PROBING THE DEEP END OF THE MILKY WAY WITH KEPLER: ASTEROSEISMIC ANALYSIS OF 854 FAINT RED GIANTS MISCLASSIFIED AS COOL DWARFS

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Received 2016 March 6; revised 2016 April 21; accepted 2016 May 2; published 2016 August 5

ABSTRACT

Asteroseismology has proven to be an excellent tool to determine not only global stellar properties with good precision, but also to infer the stellar structure, dynamics, and evolution for a large sample of Kepler stars. Prior to the launch of the mission, the properties of Kepler targets were inferred from broadband photometry, leading to the Kepler Input Catalog (KIC). The KIC was later revised in the Kepler Star Properties Catalog, based on literature values and an asteroseismic analysis of stars that were unclassified in the KIC. Here, we present an asteroseismic analysis of 45,400 stars that were classified as dwarfs in the Kepler Star Properties Catalog. We found that around 2% of the sample shows acoustic modes in the typical frequency range that put them in the red-giant category rather than the cool dwarf category. We analyze the asteroseismic properties of these stars, derive their surface gravities, masses, and radii, and present updated effective temperatures and distances. We show that the sample is significantly fainter than the previously known oscillating giants in the Kepler field, with the faintest stars reaching down to a Kepler magnitude of $K_p \approx 16$. We demonstrate that 404 stars are at distances beyond 5 kpc and that the stars are significantly less massive than for the original Kepler red-giant sample, consistent with a population of distant halo giants. A comparison with a galactic population model shows that up to 40 stars might be genuine halo giants, which would increase the number of known asteroseismic halo stars by a factor of 4. The detections presented here will provide a valuable sample for galactic archeology studies.

Key words: asteroseismology – methods: data analysis – methods: numerical – stars: distances – stars: fundamental parameters – stars: oscillations (including pulsations)

Supporting material: machine-readable tables

1. INTRODUCTION

The Kepler mission has observed more than 196,000 stars (Batalha et al. 2010) over 4 years. While the main objective of the mission was to search for exoplanets, significant effort has gone into characterizing the properties of the stars, particularly those hosting planets.

To prepare the mission, all potential targets were observed in broadband photometry, which was used to build the Kepler Input catalog (KIC, Brown et al. 2011). The choice of photometric data over spectroscopic classification was mainly due to the large number of targets. However, the KIC also made use of existing catalogs such as the Two Micron All Sky Survey, USNO-B1.0, Hipparcos, Tycho-2, and UCAC2. Since the beginning of the mission, this catalog has been widely used for characterizing the discovered exoplanet host stars or for targeting specific categories of stars for stellar physics studies. The catalog was also compared to spectroscopic observations that became available during the lifetime of the mission (e.g., Bruntt et al. 2012; Thygesen et al. 2012) or to re-calibrated KIC photometry (Pinsonneault et al. 2012). These studies showed that, on average, solar-like stars and red giants have effective temperatures 3%–5% higher than those in the KIC. The analysis of Verner et al. (2011), based on asteroseismology, showed that for a sample of main-sequence stars, the KIC overestimates the surface gravities by an average of 0.23 dex for $\log g$ above 4.0 dex and 0.30 dex for $\log g$ below 4.0 dex.

More recently, Holtzman et al. (2015) showed a similar trend for a subsample of red giants observed by the SDSS-III/ APOGEE survey.

Huber et al. (2014, hereafter H14) updated the stellar properties of the Kepler targets by fitting stellar parameters available in the literature to isochrones for a grid of stellar models. In that work, they also detected oscillations in almost 3000 stars that were unclassified in the KIC, allowing them to classify these stars as red giants. Precise knowledge of the stellar properties, and in particular the masses and radii of planet host stars, is important, as it can have a dramatic impact on the estimation of the size of the planet detected with the transit method employed by the Kepler mission.

With long-cadence data for all of the stars, we can look for signatures of oscillations in the stars which would help us to classify them as dwarfs or red giants. Indeed, for most giants and some classical pulsators, the modes are visible below the long-cadence Nyquist frequency (Huber et al. 2013). Here, we analyzed GKMs stars as described in Section 2 and classified as dwarfs in the H14 catalog to confirm their status as dwarfs. In Section 2, we briefly describe the target selection and how the Kepler light curves were calibrated. Section 3 provides the seismic analysis of the stars where we detected oscillations in the Kepler data. We also derive revised effective temperatures and distances. In Section 4, we discuss the results of this sample and we provide our conclusions in Section 5.
2. STAR SELECTION AND PHOTOOMETRIC CALIBRATION

From the H14 catalog, we selected GKM dwarfs according to the following criteria: \( \log g \geq 4.25 \) and \( T_{\text{eff}} \leq 5500 \) K. This temperature cut ensures little pollution from F stars in our sample, although we do lose the hottest G-type stars. The \( \log g \) cut ensures that we do not have subgiants in our sample. We also added a few tens of stars from the asteroseismic sample of solar-like stars from Chaplin et al. (2011) where red-giant-like oscillations were detected. These additional stars have \( T_{\text{eff}} > 5500 \) K. This led to a sample of 45,431 stars. We calibrated the long-cadence light curves following García et al. (2014a) and S. Mathur et al. (2016, in preparation) using all of the available \textit{Kepler} quarters. Given the way the \textit{Kepler} mission operated, some of these stars had a variety of observation lengths ranging from 1 month to almost 4 years. We concatenated the quarters when the stars were observed for several quarters. We also applied the gap-filling technique as described in Pires et al. (2015) to reduce the effects of the observational window function (García et al. 2014a). Gaps up to 783 data points (16 days) were filled. Then, we visually checked the light curves and their associated power spectra.

Out of the 45,431 stars, we flagged 1107 stars that clearly showed oscillation modes or a red-giant like excess of power in the power spectrum. Most of the selected stars have effective temperatures above 4000 K. This agrees with the fact that the dwarf-giant classification in the KIC is more reliable for \( T_{\text{eff}} < 4000 \) K (Mann et al. 2012).

During our visual inspection of the power spectra, we divided the stars into three different categories for the seismic analysis described in Section 3.1: (1) stars with modes located below 10 \( \mu \)Hz, (2) stars with modes between 10 and 200 \( \mu \)Hz, and (3) stars with modes above 200 \( \mu \)Hz. Because the modes of the first group are at very low frequency, we applied a high-pass filter with a lower cut-off frequency. The last category corresponds to stars where we can observe modes that are above the Nyquist frequency and that could be reflected to lower frequency (Chaplin et al. 2014). These stars were analyzed in a different way to avoid a wrong estimation of \( \log g \). This led to a sample of 121 stars to be studied with modes below 10 \( \mu \)Hz, 723 stars between 10 and 200 \( \mu \)Hz, and 137 stars above 200 \( \mu \)Hz. We also flagged 126 stars that had either a lower signal-to-noise ratio (S/N) or a less clear oscillation pattern. In the following section, we explain how to characterize these stars to confirm the existence of p-mode oscillations, and thus define the final set of stars to be studied.

In the final study sample, stars have been observed for different durations. We note that among the 1107 stars, 125 stars have less than three quarters available, which means that they have a lower frequency resolution in the power spectra.

3. SEISMIC CHARACTERIZATION OF THE STARS

3.1. Determination of The Acoustic-mode Global Parameters

We analyzed the light curves and power spectra of the 1107 stars selected above using the A2Z pipeline (Mathur et al. 2010) and the SYD pipeline (Huber et al. 2009) to determine the global parameters of the acoustic modes. In order to better observe the modes below 10 \( \mu \)Hz, we applied a high-pass filter with a boxcar width of 40 days, corresponding to a cut-off frequency of 0.29 \( \mu \)Hz, so that the high-pass filter does not affect the very low-frequency modes. For the remaining stars, we used a boxcar width of 20 days (i.e., 0.58 \( \mu \)Hz).

We applied an improved version of A2Z (hereafter A2Z+) to determine a more precise value of the mean large frequency separation, \( \Delta \nu \), which is the distance between modes of the same degree and of consecutive orders. We computed a first estimation of \( \Delta \nu \) with the auto-correlation function (Moss & Appourchaux 2009), determined the frequency of the highest \( \ell = 0 \) mode close to \( \nu_{\text{max}}(\nu_{\ell=0}) \), and then masked out the \( \ell = 1 \) modes. We recomputed the mean large frequency separation by calculating the power spectrum of the masked power spectrum (PS2) between \( \nu = 0 - k \times \Delta \nu \) and \( \nu = 0 + k \times \Delta \nu \). In general, we take \( k = 2 \) but the value of \( k \) can be different depending on the S/N and the frequency of maximum power, \( \nu_{\text{max}} \), of the star. The A2Z+ uncertainties were computed with the weighted centroids method that depends on the frequency resolution in the PS2. Given that in most cases we take the same number of orders around \( \nu_{\ell=0} \), the relative uncertainties are generally very similar for the different stars.

For those stars with modes above 200 \( \mu \)Hz, we applied a slightly different methodology as the modes observed can result from the reflection of modes oscillating above the Nyquist frequency of 283.21 \( \mu \)Hz (see Chaplin et al. 2014, for more details). The reflected modes retain the properties of the real modes, in particular, the mean large frequency separation. If the modes observed are actually oscillating above the Nyquist frequency, then the correspondence between the observed frequency of maximum power, \( \nu_{\text{max}} \), and \( \Delta \nu \) will show clear disagreement with the \( \Delta \nu \sim \nu_{\text{max}} \) relation (Stello et al. 2009). To analyze these stars, we reconstructed the power spectrum by mirroring our power spectrum above the Nyquist frequency. This allowed us to measure \( \Delta \nu \) and \( \nu_{\text{max}} \) above and below \( \nu_{\text{Nyq}} \). Then, we checked which \( \nu_{\text{max}} \) agreed with \( \Delta \nu \) according to the seismic scaling relations (Kjeldsen & Bedding 1995; Stello et al. 2009). We first confirmed 61 stars that have \( \nu_{\text{max}} \) between 200 and 285 \( \mu \)Hz. After visual inspection of the spectra, we also confirmed the detection of modes for 31 more stars with \( \nu_{\text{max}} > 285 \) \( \mu \)Hz (3 stars with modes above the Nyquist frequency according to our method and 28 stars with partially observed modes). This partial mode detection only provides a very rough estimate of \( \nu_{\text{max}} \) and it is not possible to provide a reliable estimate of a seismic \( \log g \). Finally, we checked visually the results with échelle diagrams and adjusted \( \Delta \nu \) in order to have the straightest ridges for the \( \ell = 0 \) modes and validated the seismic parameters for the A2Z+ pipeline.

We found 875 stars with modes detected by either A2Z+ or SYD below the Nyquist frequency. Among these, eight stars have a low S/N and thus the detection is less clear, particularly the determination of the mean large separation. As we do see an excess of power, we list them in the same table without any value for \( \Delta \nu \) and a special flag (“S/N”).

We compared the results of the A2Z+ and SYD pipelines for 784 stars where both pipelines returned results. A more detailed description of the comparison between the two pipelines is given in the Appendix.

3.2. Blending Effects

Some of the detected oscillations may be affected by stars polluting the photometric aperture of the giant star. To check that this was not the case, we fit the background of the power spectra following Mathur et al. (2011) and Kallinger et al.
of confirmed misclassified stars of 854 stars: 820 stars with
$v_{\text{max}}$ well below Nyquist, 31 near/super-Nyquist stars, and 3
stars that could result from pollution and that have the comment
“PP” (for Possible Pollution).

In addition to the visual check of the J-band images for this
subsample of stars, we also looked at the crowding of the whole
sample of stars. The crowding is provided on the MAST and
is defined as the ratio of the target flux to the total flux in the optimal
aperture. The optimal aperture is computed by the NASA Pre-
search Data Conditioning (for more details see Jenkins et al. 2010).
In this paper, we define a crowding value of 1 when all of the flux
belongs to the main target. Since the satellite rolls every three
months to keep its solar panels toward the Sun, the aperture, and
thus the crowding, changes every quarter (as described in the
NASA Kepler release notes). We computed the crowding as the
median value of all of the quarters. The values of crowding for
each target are listed in Tables 1 and 3. Figure 2 shows the
distribution of the crowding for the 854 stars. Most of the stars
have a crowding larger than 75%, meaning that most of the flux is
coming from the main target and the probability that there is a
nearby star polluting the light curve is low. Stars with a crowding
value below 75% should be considered very cautiously. They have
the comment “CR” (for Crowding’) in the last column of Table 1.

Tables 1 and 2 list the seismic parameters obtained by the
A2Z+ and SYD pipelines, respectively. Table 3 gives the seismic
parameters from A2Z+ for the near and super-Nyquist stars.

One of these stars, KIC 7292836, could be a seismic binary
where we see two regions with modes. After changing the
aperture for this star, by using a smaller number of pixels to
produce the light curves and inspecting the J-band image, we
could not see a nearby star. We provide the seismic parameters
of the two power excesses.

3.3. Revised Effective Temperatures and Distances

Previous estimates of the effective temperatures for this
sample were mostly based on matching broadband photometry
to models assuming a simple reddening law as part of the
classifications for the KIC. If the stars are indeed giants instead
of dwarfs, then these temperatures will be underestimated since
the stars are more distant and therefore more reddened than
initially assumed.

To determine revised temperatures and distances for the
sample, we used broadband photometry, asteroseismic observ-
ables, and a grid of Parsec isochrones (Bressan et al. 2012).
The grid ranges from 0.5 to 14 Gyr with a stepsize of 0.5 Gyr
and from $Z = 0.001$ to 0.03 with a stepsize of 0.0001
(corresponding to metallicities between $[\text{Fe}/\text{H}] = -2.18$ and $[\text{Fe}/\text{H}] = +0.42$), and was calculated with a Reimers mass loss
parameter set to $\eta = 0.2$.

Given a set of observables $x = \{J - K, H - K, g - r, r - i, v_{\text{max}}, \Delta v\}$ with Gaussian uncertainties $\sigma_x$ and a set of intrinsic
parameters $y = \{\text{age}, [\text{Fe}/\text{H}], \text{mass}\}$, we calculated the posterior
probability of the observed star having intrinsic parameters $y$ as

$$p(y|x) \propto p(y)p(x|y) \propto p(y) \prod_i \exp \left( -\frac{(x_i - \mu_i(y))^2}{2\sigma^2_{x,i}} \right). \quad (1)$$

For $p(y)$, we adopt a flat prior on age and mass, and a
metallicity prior derived from the Geneva Copenhagen survey

\footnotesize{(2014) and computed the maximum amplitudes per radial mode
of the acoustic modes. These parameters are related to the
luminosity of the stars, as already shown in previous works
(Huber et al. 2011; Stello et al. 2011). We plot in Figure 1
the maximum amplitude per radial mode as a function of $v_{\text{max}}$
for the new classified red giants and compare them to the values
calculated for a known sample of red giants studied within the
Kepler Asteroseismic Scientific Consortium (KASC). These
stars are red giants as listed in the KIC and astrometric
references stars (Batalha et al. 2010). Based on the KASC
sample, Huber et al. (2011) determined that $A_{\text{max}} \propto v_{\text{max}}^{-0.8}$.
From Figure 1, we can infer a lower limit of the relation
($5.10^2 \times v_{\text{max}}^{-0.8}$) below which there are no KASC stars. We
find 50 stars that have an abnormally low $A_{\text{max}}$. This lower
amplitude can be explained by the fact that if a red giant has a
nearby companion, then its light is going to be diluted by the
nearby star, causing a decrease of the measured amplitude of
the brightness variation. For this sample of stars, we checked
the UKIRT images in the J band within 2 arcmin of the target.
We found that 36 stars out of the 50 stars with low $A_{\text{max}}$
could indeed be polluted by a brighter nearby star. They are flagged
in the Flag column of Table 1 as “PB” (for Possible Blend). For the
remaining stars that have $A_{\text{max}}$ in agreement with the KASC
red giants, the UKIRT images suggest that 62 stars have a
nearby star that could pollute the main target.

Some of the oscillations detected could be due to a known
red giant leaking onto the pixels of the dwarf. We searched for
known red giants (either with detected oscillations or classified
as red giants in the H14 catalog) that were within a radius of
1 arcmin (15 pixels) from the misclassified stars. The compari-
on of the power spectra of nearby known red giants with the
misclassified stars showed that 52 stars out of the 875 stars with
modes below Nyquist have the same power spectra, and thus
the mode-detection results from pollution. We discarded these
52 stars from our sample. There are three additional stars (KIC
4907817, 8246648, and 9788579) where the power spectra
look similar, but the length of data available is different for the
two samples of stars without any overlapping quarters making
it more difficult to compare them. This leads to a final sample

8 http://surveys.roe.ac.uk/WSA/

9 https://archive.stsci.edu/kepler/
Table 1
Seismic and Fundamental Parameters of the Misclassified Red Giants Obtained for the A2Z+ Pipeline

| KIC     | Kp   | Teff (K) | Teff (K) | Δν (μHz) | νmax (μHz) | log g | M* (M*) | R* (R*) | d (kpc) | Crowding | Flag |
|---------|------|----------|----------|----------|------------|-------|----------|---------|---------|----------|------|
| 893233  | 11.4 | 4204±15   | 4285±9   | 1.03 ±0.18 | 6.1 ±0.4   | 1.67 ±0.03 | 1.51 ±0.56 | 29.59 ±7.58 | 1.66±0.32 | 0.98     | ...   |
| 1027110 | 12.1 | 4415±16   | 4272±8   | 1.13 ±0.11 | 6.6 ±0.4   | 1.71 ±0.03 | 1.31 ±0.29 | 26.56 ±4.01 | 2.06±0.13 | 0.98     | ...   |
| 1160684 | 14.9 | 4137±12   | 4571±9   | 3.59 ±0.10 | 27.5 ±1.4  | 2.34 ±0.02 | 1.03 ±0.11 | 13.34 ±0.75 | 3.76±0.08 | 0.91     | ...   |
| 1162220 | 11.2 | 4284±13   | 4303±8   | 1.68 ±0.05 | 11.1 ±0.7  | 1.94 ±0.03 | 1.29 ±0.16 | 20.28 ±1.56 | 1.21-0.07 | 0.99     | ...   |
| 1163114 | 12.7 | 4211±13   | 4440±8   | 1.91 ±0.20 | 14.2 ±0.7  | 2.05 ±0.02 | 1.70 ±0.39 | 20.39 ±3.20 | 2.63-0.26 | 0.97     | ...   |
| 1164356 | 14.1 | 5225±15   | 5360±12  | 3.33 ±0.09 | 27.8 ±1.8  | 2.38 ±0.03 | 1.83 ±0.24 | 14.43 ±1.14 | 6.91±0.21 | 0.74     | ...   |
| 1164584 | 14.3 | 4333±12   | 4546±9   | 3.35 ±0.12 | 28.8 ±1.4  | 2.36 ±0.02 | 1.55 ±0.18 | 13.60 ±0.97 | 3.77-0.29 | 0.95     | ...   |

Note.

* Kp, Teff, Teff*, log g, M*, R*, and d are, respectively, Kepler magnitude, the values of effective temperature from H14, the revised effective temperature from Section 3.3, surface gravity, mass, radius from scaling relations, and distance from isochrone calculation using the scaling relations grid spacing in mass, age, and metallicity.

We note that we assumed the targets to be single stars when deriving the distances, but that effect should be small.

For the stars with νmax below the Nyquist frequency, we computed the mass, radius, and log g using the scaling relations along with the updated effective temperature. The stellar parameters are all listed in Tables 1 and 2, respectively, for the A2Z+ and SYD pipelines. For those stars with modes near or above the Nyquist frequency, we only computed the log g as we only have a very rough estimate of νmax. The seismic parameters for this subsample of stars are given in Table 3.

Figure 2 shows a log g versus Teff diagram comparing the positions of the sample before and after the re-derivation of log g and Teff. Note that the log g values for the sample were calculated using the νmax scaling relations with the revised Teff.

As expected, most stars shift to hotter temperatures since the de-reddened colors assuming larger distances are bluer than the de-reddened colors assuming that the stars are dwarfs.

3.4. Mixed Modes and Evolutionary Stage

As stars evolve to become red giants, the acoustic modes in the stellar envelope start to couple with the gravity modes in the core, which leads to the so-called mixed modes (Dupret et al. 2009). Mixed modes have been observed in several thousand giants in the Kepler field (e.g., Beck et al. 2011; Bedding et al. 2011; Mosser et al. 2012; Stello et al. 2013). Because of their partly gravity-mode nature, they are sensitive to the stellar core properties and, in particular, whether a star is ascending the red giant branch (with an inert core and only burning hydrogen in a shell) or if it is a red clump star also burning helium in the core (Bedding et al. 2011; Mosser et al. 2014). This classification into red giant branch and red clump stars shows up as a difference in the period spacing of consecutive overtone mixed modes. We therefore attempted to measure the median period spacing for each star in our sample using the method by Stello et al. (2013). Figure 4 shows the median period spacing versus Δν for the 279 stars where we could obtain a clear classification after verification by visual inspection of the power spectra. Some of the red giant branch stars at low Δν are artificially pushed up to larger period spacings by the method. In this region, between the red clump and the red giant branch, the classifications, shown by symbol type, rely on the visual inspection of the power spectra. Compared to the large “typical” Kepler sample of giants...

Figure 2. Histogram of the crowding as described in Section 3.2 for the 854 misclassified red giants.

(Casagrande et al. 2011), which has been shown to agree well with the metallicity distribution of Kepler targets (Dong et al. 2014). We used 2MASS J − H and H − K colors if all three bands have the highest photometric quality flag (Qflag = “AAA”), and KIC g − r, r − i colors otherwise. For the KIC photometry, we interpolated uncertainties as a function of KP using the typical values taken from Figure 3 in Brown et al. (2011). Nine stars did not have all the colors available or an insufficiently high quality flag, and so they do not have results from this method. Model colors and distances are calculated from absolute magnitudes, which are reddened using the three-dimensional (3D) extinction map by Amôres & Lépine (2005) for distances corresponding to the apparent magnitude (either J band or g band) and galactic coordinates of a given target. Values for νmax and the Δν values for each model were calculated using the scaling relations (Kjeldsen & Bedding 1995), assuming solar reference values of νmax = 3090 μHz and Δν = 135.1 μHz (Huber et al. 2011). Temperatures and distances were then derived from the median and 1σ confidence interval of the probability distribution function obtained by integrating p(y|x) along the isochrone grid, weighted by local grid spacing in mass, age, and metallicity (Serenelli et al. 2013).
analyzed by Stello et al. (2013, their Figure 4(a)), we see that our new sample here is strongly dominated by low-mass stars; only very few clump stars with masses above about 2 $M_\odot$ are present (marked 2ndRC). The classifications along with the value of the median period spacings are given in Table 4. We note that given the method to determine the median period spacings, they are not suitable for direct model comparison and serve here merely as a way to classify the stellar evolutionary state.

4. DISCUSSION OF THE SAMPLE

4.1. Faint Stars and Distances

We looked at the distribution of some of the stellar properties of the misclassified red giant sample. Figure 5 shows the distribution of the Kepler magnitude for the confirmed red giants and for the ~13,000 public red giants in Huber et al. (2011). We clearly see that the new red giant sample is very different from the known red giants.
giants sample: they are much fainter than the previously known sample. Even though the stars are so faint, we are still able to detect solar-like oscillations and characterize their global properties. It seems from Figure 5 that Kepler would have been able to detect oscillations in giants even fainter than $K_p = 16$ if they had been observed. This result is very promising for missions like K2 (Howell et al. 2014) and its galactic archeology program (Stello et al. 2015) and the Transiting Exoplanet Survey Satellite (Ricker et al. 2015).

Figure 6 shows the distance distribution of the newly classified red giants of our sample (solid line) compared to the distances of the APOKASC red giants (dashed line) from Rodrigues et al. (2014).

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Figure 6 shows the distance distribution of the newly classified red giants compared to another sample of red giants observed by Kepler. Rodrigues et al. (2014) determined the distances of $\sim 2000$ Kepler red giants that also had spectroscopic observations with the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2015). Their sample of stars (hereafter called the APOKASC sample) had distances up to $\sim 4$ kpc. We note that the distances of the new red giants are quite large compared to the APOKASC sample and go well beyond 10 kpc. Our sample of new red giants has 404 stars at a distance larger than 5 kpc. This new sample allows us to probe our Galaxy further away and study stellar populations in a different region compared to what has been done so far with the CoRoT and Kepler missions. This can be seen in Figure 7, which is an update of Figure 2 of Miglio et al. (2015).
We also computed the heights of the stars with respect to the Galactic plane to infer the possible number of halo stars present in our sample. Their positions in the Galaxy are shown in the bottom panel of Figure 7. Figure 8 shows the distribution of the heights of the misclassified stars. We compared this distribution with a synthetic population of halo stars in the Kepler field with $J < 16$ generated using Galaxia (Sharma et al. 2011), which shows that the majority of stars ($\geq 60\%$) above 5 kpc are halo stars, while the fraction of halo stars drops rapidly toward the galactic plane ($\leq 2\%$ below 2 kpc). We divided the fraction of halo stars from the Galaxia model and our observed sample in height bins of 2 kpc to estimate the number of potential halo stars in each bin, yielding a total of about 40 red giants in our sample which could be halo stars. We note that this estimate is statistical only, and may be affected by systematic errors in the Galaxy model.

4.2. Mass Distribution of The Sample

Figure 9 (top panel) presents the mass distribution of the newly classified red giants and the KASC sample of red giants (e.g., Huber et al. 2011, red dashed line). Both samples peak at around $1.2 M_\odot$. However, we clearly see that the number of high-mass ($M$ larger than $1.3 M_\odot$) stars is smaller in our new sample compared to the KASC one, as already noted in Section 3.4. There are slightly more stars with masses below $1.1 M_\odot$. This agrees with the fact that these stars are more distant, and thus possibly halo stars. In the middle panel of Figure 9 we also note that the low-mass stars are generally fainter ($K_p > 14$).

In fact, the generally lower mass of the sample would imply larger expected amplitudes at a given $\nu_{\text{max}}$ (Stello et al. 2011). In Figure 1, we note that there are some stars with a slightly higher mode amplitude ($A_{\text{max}}$) compared to the general trend. We looked at the masses of the low-amplitude mode stars but did not find any systematic low-mass stars.

Given that some of these stars could belong to the halo and are thus metal-poor stars, some of the masses derived with the scaling relations should be taken cautiously. Indeed, Epstein et al. (2014) studied a sample of halo stars observed by Kepler and showed that the scaling relations seem to deviate. As we do not have reliable metallicity measurement for these stars yet, we cannot remove the metal-poor stars from the sample.
We note that there are two stars (KIC 4850755 and 6266309) with mass below 0.4 \( M_\odot \). Their parameters seem correct, although KIC 4850755 seems a little odd based on visual inspection with a low number of modes observed and low amplitude for the \( l = 1 \) modes as reported, for example, by García et al. (2014b), and theoretically explained by Fuller et al. (2015) and Stello et al. (2016). It could also be that scaling relations are not valid for such low-mass stars. More stars of this type would be needed to verify the validity of the scaling relations in this mass regime.

We also looked at differences in the mass distribution as a function of distance (see bottom panel of Figure 9). We divided the sample into stars with distances larger than 5 kpc and stars with distances smaller than 5 kpc. The general distribution of both samples is very similar.

### 4.3. Possible Explanations for Dwarf Classification

We checked the type of data and analysis that were used in the Kepler H14 catalog to derive the effective temperature and the surface gravity of the 854 confirmed red giants. The majority of the stars of our sample have values obtained from the KIC. However, 24 stars have their \( \log g \) determined by Huber et al. (2014) based on photometric observations and 8 stars were characterized by the work of Dressing & Charbonneau (2013), who analyzed optical and near-infrared photometry from the KIC to improve the stellar parameters of the cool Kepler dwarfs.

Recently, Gaidos et al. (2016) classified the cool Kepler dwarfs. We found six stars that overlap with our sample. They have the flag “PM” for “Possible M dwarfs.” Four of them either display a low crowding value or are possible pollution.

We previously mentioned that the misclassified stars have their parameters determined from photometric observations. Distinguishing the luminosity class between dwarf and red giants can be a difficult task when only using multi-color photometry and the respective color indices. In approximately 4% of KIC targets, there were significant discrepancies between different photometric temperature indicators (Pinsonneault et al. 2012). This fraction was comparable to the 3.8% of targets with significant blends, estimated from a comparison of KIC photometry to that of the higher angular resolution SDSS photometry. In an even smaller minority of cases, the gravity classification was also in significant error, most likely due to a similar cause. Thus, it is not surprising that 854 stars (less than 0.5% of the Kepler targets) were misclassified. This number of stars is actually remarkably low given the large number of targets.

### 4.4. Planet-candidate Host Stars

Five of the newly classified red giants are planet-candidate hosts stars. In Table 5, we compare the new seismic stellar characteristics of these stars with those of the known planet-host stars from the Kepler mission.
radius with the H14 value. Most of these stars were classified as M dwarfs but, now that they are classified as red giants, their new radii are 7–21 times larger than the ones listed in the H14 catalog.

We combined our revised stellar radii with the transit depths listed at the NASA Exoplanet Archive\(^{10}\) to re-calculate the planet-candidate radii, also given in Table 5. To calculate the uncertainties on the planet radius, we used a symmetric uncertainty on the ratio \(R_p/R_\star\) where we decided to take the largest values of the positive and negative values and then propagated the error bars. Given the new classification of the host stars, the estimated planet sizes have changed from Earth-size/superEarth-size planets to objects bigger than \(5 \times R_\oplus\).

To re-evaluate the planet-candidate status, we used the revised stellar mass and radius to estimate the expected transit duration for a circular orbit and compared this to the observed transit durations. For three planet-candidate hosts (KOI-5652, KOI-5859, KOI-2813), the observed durations are significantly shorter than expected for a planet orbiting an evolved star, indicating that the planet candidate would have to be either on a highly eccentric orbit or have an extremely high impact parameter. Inspection of the data validation reports showed that KOI-5652 and KOI-5859 both have low S/Ns, and hence are likely spurious detections due to the high correlated noise in giants due to stellar granulation. KOI-2813 is flagged as a likely false positive according to spectroscopic follow-up observations by the Kepler Community Follow-Up\(^{11}\), which is supported by our reclassification of the host star. Finally, KOI-4902.01 and KOI-6217.01 show transit durations which are shorter than expected for a planet orbiting an evolved star, likely false positive according to spectroscopic follow-up studies (e.g., Miglio et al. 2013; Stello et al. 2015) as these stars probe the edge of the Milky Way. They will be observed by APOGEE in order to study their composition and obtain additional information to better understand the chemical evolution of the Galaxy.

The authors would like to thank A. Miglio for his help to make Figure 7 of this paper. The authors would like to thank M. H. Pinsonneault for useful discussions. The authors are also thankful to J. L. van Saders for her help with the UKIRT J-band images. S.M. acknowledges support from the NASA grant NNX12AE17G. S.M. and D.H. acknowledge support by the National Aeronautics and Space Administration under grant NNX14AB92G issued through the Kepler Participating Scientist Program. R.A.G., P.G.B., and K.H. acknowledge the support of the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 269194 (IRSES/ASK). R.A.G. and P.G.B. acknowledge the support by the French ANR/IDEE grant. This research was supported in part by the National Science Foundation under grant No. NSF PHY11-25915. D.H. acknowledges support by the Australian Research Council’s Discovery Projects funding scheme (project number DE140101364). This work has received funding from the CNES.

### 5. CONCLUSIONS

The analysis of 45,431 dwarfs from the Q1-Q16 Kepler star properties catalog (Huber et al. 2014) led to the reclassification of 854 stars as red giants, among which 31 stars have modes close to or above the Nyquist frequency. A comparison of the power spectra with known red giants and inspection of the UKIRT J-band images suggests that some of these newly classified red giants could still result from the presence of a nearby star.

We analyzed the light curves with two different pipelines, \(\Delta z^+\) and SYD, and measured the global parameters of the acoustic modes. We then computed stellar fundamental parameters such as mass and radius from scaling relations and revised effective temperatures and distances from the isochrone fitting for stars with modes below Nyquist frequency and for which colors were available. Among that sample of stars, we determined the evolutionary stage of 279 stars based on the period spacing of mixed modes.

We find that the new red giants in this sample are less massive, fainter, and more distant than the previously known sample of red giants observed by Kepler, extending the parameter space. This work demonstrates that we can push the mode-detection limits in red giants to much fainter stars up to \(K_p\) around 16.

These faint red giants represent a goldmine for galactic archaeology studies (e.g., Miglio et al. 2013; Stello et al. 2015) as these stars probe the edge of the Milky Way. They will be observed by APOGEE in order to study their composition and obtain additional information to better understand the chemical evolution of the Galaxy.

### APPENDIX

## COMPARISON OF THE \(\Delta z^+\) AND SYD PIPELINES

### A.1. Seismic Parameters

The \(\Delta \nu\) and \(\nu_{\text{max}}\) comparison for 748 stars is shown in Figure 10. For 97.7% of the stars, the agreement in \(\Delta \nu\) is better than 1\(\sigma\). Concerning \(\nu_{\text{max}}\), both pipelines agree within 1\(\sigma\) for \(\sim 98.7\%\) of the stars. The relative difference in \(\Delta \nu\) (resp. \(\nu_{\text{max}}\)) is lower than 3\% (resp. 85\%) of the stars. The disagreement is larger in two regions; at very low frequency (\(\nu_{\text{max}} < 10 \mu\text{Hz}\) and \(\Delta \nu < 2.5 \mu\text{Hz}\)) and around \(\nu_{\text{max}} \sim 30 \mu\text{Hz}\) and \(\Delta \nu \sim 4 \mu\text{Hz}\).
At very low frequency, due to the limited resolution and lower number of modes observed, it can be more difficult to fit a Gaussian to the excess power (method used by A2Z+ to estimate $\nu_{\text{max}}$). Moreover, the computation of $\nu_{\text{max}}$ is obtained after subtracting the background. As a consequence, if the background is fit slightly differently by each method, then it can affect the position of the maximum power. Moreover, in this frequency range, the modes show stronger non-asymptotic behavior (Stello et al. 2014). So a slight difference in the number of orders taken to compute the mean large frequency separation and the frequency range can have an impact on the final estimate of $\Delta \nu$. We performed a few tests with A2Z+ and found that, in some cases, it can lead to more than 3% change in $\Delta \nu$ for low $\nu_{\text{max}}$.

The second frequency range where the largest disagreements are found corresponds to the clump stars where the mixed modes (resulting from the coupling between the p-mode and g-mode cavities) are clearly present, making the determination of $\Delta \nu$ more difficult to obtain.

There are 18 stars that disagree by more than 1σ in terms of $\Delta \nu$. For 11 of them, the difference is of the order of a few 0.01 $\mu$Hz. For the remaining 7 stars, the S/N is too low to see if one value is better than the other. In terms of $\nu_{\text{max}}$, 10 stars disagree by more than 1σ among which two (KIC 5351659 and 10587397) have very low S/Ns. After visual inspection, for six stars (KIC 2422890, 4383163, 5976435, 9589159, 9712670, and 12599753), the A2Z+ value seems to be a better representation of $\nu_{\text{max}}$ while for two stars (KIC 5036900 and 6525060) the SYD value seems to be closer to the observed $\nu_{\text{max}}$.

We note that the uncertainties provided by the two pipelines are quite different. For $\nu_{\text{max}}$, SYD has an average uncertainty of $\sim 2\%$ and A2Z+ around $6\%$. For $\Delta \nu$, SYD has an average uncertainty of 0.6% compared to 3% for A2Z+. This difference is due to the different methods used. A2Z+ uncertainties are computed based on power centroids methods as described in Hekker et al. (2010), which is known to be quite conservative. The uncertainties of the SYD pipeline are computed through Monte-Carlo simulations by perturbing the power spectrum according to a $\chi^2$ distribution with two degrees of freedom, and

![Figure 10](image1.png)

**Figure 10.** Difference in the mean large separation (left panel) and the frequency of maximum power (right panel) between the two pipelines A2Z+ and SYD as a function of the A2Z+ values (top panel) and in units of $\sigma$ computed as the quadratic sum of the uncertainties from A2Z+ and SYD (bottom panel).

![Figure 11](image2.png)

**Figure 11.** HR Diagram obtained for the two pipelines where the effective temperature was computed with the isochrone fitting code (see Section 3.4) and the surface gravities were calculated from the scaling relations.
repeating the $\nu_{\text{max}}$ and $\Delta \nu$ measurements 500 times per star. The uncertainties are then estimated from the standard deviation of the resulting $\nu_{\text{max}}$ and $\Delta \nu$ distributions.

A.2. Stellar Fundamental Parameters

As explained in Section 3.3, we computed the revised effective temperature of these stars by fitting isochrones and using constraints on the colors and the seismic parameters ($\Delta \nu$ and $\nu_{\text{max}}$). Figure 11 represents the HR Diagram for the two pipelines with the revised effective temperature and the seismic $\log g$ from scaling relations. We can see that they look very similar even with slightly different seismic parameters.

Figure 12 represents the comparison of the effective temperature and the distance for both pipelines. We note that the stellar parameters obtained from the isochrones fitting agree well within the uncertainties. Since the main contributors for the determination of the effective temperatures are the colors, the difference in the uncertainties on this parameter between A2Z+ and SYD is small. The seismic parameters have more impact on the distance derivation. We note that while the average uncertainty on $\Delta \nu$ (resp. $\nu_{\text{max}}$) is five times (resp. three times) larger for A2Z+ compared to SYD the mean relative uncertainty on the distance is 1.6 times larger for A2Z+ than for SYD.

Finally, we compare the distribution in radius and mass computed with uncorrected scaling relations between A2Z+ and SYD in Figure 13. We can see that the distributions are quite similar and agree well within the uncertainties. Here, we can note the difference in the uncertainties due to the larger uncertainties on the seismic parameters for the A2Z+ pipeline as explained in the previous section.

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ERRatum: “Probing the Deep End of the Milky Way with KeplEr: AsteroSeismic Analysis of 854 Faint Red Giants Misclassified as Cool Dwarfs” (2016, ApJ, 827 50)

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Received 2016 October 3; published 2016 December 21

Supporting material: machine-readable tables

1. NEW DISTANCES

We report here new distances of the misclassified red giants after noticing a coding error in the isochrone fitting code used to derive them (also explained in Mathur et al. 2016). Briefly the extinctions for the g band and the J band were swapped leading to incorrect distances. This affects the effective temperatures of 40 stars (less than 5% of the sample) with a 0.2% change in average. This has a very negligible impact on the other stellar parameters (mass, radius, surface gravity). We provide here the updated figures and tables with the correct distances. The distances are in average 20% larger than before and up to 50% for some individual stars. The conclusions of the main paper remain the same. The number of possible halo stars also increases from 40 to 44.

Figure 1. Normalized distribution of the distances in parsec for the confirmed red giants of our sample (solid line) compared to the distances of the APOKASC red giants (dashed line) from Rodrigues et al. (2014).
Figure 2. Position in the Galaxy of the new red giants (green circles) compared to the stars in the CoRoT (blue dots), Kepler (red dots), and K2 fields (solid lines) as a function of x and y (top panel) and x and z (bottom panel).
Figure 3. Distribution of the heights of the misclassified red giants.

Figure 4. Comparison of the effective temperature and distance obtained from the isochrone fitting code for the two pipelines.

Table 1

| KIC      | d (kpc) |
|----------|---------|
| 893233   | 2.12^{+0.40}_{-0.40} |
| 1027110  | 2.66^{+0.87}_{-0.17}  |
| 1160684  | 4.81^{+1.12}_{-0.30}  |
| 1162220  | 1.53^{+0.25}_{-0.09}  |
| 1163114  | 3.40^{+0.44}_{-0.33}  |
| 1164356  | 9.00^{+0.32}_{-0.22}  |
| 1164584  | 4.90^{+0.38}_{-0.71}  |
| 1292147  | 4.08^{+0.90}_{-0.39}  |
| 1293587  | 2.78^{+0.23}_{-0.16}  |
| 1429629  | 5.0^{+0.88}_{-0.41}   |
| 1431059  | 1.3^{+0.10}_{-0.09}   |

(This table is available in its entirety in machine-readable form.)
Table 2
Distances of the Misclassified Red Giants Obtained for the SYD Pipeline

| KIC     | d (kpc)               |
|---------|-----------------------|
| 893233  | $1.85^{+0.08}_{-0.04}$ |
| 1027110 | $2.74^{+0.19}_{-0.16}$ |
| 1160684 | $4.82^{+0.12}_{-0.10}$ |
| 1162220 | $1.56^{+0.14}_{-0.08}$ |
| 1163114 | $3.37^{+0.20}_{-0.13}$ |
| 1164356 | $8.00^{+0.05}_{-0.08}$ |
| 1164584 | $4.89^{+0.10}_{-0.27}$ |
| 1292147 | $3.90^{+0.16}_{-0.14}$ |
| 1429629 | $4.90^{+0.23}_{-0.13}$ |
| 1431059 | $1.31^{+0.05}_{-0.04}$ |
| 1431599 | $4.17^{+0.19}_{-0.19}$ |

(This table is available in its entirety in machine-readable form.)

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