OSCILLATING RED GIANTS OBSERVED DURING CAMPAIGN 1 OF THE KEPLER K2 MISSION:
NEW PROSPECTS FOR GALACTIC ARCHAEOLOGY

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ABSTRACT

NASA’s re-purposed Kepler mission—dubbed K2—has brought new scientific opportunities that were not anticipated for the original Kepler mission. One science goal that makes optimal use of K2’s capabilities, in particular its 360° ecliptic field of view, is galactic archaeology—the study of the evolution of the Galaxy from the fossil stellar record. The thrust of this research is to exploit high-precision, time-resolved photometry from K2 in order to detect oscillations in red giant stars. This asteroseismic information can provide estimates of stellar radius (hence distance), mass, and age of vast numbers of stars across the Galaxy. Here we present the initial analysis of a subset of red giants, observed toward the north galactic gap, during the mission’s first full science campaign. We investigate the feasibility of using K2 data for detecting oscillations in red giants that span a range in apparent magnitude and evolutionary state (hence intrinsic luminosity). We demonstrate that oscillations are detectable for essentially all cool giants within the log g range ∼1.9–3.2. Our detection is complete down to $K_p \sim 14.5$, which results in a seismic sample with little or no detection bias. This sample is ideally suited to stellar population studies that seek to investigate potential shortcomings of contemporary Galaxy models.

Key words: Galaxy: evolution – Galaxy: stellar content – Galaxy: structure – stars: fundamental parameters – stars: oscillations

1. INTRODUCTION

The study of red giant stars has arguably been one of the greatest success stories of NASA’s Kepler mission (e.g., García 
& Stello 2015 and references therein). However, a failure of the second of four momentum wheels ended the mission in 2013 because the spacecraft could no longer acquire stable pointing toward its original field of view. Fortunately, ingenious use of the remaining spacecraft capabilities by NASA and Ball Aerospace engineers rejuvenated the mission as K2—a mission capable of stable pointing at any field along the ecliptic for up to approximately three months per pointing (Howell et al. 2014). In this configuration, the Kepler roll angle drifts due to a torque applied by solar radiation pressure, but this can be counteracted by thruster firings every six hours to maintain the spacecraft pointing. The K2 mission has enabled a broad range of new science including stellar clusters (Nardiello et al. 2015), planets around bright cool stars (Crossfield et al. 2015; Montet et al. 2015; Sanchis-Ojeda et al. 2015; Vanderburg et al. 2015), solar system objects (Szabó et al. 2015), stellar activity (Ramsay & Doyle 2015), eclipsing binaries (Conroy et al. 2014), asteroseismology (Jeffery 
& Ramsay 2014; Chaplin 2015; Lund et al. 2015), and, in particular, asteroseismological studies of the Galaxy.

The potential for asteroseismic investigations of large populations of red giants aimed at Galactic studies was recently demonstrated using data from CoRoT and Kepler (Miglio et al. 2009; Chaplin et al. 2011; Miglio et al. 2013; Casagrande 2015). However, the scope of these early studies was limited for two reasons: the small number of distinct directions in the Galaxy probed by those missions, and the highly complex (and, at some level, not fully documented) selection function of the observed red giants (S. Sharma et al. in preparation). With K2’s 360° coverage of the ecliptic the collated efforts from the K2 observing campaigns, provide a unique opportunity to probe different regions of the Galaxy, including the thin and thick disks, the halo, and the bulge, based on a purpose-built selection approach suitable for population studies.
In this Letter, we present initial results from the K2 Campaign 1 data. Based on a sample of red giants specifically selected to study stellar populations on a galactic scale, our aim is to determine if we can obtain an unbiased sample of stars showing oscillations—a crucial first step if these stars are to be used for galactic archaeology studies.

2. OBSERVATIONS AND LIGHT CURVE PREPARATION

We used observations obtained as part of the K2 Galactic Archaeology Program Campaign 1 (C1 proposal GO1059).\(^\text{17}\) For the purpose of this Letter, we focused on a targeted set of red giant candidates based on their spectroscopic log g values (log g < 3.8) drawn from APOGEE (Majewski et al. 2010), part of the Sloan Digital Sky Survey III (Eisenstein et al. 2011). The APOGEE survey used a wide-field multi-object H-band spectrograph (Wilson et al. 2010) on the 2.5 m Sloan Foundation telescope at Apache Point Observatory (Gunn et al. 2006). The red giants discussed here were observed as part of the main survey (Zasowski et al. 2013).

The spectra were reduced, wavelength-calibrated, and co-added as described by Nidever et al. (2015). The determination of stellar parameters from the automated pipeline is described by E. Garcia-Perez et al. (2015, in preparation). We used the parameters from Data Release 12 (Alam et al. 2015); the calibration and verification of the APOGEE DR 12 results is described by Holtzman et al. (2015). Of the 121 red giant candidates that satisfy the above-mentioned log g cut, 117 were observed in the K2 campaign. The stars span 2.8 dex in log g and seven magnitudes in apparent magnitude (9 ≤ Kp ≤ 16), and hence serve as a suitable benchmark set to characterize the K2 data fidelity, including the ability to detect oscillations for different levels of intrinsic and apparent brightness.

The photometric time series (light curves) from the raw K2 pixel data are currently not available from NASA. However, light curves created by Vanderburg & Johnson (2014, VJ hereafter) are publicly available\(^\text{18}\) and we used these data in our study. Power spectra of the light curves denoted “corrected” by VJ are shown in Figure 1 (black curves) for three stars. The 80-day duration of the light curves provides a nominal frequency resolution of ∼0.14 μHz, which imposes a lower limit on the frequency separation between overtone modes, Δν, that we can reliably determine (Huber et al. 2010; Hekker et al. 2012).

Through the tight correlation between Δν and ν_{max} (Stello et al. 2009), this translates into a lower limit of about 10 μHz in ν_{max}, and hence to the frequency range in which we can fully characterize the oscillations. By restricting our attention to higher-frequency stars, we are then free to apply a high-pass filter without compromising the oscillation signal. We chose a boxcar filter with a width of two days, resulting in a cutoff frequency of about 3 μHz (Figure 1, red spectra), without affecting the oscillation signal of our target stars. Applying a high-pass filter gives a significant reduction in the noise floor at all frequencies because it reduces spectral leakage of low-frequency power to higher frequencies, as seen by comparing the black and the red spectra in Figure 1.

Due to the roughly 6 hr drift and repositioning cycle, K2 data generally show trends on that time scale, and typically one data point is flagged unsuitable during the repositioning (see Vanderburg & Johnson 2014). The resulting regular gaps, combined with the slow drifts, can result in significant leakage of power toward higher frequencies in the power spectra. This offset can be avoided if the gaps are filled (García et al. 2014; Pires et al. 2015), for which we used linear interpolation for all gaps of up to three consecutive data points. Larger gaps were not filled. The interpolation used only the two points that bracketed each gap. In agreement with García et al. (2014) and Pires et al. (2015), we found that the stellar signal was not markedly affected. However, our ability to detect the oscillations was increased, particularly for stars oscillating at relatively high frequencies. This improvement is illustrated by comparing the red and green spectra in Figure 1. While gap filling should be used with caution, it is generally safe when the gaps are short and few compared to the total number of data points in the light curve (García et al. 2014; Pires et al. 2015). Here, we filled 3%–4% of all data points. For these K2 data, the gap filling results in almost complete removal of peaks in the power spectra at the re-positioning frequency and its harmonics (Figure 1, dotted lines), which are otherwise disruptive for the automated detection of oscillations and extraction of the global seismic properties. In the following analysis, we use the high-pass filtered, gap-filled light curves.

In future work, we will explore other schemes for directly modeling instrumental variability. In particular, Angus et al. (2015) have recently proposed a scheme that alleviates the need for gap filling in time series data to produce K2 power spectra that are less sensitive to systematic effects.

17 http://keplerscience.arc.nasa.gov/K2/index.shtml
18 https://www.cfa.harvard.edu/~avanderb/k2.html
3. OSCILLATION ANALYSIS

The power spectra of many stars in our sample reveal clear oscillations ranging from low-luminosity giants near the bottom of the red giant branch to stars more luminous than the red clump. The detected oscillations cover the same frequency range as early Kepler light curves of similar length (Huber et al. 2010). Figure 2 presents power spectra of a representative subset of our sample. In each star, we see the oscillation power excess forming a near regular series of peaks from overtone modes within a broad envelope, from which \( v_{\text{max}} \) and \( \Delta \nu \) can be measured.

We carried out a systematic search for oscillations using the pipeline developed by Huber et al. (2009). After inspecting the power spectra and the diagnostic output from the automated detection algorithm, we classified the stars into three groups. A total of 59 stars provided clear detections of both \( v_{\text{max}} \) and \( \Delta \nu \), 14 stars were classified marginal, and 44 were non-detections. Marginal detections refer to stars where either \( v_{\text{max}} \) or \( \Delta \nu \) were not determined unambiguously. Non-detections are mostly those stars where we did not find any evidence of oscillations. Some were slowly pulsating (very luminous) giants, which in some cases did show evidence of oscillation power, but due to the small \( v_{\text{max}} \) and \( \Delta \nu \) we are not confident in claiming those as marginal detections. Based on previous experience with Kepler data, most of the marginal detections and almost all of the non-detections extend over regions in \( \log g - T_{\text{eff}} \) space that render them unlikely to result in measurable \( v_{\text{max}} \) and \( \Delta \nu \) values.

To illustrate this property, we show \( \log g \) and \( T_{\text{eff}} \) from APOGEE in Figure 3(a) of all 117 stars in our sample superimposed on a stellar evolutionary track (gray curve) of a 1.2\( M_\odot \), roughly solar metallicity MESA model (Paxton et al. 2011, 2013) taken from Stello et al. (2013). From stellar evolution models, we would generally not expect to find giants hotter than \( T_{\text{eff}} = 5000 \) K (except for rare extremely metal-poor and/or massive stars. Indeed, previous results from long-term observations by Kepler, showed only two oscillating giants hotter than APOGEE \( T_{\text{eff}} = 5000 \) K (Pinsonneault et al. 2014); one on the lower red giant branch and one red clump star out of 1916 stars in total. Our K2 results appear to be in line with those results, and we should therefore discount stars that appear to be hotter than this \( T_{\text{eff}} \) threshold when assessing our detectability capabilities (Figure 3(a), vertical dotted line). However, we do not advice to apply a \( T_{\text{eff}} \) selection for future large scale population studies, and only do so here to remove what appears as somewhat incompatible \( T_{\text{eff}} \) measurements of a few stars in our sample. As mentioned in Section 2, oscillations of stars with \( v_{\text{max}} \lesssim 10 \) \( \mu \)Hz cannot be reliably characterized with 80-day time series—the typical length of a K2 campaign. From the \( v_{\text{max}} \propto g/T_{\text{eff}}^{1/2} \) relation (Brown et al. 1991), this essentially translates into a lower limit on \( \log g \), as indicated by the upper horizontal dashed line (Figure 3(a)). Similarly, the cadence of the data (\( \sim 29.4 \) minutes) results in a Nyquist frequency of about 283 \( \mu \)Hz, which defines an upper limit on \( v_{\text{max}} \) of about 270 \( \mu \)Hz, and hence on \( \log g \) (Figure 3(a), lower horizontal dashed line). Oscillation frequencies above this limit will be too close to the Nyquist frequency, compromising automated robust measurement of both \( v_{\text{max}} \) and \( \Delta \nu \) (Stello et al. 2013). This includes stars oscillating beyond the Nyquist frequency. Again, our K2 results confirm these boundaries, with all but three detected oscillating stars falling within the APOGEE \( \log g \) range 2.1–3.35.

Comparing the APOGEE \( \log g \) with the asteroseismic values, we see in Figure 3(b) that there is an offset of about 0.2 dex between the two, in agreement with the findings of Holzman et al. (2015). Note that we derived the seismic \( \log g \) using the above \( v_{\text{max}} \) scaling relation with \( T_{\text{eff}} \) from APOGEE. We also note a large scatter, and in some cases a very large deviation (stars indicated by arrows). The seismic \( \log g \) has a typical internal uncertainty of about 0.03 dex for the length of data used here (Huber et al. 2010), much smaller than can be obtained from spectroscopy. Hence we attribute the scatter in Figure 3(b) to the uncertainties in the spectroscopic determinations. This suggests an rms scatter of 0.2 dex of the spectroscopic \( \log g \), in agreement with Pinsonneault et al. (2014); for a
few stars a deviation of up to 1.5 dex is seen. The latter extreme cases could potentially be blends in the K2 data, where a more evolved, intrinsically brighter star with lower log $g$ is detected seismically, while a less evolved star is the source in the APOGEE spectra. If they are not blends, the two hottest stars marked by arrows must also be much cooler given their seismic signal, which indicates they are evolved red giants more luminous than the red clump. With these uncertainties in mind, we would expect that log $g$ and $T_{\text{eff}}$ in Figure 3(a) for some stars are not necessarily representative of their true values. Hence, even in the scenario where we have 100% detection rates, we should find some stars with detected oscillations outside the log $g-T_{\text{eff}}$ region of expected detectable oscillations (Figure 3(a), middle-left region bracketed by the dashed and dotted lines), and some non-detections inside this region; this indeed appears to be the case.

Finally, we examine our success rate in detecting oscillations which, based on the above considerations, needs to be evaluated only for the stars expected to show oscillations. Within the log $g-T_{\text{eff}}$ region of expected detectable oscillations, there are 67 stars, of which 55 are clear detections, 7 are marginal detections, and 5 are non-detections. We note that it is not inconceivable that all 5 non-detections have true values of log $g$ and $T_{\text{eff}}$ that would make them fall outside the detectable region given that we find a similar number of detections outside the detectable region. However, some of these stars could be genuinely non-oscillating red giants suppressed by strong binary interactions (Derekas et al. 2011; Gaulme et al. 2014).

To judge whether the non-detections are simply caused by poor photometry, we show the white noise level versus apparent brightness for all 67 stars in Figure 4. We see no clear trend between the detection category and the apparent magnitude, and hence noise level, which suggests that the non-detections are not generally caused by noisy photometry. We do see a possible hint of a faint limit at $K_p \gtrsim 15$ mag, but the low number of faint stars prevents any definitive conclusion. However, for the stars with detected oscillations, we calculated the correlation between $K_p$ and seismic log $g$ and found it to be essentially zero ($\rho_{K_p, \log g} = 0.04$). Hence, even our least-evolved giants (highest log $g$), which have the smallest oscillation amplitudes, span the entire magnitude range down to $K_p = 14.75$. Taking the uncertainty in $K_p$ into account and being conservative, this result suggests that we will be able to detect oscillations in any red giant down to $K_p \sim 14.5$, as long as they are within the required log $g$ range, which for the seismic log $g$ is $\sim 1.9-3.2$.

4. SUMMARY AND OUTLOOK

We have performed initial asteroseismic analyzes of K2 C1 data for over one hundred stars expected to be red giants based on their spectrosopically determined log $g$ and $T_{\text{eff}}$. We detect oscillations in almost all stars hotter than 5000 K within 2.1–3.35 in log $g$ (on the scale of the “raw” data in Holtzman et al. 2015), which comprise the target stars of ongoing K2-based galactic archaeology studies. The results indicate that our

**Figure 3.** (a) log $g$ vs. $T_{\text{eff}}$ from APOGEE (Majewski et al. 2010) for all 117 observed stars in our sample. We plot the values called “raw” in Equations (2) and (3) of Holtzman et al. (2015) because their “corr” (ected) values are not available for all stars in our sample. Filled blue circles mark stars with detected oscillations, filled cyan circles show marginal detections, and empty circles are stars with no detected oscillations. A typical error bar is shown at (log $g$, $T_{\text{eff}}$) = (3.0, 4100 K). Dashed lines mark the log $g$ range of stars with $\nu_{\text{max}}$ between 10 and 270 Hz—the detectable range using K2 long cadence data spanning one full campaign (∼80 days). The vertical dotted line marks the upper limit in $T_{\text{eff}}$ typically found for oscillating red giants in previous Kepler data (Pinsonneault et al. 2014). The gray solid curve shows a representative MESA stellar evolution track of a 1.2 $M_\odot$ model. Arrows indicate stars that potentially have a log $g$ very different from the APOGEE value. (b) Relation between APOGEE and seismic log $g$ of the stars with clear seismic detection. The solid line shows a one-to-one relationship.
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Figure 4. Noise level in power spectra as function of Kp magnitude for all stars with APOGEE T eff < 5000 K and APOGEE log g in the range 2.1–3.35 (see Figure 3(a)). The noise is measured as the median power in the range 260–280 μHz. For reference we show a fiducial line described by log(WhiteNoise) = 9.77 − 1.57Kp + 0.074Kp 2 ppm/μHz that follows the lower envelope of the magnitude-dependent noise floor (red curve). The saturation limit of K2 is indicated by the dotted line. The increased noise for saturated stars can be mitigated using larger aperture masks than in the VJ photometry used here (Lund et al. 2015).
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