milky Way (by volume) less than fully understood.

This *Article* is organised in the following manner. In Section 2 we use public photometry and spectral data available in the *Kepler* field to re-derive a giant photometric selection with high completeness and negligible contamination. We show that the stars in the resulting photometrically-selected giant sample have spectroscopic metallicities that are strongly correlated with infrared colours. Confident in our photometric selection, we then use photometrically-selected metal-poor giant stars with publicly available asteroseismic parameters $\Delta\nu$ and ν_{max} to show that masses inferred using scaling relations are systematically over-estimated for metal-poor stars. This observation suggests that a modification to the asteroseismic scaling relations is warranted in the metal-poor regime. In Section 3 we discuss how these results extend existing work on searches for metal-poor stars using mid-infrared photometry and the implications for asteroseismic scaling relations. Our conclusions follow in Section 4.

2 DATA & ANALYSIS

2.1 Photometric Selection

We constructed our photometric selection using the extensive public photometric and spectroscopic data available in the *Kepler* field. We first cross matched the *Kepler Input Catalogue* (hereafter *KIC*, Brown et al. 2011) against *LAMOST* Data Release (DR) 3 (Luo et al. 2015) using a $1''$ search radius. This match revealed 53,090 sources. We cross matched the resulting sample against the *ALLWISE* catalogue (Wright et al. 2010) using the *IRSA* web service and an increased search radius of $2''$ to account for the larger point spread function in *ALLWISE*. This revealed 48,999 unique sources. We corrected bright *WISE* photometry using the prescription of Patel et al. (2014), and we discarded stars based on a number of quality criteria. First, we required that all stars have reported magnitudes in g, i, DDO_{51}, $W1$ and $W2$. We further removed stars where there was uncertainty in the *WISE* photometry: $\sigma(W1) > 0.025$ mag, or $\sigma(W2) > 0.022$ mag, or if the χ^2 value in the $W1$ or $W2$ profile fitting exceeded 2. We made no quality cuts based on spectroscopy (e.g., using any information from *LAMOST*). The distilled sample contains 25,668 stars.

We use $g-DDO_{51}$ colour to separate dwarf and giant stars, as shown in Figure 1. In the first panel we show the effective temperature $T_{\rm eff}$ and surface gravity $\log g$ for all *LAMOST* stars in our sample, where we have separated main-sequence and giant stars with $\log g > \max\{6.1 - 2.4(T_{\rm eff}/6000), 4.1\}$. The $g-i$ and $g-DDO_{51}$ colours of the main-sequence and giant star samples are shown in the second and third panels of Figure 1, where it is clear that the lack of spectral absorption in the giant stars separates them very neatly from the dwarfs in the $\{g-i, g-DDO_{51}\}$ colour space, as shown in previous studies. We note that the separation we find in $g-DDO_{51}$ appears qualitatively better than existing studies using this selection, presumably because these stars are relatively bright and the DDO_{51} imaging obtained for the *KIC* is of high quality. Using the $g-i$ colour, it is clear that the dwarf/giant separation is maintained for effective temperatures as low as $\sim$4000 K. The separation for cooler stars is less distinct for $g-r$, J, H, and K_s, but comparable for $g-z$. For stars below $\sim$4000 K, $V-K$ and $J-H$ can be effectively used to separate dwarfs from giants (Bessell & Brett 1988). On the hotter end, however, we caution that $\log g$ sensitivity is largely lost for stars with $T_{\rm eff} \gtrsim 5250$ K. Giant stars in this temperature regime overlap with main-sequence stars (of all metallicities) and cannot be efficiently selected using only g, i, and DDO_{51} magnitudes without introducing considerable contamination by main-sequence stars. For this reason, we

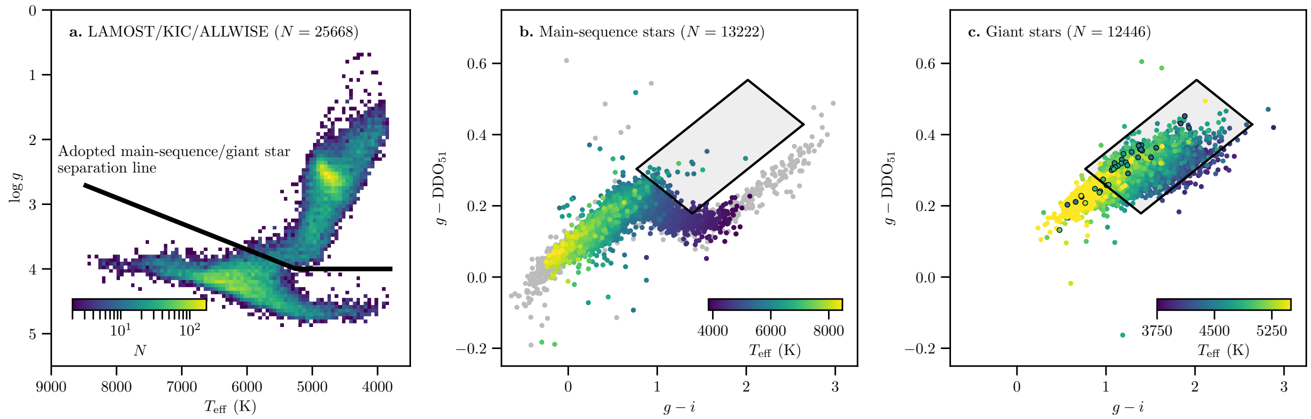

Figure 1. a. Spectroscopically-derived stellar parameters for stars in the *LAMOST*/*KIC*/*ALLWISE* sample, with the line we adopted to separate main-sequence stars from giant stars. **b.** The $g-i$ and $g-$DDO$_{51}$ colours of (spectroscopically-selected) main-sequence stars in this *LAMOST*/*KIC*/*ALLWISE* sample. The criteria box we adopt to photometrically select giant stars is shown in panel (b) and (c). In (b) we also show main-sequence stars in *APOGEE* sample to demonstrate how redder main-sequence stars (which are not present in *LAMOST*) appear in this colour plane. **c.** $g-i$ and $g-$DDO$_{51}$ colours of spectroscopically-selected giant stars in *LAMOST*/*KIC*/*ALLWISE*, coloured (and ordered on the plot) by their effective temperature. Stars with [Fe/H] < -1.5 are drawn with black edges, showing a mild metallicity dependence in the $g-$DDO$_{51}$ colour. Most giants fall within the photometric selection, although the completeness drops for stars $T_{\rm eff} \gtrsim 5250$ K as they overlap with main-sequence star colours in this plane.

can expect that any effective dwarf/giant selection using the $g-$DDO$_{51}$colour will be biased against hotter stars near the base of the red giant branch.

The photometric selection we adopt for giant stars in this work is,

$$g - \mathrm{DDO}_{51} > \max\{0.46 - 0.2(g-i), -0.10 + 0.2(g-i)\}$$

and

$$g - \mathrm{DDO}_{51} < \min\{0.15 + 0.2(g-i), +0.96 - 0.2(g-i)\}.$$

Using this selection we classify 8,947 stars as likely giants from the *LAMOST*/*KIC*/*ALLWISE* catalogue (of the 25,668 that met our photometric quality cuts). Of these, 8,891 (99.4%) are spectroscopically-confirmed giant stars, giving a contamination rate of main-sequence stars of 0.6%. The completeness fraction is 71%. While the photometric selection could be adjusted to improve completeness, here we have chosen simple criteria to maintain a low contamination fraction. Note that the completeness fraction is temperature-dependent, and drops quickly for higher effective temperatures near $T_{\rm eff} \gtrsim 5250$ K, as main-sequence stars and hotter giant stars share similar $g-i$ and $g-$DDO$_{51}$colours. The completeness fraction for *LAMOST* giant stars with $T_{\rm eff} < 5250$ K is 76%. We stress, however, that the contamination and completeness fraction is subject to the *LAMOST* selection function (e.g., magnitude range, biases towards or against spectral types), and by the quality constraints that we have enforced on the *ALLWISE* photometry.

We repeated the steps above using the *APOGEE* DR14 (Abolfathi et al. 2017) to investigate the impact on completeness and contamination. We find 20,124 matches between *APOGEE* and the *KIC*, and 19,952 unique sources that also have *ALLWISE* photometry. After applying the same quality cuts described above, our distilled *APOGEE*/*KIC*/*ALLWISE* sample contained 13,555 stars. Most of these stars are giants, a reflection of the *APOGEE* selection bias towards giant stars (Zasowski et al. 2013). Despite this strong bias in favour of observing giant stars, we find that the estimated completeness and contamination fraction arising from our photometric selection do not change considerably. The completeness fraction is about 80% – whether or not we restrict the sample to $T_{\rm eff} > 5250$ K – and the contamination fraction is 0.6%. Since *APOGEE* is biased towards giant stars, this completeness fraction may be representative of an upper limit of what could be expected from our colour selection, unless we were to adjust it for the sake of increasing contamination. Nevertheless, although these estimated rates are sample-dependent, it is clear that the DDO$_{51}$ filter can be used to identify giant stars with very little contamination whilst maintaining a reasonably high completeness fraction. From the *APOGEE* and *LAMOST* samples investigated, both showed comparable completeness and contamination rates: the photometric selection for giant stars recovered about 75% of the true number of giants (as determined by spectroscopy), and the contamination of main-sequence stars is $\lesssim$1%.

Using the *APOGEE* sample, in Figure 2 we plot *WISE* $W1-W2$ colour as a function of $J-K_s$, showing the same bifurcation in dwarf and giant stars noted by Bessell & Brett (1988) for purely near-infrared colours. From Figure 2 it can also be seen that all metal-poor giant stars have a *WISE* $W1-W2$ colour of $\gtrsim -0.05$, with a negligible temperature dependence. The most metal-poor stars can be retained by keeping giant stars with the reddest *WISE* $W1-W2$ colour. However, the vast majority of giants in our sample are sufficiently warm that a purely near-infrared selection of metal-poor giant stars would suffer heavy contamination by main-sequence stars. Coupled with our $g-$DDO$_{51}$photometric selection to cleanly distinguish main-sequence stars from giant stars, we can now illustrate how this sample permits the easy identification of metal-poor giant stars using only photometry.

Continuing with the *APOGEE* sample, in Figure 3 we

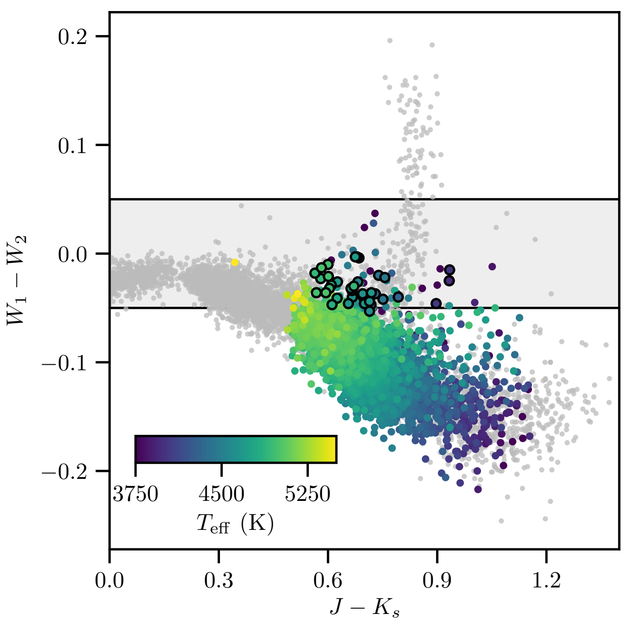

Figure 2. $J - K_s$ colours (Skrutskie et al. 2006) against $W1 - W2$ colours for the *APOGEE*/*KIC*/*ALLWISE* sample. Spectroscopically-confirmed giant stars are coloured by their effective temperature $T_{\rm eff}$ (Abolfathi et al. 2017), and all other points are shown in gray. Metal-poor giant stars ([Fe/H] < -1.5) are marked with black edges, showing that all metal-poor giant stars in this sample have $-0.05 \lesssim W1 - W2 \lesssim 0.05$ (indicated by the coloured region). A photometric selection using only $W1-W2$ colour would be severely contaminated by main-sequence stars (shown in grey).

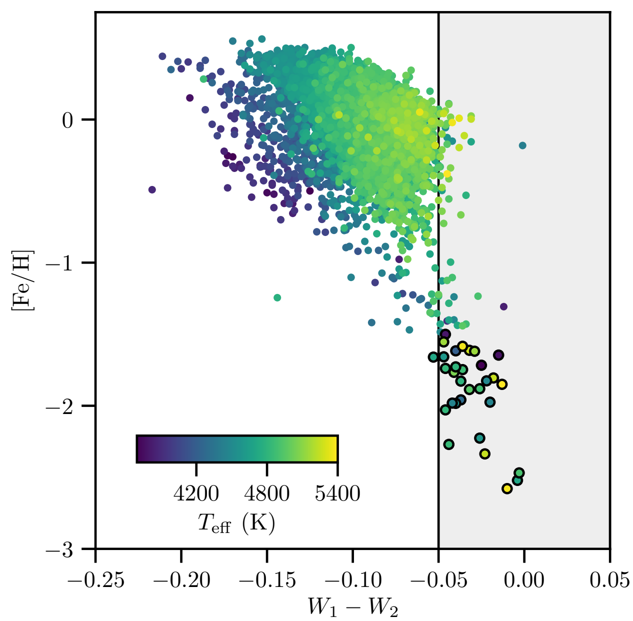

Figure 3. Metallicity of the *APOGEE*/*KIC*/*ALLWISE* photometrically-selected giant sample ($N = 7,432$) as a function of $W1 - W2$ colour. Points are coloured by their *APOGEE* effective temperature. Another 487 (6%) photometrically-selected giant stars are not shown because they do not have metallicities in *APOGEE*, likely due to analysis issues (see text).

show the relation between *WISE* colour and *APOGEE* metallicities for 7,432 stars that meet our photometric giant star selection. There are another 487 (6%) stars that we identify as likely giant stars (from photometry), but *APOGEE* does not report a metallicity. Metallicity may not be reported for a number of reasons, including: problems related to the data reduction and/or analysis, or if *APOGEE* suspects that the source is a main-sequence star. Given the low contamination fraction we find from *LAMOST* (e.g., $\lesssim$1%), we suspect most of these 487 photometrically-selected giant stars do not have reported metallicities due to the data reduction or analysis issues. We checked those 487 photometrically-selected giant stars without *APOGEE* metallicities and found that 158 have stellar parameters reported by *LAMOST*, and nearly all (152/158) are giant stars according to *LAMOST*. Based on the $W1 - W2$ colour separation of metal-poor giant stars ([Fe/H] < -1.5) visible in Figures 2 and 3, we adopt $-0.05 \leqslant W1 - W2 \leqslant 0.05$, in conjunction with our $g-$DDO$_{51}$ colour selection, to distill a relatively clean sample of metal-poor giant stars.

Figure 4 demonstrates the effectiveness of using the $g-$DDO$_{51}$ filter and *WISE* colours to identify metal-poor giant star candidates. The greyed area shows the fraction of metal-poor giant stars ([Fe/H] < -1.5) per $W1-W2$ colour bin for the *LAMOST* and *APOGEE* samples. Given a single photometric selection in $W1 - W2 > -0.05$, without any giant/dwarf selection, the fraction of metal-poor stars is $\sim$ $1 : 1,000$ stars per bin. In Figure 4 we also show the fraction of metal-poor stars per colour bin for our photometrically-selected sample of giants. Above $W1 - W2 > -0.05$, the fraction of stars with [Fe/H] < -1.5 exceeds 25%. Thus, our photometric selection has increased the yield of metal-poor giant stars recovered by a factor of $\sim$250 over a randomly selected sample.

2.2 Weighing the Giants

We have presented an efficient and effective photometric selection to identify giant metal-poor stars. Given the paucity of known metal-poor stars in the *Kepler* field and the routine use of asteroseismic scaling relations to estimate stellar masses and radii, this provides us with a unique opportunity to critically examine the existing scaling relations. While the number of metal-poor giant stars with publicly-available asteroseismic fundamental parameters ($\nu_{\rm max}$, $\Delta\nu$) is very small, there is theoretical and observational evidence to suggest that the current scaling relations warrant a metallicity-dependent term in order to reconcile systematically over-estimated masses inferred from metal-poor stars (e.g., White et al. 2011; Mosser et al. 2013; Epstein et al. 2014; Gaulme et al. 2016; Guggenberger et al. 2016; Sharma et al. 2016; Huber et al. 2017). Here we cross match our catalog of photometrically-selected metal-poor stars with publicly available asteroseismic fundamental parameters to infer their masses and radii, and explore whether any correction is necessary to the existing scaling relations.

We cross matched the *KIC* and *ALLWISE* and se-

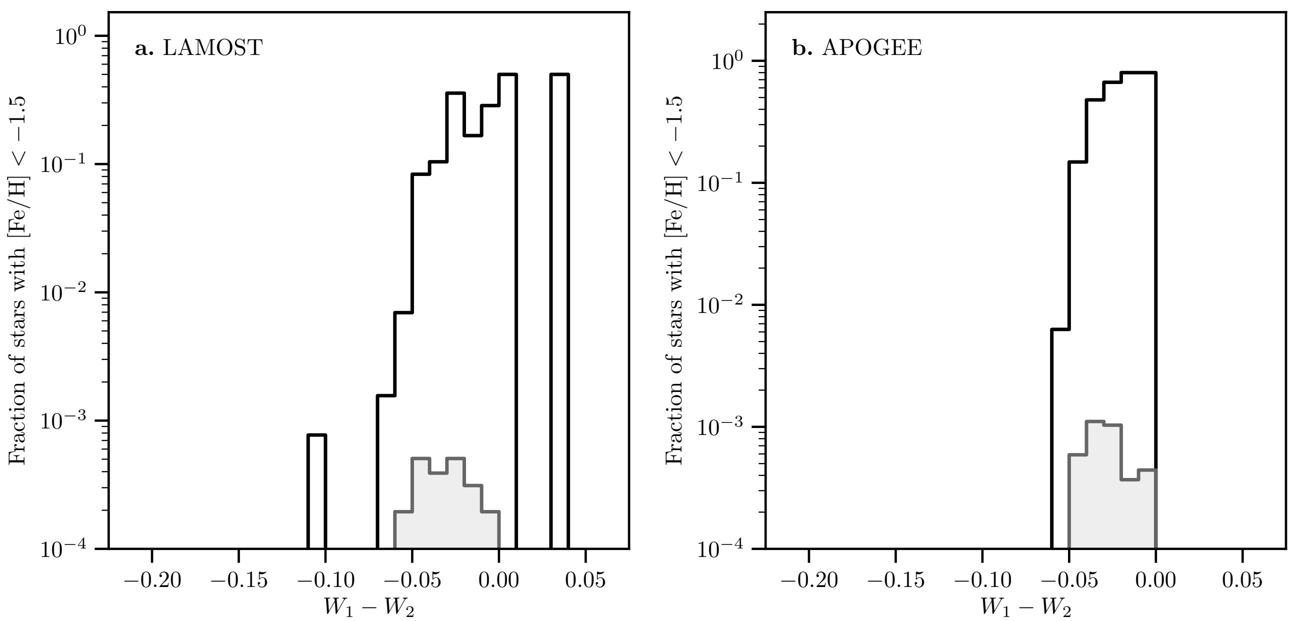

Figure 4. Effectiveness in photometrically selecting metal-poor ([Fe/H] < -1.5) giant stars from $g-\mathrm{DDO}_{51}$ and $W1 - W2$ coloured (black) over a random sample (grey). The lines indicate the fraction of metal-poor stars per $W1 - W2$ colour bin. The use of the $g-\mathrm{DDO}_{51}$ colour selection removes most metal-rich contaminants for colour bins at $W1 - W2 \geqslant -0.05$.

lected likely metal-poor giant stars based on $g-\mathrm{DDO}_{51}$ and $W1 - W2$ colours, while maintaining the photometric quality cuts described earlier. We cross matched the resulting sample against the Hekker et al. (2011) catalog, which includes a thorough comparison of six different asteroseismic pipelines. Our search revealed four new highly likely metal-poor ([Fe/H] $\lesssim -1.5$) giant stars with measured $\Delta\nu$ and ν_{max} from multiple pipelines: *KIC*s 6304081 (all 6 pipelines), 6231193 (6), 7729396 (3), and a fourth which will appear in a subsequent paper (Schlaufman et al. 2018, in preparation). The pipeline measurements are typically in agreement within a few percent for all three stars (see Table 1).

We assume $T_{\mathrm{eff},\odot} = 5777$ K for the Sun, and adopt $\Delta\nu_\odot = 135.0 \pm 0.1$ μHz and $\nu_{\mathrm{max},\odot} = 3140 \pm 30$ μHz as per Epstein et al. (2014). If we employ the photometric temperatures from the *KIC* and take the mean ν_{max} and $\Delta\nu$ values from Table 1, the asteroseismic scaling relations imply respective solar masses of 1.01, 2.19, 1.04, and solar radii of 10.7, 10.6, 20.5 for our metal-poor giant star candidates. The estimated uncertainties on these masses is of order 10% (e.g., Chaplin & Miglio 2013). The indicated masses are relatively high for metal-poor stars. Metal-poor stars are generally thought to be ancient, which demands that they should have masses of $\approx 0.8 M_\odot$ in order to survive to the present day. Masses higher than $\approx 0.8 M_\odot$ for ancient stars suggest that they would live relatively short lifetimes and not remain observable today. Given the good agreement in global oscillation parameters reported from multiple pipelines, the choice of mean oscillation parameters or those from any individual pipeline has little impact on the inferred masses and radii. For example, the scatter in oscillation parameters for KIC 6231193 translates to a scatter in inferred mass of just $\sigma(M) = 0.03\,M_\odot$. We also note the effective temperatures estimated by the *KIC* catalog agree excellently with the distribution of temperatures found for confirmed metal-poor giant stars in the Schlaufman & Casey (2014) catalog. The photometric temperatures would have to be systematically overestimated by ~2,500 K to bring all inferred masses within 0.8 $M_\odot$.

3 DISCUSSION

We have leveraged existing public photometry and spectroscopy in the *Kepler* field to verify that the DDO_{51} filter is successful in separating FGK dwarf and giant stars. While late-type (M0.0 and later) giant stars are difficult to separate from dwarf stars given the $g-\mathrm{DDO}_{51}$ colour, infrared photometric selections already exist that allow for a clean selection of M-type giant stars (Bessell & Brett 1988). Our photometric selection for giants is extremely simple (i.e., we did not choose to optimise parameters to maximise yields), and we estimate the contamination in our giant sample to be ~1%, subject to the selection function of the *APOGEE* and *LAMOST* samples used. The completeness fraction is estimated to be about 75%, with a bias against giant stars with $T_{\mathrm{eff}} \gtrsim 5150\,$K.

The dwarf/giant separation power of DDO_{51} is well established, and there is no doubt it was the primary reason that the *KIC* was successful in identifying dwarf stars (Verner et al. 2011). Here we have shown that the giant stars in the resulting sample have spectroscopic metallicities that are strongly correlated with $W1 - W2$ infrared colour. This correlation is not present in dwarf stars at a level that permits metal-poor stars to be easily identified. Indeed, Figure 2 demonstrates that dwarf stars of all metallicities display

KIC	COR		CAN		A2Z		SYD		DLB		OCT		
	$\nu_{\rm max}$	$\Delta\nu$	$\nu_{\rm max}$	$\Delta\nu$	$\nu_{\rm max}$	$\Delta\nu$	$\nu_{\rm max}$	$\Delta\nu$	$\nu_{\rm max}$	$\Delta\nu$	$\nu_{\rm max,1}$	$\nu_{\rm max,2}$	$\Delta\nu$
	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz	μHz
6231193	31.5	3.93	31.22	3.91	31.4	3.92	31.84	3.93	29.09	3.74	31.72	32.84	3.89
6304081	69.1	5.78	68.57	5.48	67.03	5.79	69.36	5.9	60.65	6.23	67.75	65.95	5.79
7729396	8.3	1.41	···	···	···	···	8.76	1.39	9.35	1.65	···	···	···

Table 1. Global oscillation parameters measured from six different pipelines for photometrically-selected metal-poor giant star candidates. Pipeline acronyms are as per Hekker et al. (2011).

infrared colours that are indistinguishable from metal-poor giant stars. For this reason, a dwarf/giant discriminant is required to reveal the correlated signature between stellar metallicity and infrared colour.

An examination of theoretical stellar spectra reveals the explanation for this strong correlation between metallicity and $W1-W2$ colour. Using the PHOENIX spectral library (Husser et al. 2013), Kennedy & Wyatt (2012) and Schlaufman & Casey (2014) showed that the dependence of metallicity on $W1-W2$ relies on the presence of strong CO absorption at $\approx 4.5\,\mu$ (i.e., in the middle of $W2$). This bandhead is strong, and only begins to disappear at [Fe/H] $\lesssim -2$ for a giant star with $T_{\rm eff} \approx 4800$ K. There are no strong stellar absorption features in wavelengths covering the $W1$ band, therefore making $W1-W2$ a sensitive proxy for stellar metallicity.

Schlaufman & Casey (2014) first utilised $W1-W2$ colour to efficiently identify bright metal-poor stars from existing public data. Their selection is as efficient as existing studies seeking metal-poor stars, while the candidates they identify are several magnitudes brighter. This property minimises the requisite telescope time for spectroscopic confirmation and subsequent detailed chemical abundance analysis. A number of photometric cuts are employed by Schlaufman & Casey (2014) in addition to the $W1-W2$ colour. Some cuts accounted for expected temperature dependencies, while others were included because they empirically improved the yield of metal-poor giant stars.

Young, relatively metal-rich dwarf stars are the primary contaminant that result from the original Schlaufman & Casey (2014) photometric selection. Our analysis of public photometry and spectroscopy in the *Kepler* field has revealed the reason for this contamination and further verified the potential in using infrared colours to select metal-poor giant stars. When coupled with a simple dwarf/giant photometric selection, our analysis shows that the $W1-W2$ infrared sensitivity alone is sufficient to effectively select metal-poor stars. It would appear the additional empirical photometric cuts employed by Schlaufman & Casey (2014) primarily served to minimise the dwarf contamination, thereby improving the overall yield of metal-poor giant stars.

Infrared photometric selections are advantageous because they are minimally affected by strong absolute or differential extinction. While we have shown the metallicity sensitivity in giants is principally correlated with the mid-infrared $W1-W2$ colour, the central wavelengths of g and $\rm DDO_{51}$ nearly overlap at 510 nm. Due to the their bluer wavelengths, one might expect the g and $\rm DDO_{51}$ filters to be considerably impacted by extinction. However, because the g and $\rm DDO_{51}$ filters have central wavelengths that are very similar, both filters are affected by dust in a similar way. For this reason, the $g-\rm DDO_{51}$ colour has a very small dependence on extinction. Therefore, a photometric selection of metal-poor stars that makes use of $g-\rm DDO_{51}$ and $W1-W2$ will be minimally impacted by dust. This is particularly relevant for metal-poor star searches in the inner Galaxy, where absolute and differential extinction is strongest. This is important, as theoretical models of galaxy formation predict that the oldest stars in the Milky Way should be metal-poor stars found in the bulge (e.g., Tumlinson 2010).

We have employed our photometric selection to identify likely metal-poor giant star candidates with publicly available global oscillation parameters. There is excellent agreement between reported parameters from different pipelines for our candidates. Standard asteroseismic scaling relations imply masses exceeding 1 $M_\odot$, up to 2.19 $M_\odot$ for the most extreme case. For metal-poor giant stars – which are presumably old halo stars – the expected masses are $\sim$0.8 $M_\odot$. Higher masses are inconsistent with the requisite ancient age of the halo stars. Although our sample size is small ($N = 3$), this discrepancy implies that the standard scaling relations would have to be over-predicting the masses of metal-poor stars by 25% to $\sim$175% in order to be consistent with the observations. Although there are theoretical modifications to standard scaling relations that attempt to correct for some of this discrepancy (e.g., White et al. 2011), the impact is of the order 5%. Therefore, our metal-poor giant star candidates suggest that either a stronger metallicity-dependent correction is necessary to resolve this discrepancy, or that metal-poor stars have much higher masses than expected from stellar evolution.

4 CONCLUSIONS

We have derived a simple photometric selection for FGK-type giants based on public g, i, and $\rm DDO_{51}$ photometry in the *Kepler* field. Given a single two-colour cut, we find giant completeness rates of $\sim$75%, with $\lesssim$1% contamination of dwarfs, subject to the selection functions of *LAMOST* and *APOGEE*, and the magnitude ranges considered. We distill a sample of photometrically-selected giant stars and show a strong correlation between spectroscopic metallicity and mid-infrared $W1-W2$ colour. This relationship is not present in dwarfs, so metal-poor candidate stars selected solely from mid-infrared $W1-W2$ excess will be contaminated by dwarf stars across all metallicities.

Our work extents that of Schlaufman & Casey (2014), who first showed that metal-poor stars could be successfully identified through infrared colours (see also Kennedy & Wyatt 2012). Here we have shown that the additional cuts used in Schlaufman & Casey (2014) to empirically improve the yield of metal-poor giant stars primarily act to minimise the number of dwarf stars in the sample, rather than principally discriminating on metallicity.

Our photometric cuts are well-founded theoretically. The $\log g$ sensitivity in $g{-}\mathrm{DDO}_{51}$ arises from pressure-sensitive spectral features that are strong in dwarfs but weak or non-existent in giants of the same temperature. Similarly, the dependence of $W1 - W2$ colour on metallicity relies on negligible spectral features in $W1$, but strong molecular CO absorption present in giant stars at $\approx 4.5\ \mu$ (i.e., in $W2$). Here we have demonstrated that coupling these two simple photometric selections provides enormous potential in robustly identifying metal-poor stars, even in heavily extincted regions (e.g., the bulge). For these reasons, we argue that a photometric selection that employs $g{-}\mathrm{DDO}_{51}$ and $W1 - W2$ colours to identify metal-poor star candidates in the inner Galaxy may be the most promising way to discover any remaining low-mass Population III in the Galaxy.

We have identified metal-poor giant star candidates in the *Kepler* field that have publicly available global oscillation parameters from asteroseismic pipelines. There is good agreement between different asteroseismic pipelines for these stars. However, the masses inferred from standard scaling relations are higher than expectations for ancient metal-poor stars. These results imply that either asteroseismic scaling relations over predict masses for metal-poor giant stars, or that the metal-poor giant stars examined here are younger than expected.

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