Super-Nyquist asteroseismology of solar-like oscillators with *Kepler* and *K2* – expanding the asteroseismic cohort at the base of the red giant branch

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**ABSTRACT**

We consider the prospects for detecting solar-like oscillations in the ‘super-Nyquist’ regime of long-cadence (LC) *Kepler* photometry, i.e. above the associated Nyquist frequency of \( \approx 283 \mu \text{Hz} \). Targets of interest are cool, evolved subgiants and stars lying at the base of the red giant branch. These stars would ordinarily be studied using the short-cadence (SC) data, since the associated SC Nyquist frequency lies well above the frequencies of the detectable oscillations. However, the number of available SC target slots is quite limited. This imposes a severe restriction on the size of the ensemble available for SC asteroseismic study. We find that archival *Kepler* LC data from the nominal mission may be utilized for asteroseismic studies of targets whose dominant oscillation frequencies lie as high as \( \approx 500 \mu \text{Hz} \), i.e. about 1.75-times the LC Nyquist frequency. The frequency detection threshold for the shorter duration science campaigns of the re-purposed *Kepler* mission, *K2*, is lower. The maximum threshold will probably lie somewhere between \( \approx 400 \) and \( 450 \mu \text{Hz} \). The potential to exploit the archival *Kepler* and *K2* LC data in this manner opens the door to increasing significantly the number of subgiant and low-luminosity red giant targets amenable to asteroseismic analysis, overcoming target limitations imposed by the small number of SC slots. We estimate that around 400 such targets are now available for study in the *Kepler* LC archive. That number could potentially be a lot higher for *K2*, since there will be a new target list for each of its campaigns.

**Key words:** asteroseismology – methods: data analysis – stars: oscillations.

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**1 INTRODUCTION**

The NASA *Kepler* mission has provided photometric observations of exquisite quality for asteroseismic studies of a diverse range of pulsating stars (Gilliland et al. 2010). Particularly noteworthy has been the large volume of data collected on cool main-sequence, subgiant and red giant stars showing solar-like oscillations, pulsations that are excited and intrinsically damped by near-surface convection (Chaplin & Miglio 2013). The successful asteroseismology programme looks set to continue in the re-purposed *Kepler* mission, *K2* (Howell et al. 2014). The quality of the *K2* photometry for asteroseismic studies of coherent pulsators has already been demonstrated by results from engineering test data (Hermes et al. 2014; Jeffery & Ramsay 2014). The photometric performance has also confirmed the predicted potential for studies of solar-like oscillators (Chaplin et al. 2013), studies that will be made possible by the longer, full-campaign science data.

*K2* data were collected in two cadences (Koch et al. 2010) during the 4-yr-long nominal mission. Data on up to 170 000 targets were available in the 29.4-min long cadence (LC), whilst a much smaller total of up to 512 targets could be observed simultaneously in the 58.85-s short cadence (SC). These cadences establish Nyquist frequencies for the two modes of operation of \( \approx 283 \) (in LC) and \( \approx 8496 \mu \text{Hz} \) (in SC). The LC Nyquist frequency coincides with the dominant periods of oscillation shown by cool stars that lie just above the base of the red giant branch. Both cadences have been maintained for the *K2* mission, but the total number of targets...
for each observing campaign has been reduced – to approximately 10 000 and 50 targets, respectively – because of the need for larger pixel target masks.

The detection of solar-like oscillations in cool main-sequence and subgiant stars, and stars at the very bottom of the red giant branch, demands that the target-limited SC data be utilized since the dominant periods of oscillation are shorter than one hour. Observations made in the numerous LC slots are sufficient to detect oscillations in more evolved red giants, because the relevant pulsation periods are longer.

Oscillations have already been detected in around 16 000 red giants in the nominal mission LC data (Hekker et al. 2011; Stello et al. 2013; Huber et al. 2014). Whilst Kepler increased the number of cool main-sequence and subgiant stars with asteroseismic data by over an order of magnitude, to around 700 targets (Chaplin et al. 2011a, 2014; Huber et al. 2013), totals were nevertheless limited by the available number of SC target slots. The possibility of detecting solar-like oscillations in LC data above the LC Nyquist frequency – i.e. in the ‘super-Nyquist’ regime – offers the potential to increase significantly the number of evolved subgiant and low-luminosity red giant targets amenable to asteroseismic study.

The use of LC data for super-Nyquist studies of coherent pulsators has been considered in some detail by Murphy, Shibahashi & Kurtz (2013). Baran et al. (2012) also employed a super-Nyquist analysis of a compact pulsator observed in SC. While Gaulme et al. (2013) and Beck et al. (2014) identified a few red giants with oscillation frequencies above the LC Nyquist frequency, the prospects for studying solar-like oscillators in the LC super-Nyquist regime have not yet been explored in any detail. Our aim in this paper is to consider the utility of the archival Kepler and future K2 data for such studies.

The layout of the rest of the paper is as follows. We begin in Section 2 with a summary of some of the basic principles from Fourier analysis that are relevant to our study. We then consider in Section 3 the specific case of Kepler LC observations; and in Section 4, we go on to consider the characteristics of the super-Nyquist spectrum shown by solar-like oscillators, considering the impact of the finite mode lifetimes (Section 4.1), the use of a priori information to discriminate true from aliased peaks in the frequency spectrum (Section 4.2), and the reduced S/N above the Nyquist frequency (Section 4.3). We include model predictions for subgiant and low-luminosity red giant stars, and real super-Nyquist examples from the Kepler archive (Section 4.4). We finish the paper in Section 5 with concluding remarks.

2 BASIC PRINCIPLES

Let us begin by considering the simple case of a sinusoidal signal of frequency ν, sampled at regular intervals Δt in time. This establishes a sampling frequency νs = (Δt)^{-1}. The well-known sampling theorem (Nyquist 1928; Shannon 1949) tells us that when ν ≤ νs/2, the sampling is sufficient to completely determine the signal – we say the signal is oversampled – and there is no ambiguity in the measured frequency. We may also write the sampling requirement as ν ≤ νNyq, where the Nyquist frequency, νNyq, is defined as

\[ νNyq \equiv \frac{νs}{2} \equiv (2Δt)^{-1}. \]  

What happens if instead the signal is undersampled, so that ν > νNyq? Power will be present in the ‘super-Nyquist’ regime of the frequency spectrum at the true frequency, ν; and it will also now be reflected, or aliased, back into the frequency region below νNyq. If we write the true frequency as ν = νNyq + ν′, there will be peaks at νNyq + ν′ and νNyq − ν′. There is now an ambiguity in the estimated frequency, and we are completely reliant on using other knowledge to pick the true frequency. We shall see that irregular time sampling offers the potential to lift this degeneracy provided the signal is coherent, or nearly coherent, over the duration of the observations (of which more in Section 3 below).

The appearance of the frequency spectrum is also affected by the amount of time during each cadence Δt that is used to collect data, i.e. in our case, to integrate photons from the target star. If a high fraction of each cadence is used to collect data, we may significantly underestimate the true amplitude because each datum may average the time-varying signal. If the integration time per cadence is Δt′, then a signal of frequency ν will have its amplitude attenuated by the factor (e.g. Campante 2012)

\[ η = \text{sinc} \left( \pi (νΔt') \right). \]

(2)

When the fraction of each cadence given over to integration is unity, so that Δt′ = Δt, the attenuation may then be written as (e.g. Chaplin et al. 2011b; Huber et al. 2011b; Murphy 2012)

\[ η = \text{sinc} \left[ π (νΔt) \right] = \text{sinc} \left[ π \left( \frac{ν}{νs} \right) \right] \equiv \text{sinc} \left[ π/2 \left( \frac{ν}{νNyq} \right) \right]. \]

(3)

The attenuation in power is given by the square of the sinc function, η². Even when the integration duty cycle is close to 100 per cent and the attenuation is at its strongest – which is the case for Kepler; see Section 3 below – equation (3) indicates that one still has sensitivity to signals in the super-Nyquist regime (ν > νNyq) since the first zero of the sinc function does not occur until ν = νs ≡ 2νNyq. It is also worth remarking that even when signals are oversampled, so that ν ≤ νNyq, there is still significant attenuation close to the Nyquist frequency.

3 Kepler LC OBSERVATIONS

The Kepler LC data are comprised of Δt = 29.4-min cadences (Jenkins et al. 2010) that are exactly regular in the spacecraft frame of reference. This establishes a notional LC Nyquist frequency of νNyq ≃ 283 μHz. Each 29.4-min cadence is in turn a summation of 270 individual ~6-s readouts (e.g. Gilliland et al. 2011). Most of each cadence is therefore given over to the collection of photons. The very high fractional duty cycle for the Kepler integrations means the signal attenuation follows closely that described by equation (3).

The left-hand panel of Fig. 1 shows the frequency-power spectrum of idealized observations, made on a regular Kepler-like cadence, of several undersampled sinusoids. The sinusoids are all of unit amplitude and have frequencies lying in the super-Nyquist regime between 310 and 460 μHz. Peaks due to the true frequencies are rendered as black lines. The vertical dashed lines mark multiples of νNyq. Peaks in grey are therefore aliases of the true frequencies. The spectrum is repeated every 2νNyq because of the discrete nature of the calculation.

This power spectrum has been calibrated¹ so that a sinusoid of unit amplitude with an infinite sample rate would show a maximum

¹ Here, and throughout the rest of the paper, we show spectra calibrated in power per bin or power per Hz – as opposed to amplitude per root bin or per root Hz – since this is the usual approach when analysing solar-like oscillators (which we will come to later in Section 4 below).
power per bin of unity. The observed powers at the true frequencies are much lower than unity, the true power. This is due to the sinc-function attenuation described by equation (3). The dotted line marks the sinc-squared suppression envelope in power, i.e. $\eta^2$.

The above is not quite the whole story as far as timing issues for the Kepler observations are concerned. Kepler lies in a 372.5-d heliocentric, Earth-trailing orbit. Observations of the pulsations of a Kepler target – be it one in the original field, or in the K2 fields in the ecliptic plane – will be phase modulated in the spacecraft frame of reference. This is because there is a component of the orbital motion of Kepler along the line-of-sight (target) direction, which delays or advances the arrival time of light from the star. The annual size of the effect is approximately $\pm 190$ s for targets in the original field, and approximately $\pm 500$ s for targets in the ecliptic (where the K2 fields lie).

To compensate for this effect, the Kepler time stamps are corrected to Barycentric arrival times (actually Barycentric Dynamical Time; see e.g. García et al. 2014). An important consequence is that the intervals between time stamps are no longer regular, but are modulated periodically on an $\sim 1$-yr time-scale. This periodic modulation splits the aliased peaks in the frequency spectrum into many components, as discussed in detail by Murphy et al. (2013).

The right-hand panel of Fig. 1 shows the result of simulating LC observations of an idealized star in the original Kepler field undergoing coherent pulsations. The artificial data span four simulated years and include the aforementioned timing effects. The simulated pulsations are the same, undersampled sinusoids from the left-hand panel. Note how the aliases are no longer exact, reflected copies about multiples of $\nu_{Nyq}$. Some copies have different maximum power spectral densities (i.e. peak heights in the spectrum) than others. The reason for this is that the splitting of the power into several components reduces the maximum heights in Fig. 1, relative to those expected for simple reflected aliases (the total integrated power in the aliases is conserved).

The top-left panel of Fig. 2 shows a zoom of the peak due to the true frequency marked ‘a’ in the right-hand panel of Fig. 1, whilst the other panels show zooms of the aliases marked ‘b’, ‘c’, and ‘d’ on Fig. 1. As explained by Murphy et al. (2013), the exact manner in which the alias peaks are affected by the timing modulation depends on the relation of their frequencies to the sampling frequency. If the true frequency is $\nu$, then aliases at $n\nu_{Nyq} \pm \nu$, or equivalently $2n\nu_{Nyq} \pm \nu$, will share the same structure, e.g. what is predominantly a triplet structure when $n = 1$, or a quintuplet structure when $n = 2$, with the frequency splitting between adjacent components being $\sim 1$ yr$^{-1}$.

Murphy et al. (2013) pointed out that for high-amplitude, coherent pulsations the introduction of sideband structure, which is well resolved in the nominal mission Kepler data, allows one to discriminate the real and aliased peaks. What about solar-like oscillations, which are not coherent and typically have much lower amplitudes (and hence lower S/N levels in the frequency spectrum) than coherent pulsations?

### 4 Super-Nyquist Spectrum of Solar-Like Oscillations

#### 4.1 Impact of finite mode lifetimes

The first issue we confront is that solar-like oscillations have finite lifetimes. In most cases, the lifetimes $\tau$ of detectable oscillations are significantly shorter than the duration $T$ of the observations (e.g. Dupret al. 2009). Only for some gravity-dominated mixed modes of red giants do the lifetimes of detected oscillations approach or exceed lengths commensurate with multi-month-long observations. One might therefore not usually expect to be able to resolve the aforementioned sideband structure in the frequency domain.

The underlying noise-free or ‘limit-spectrum’ profiles due to solar-like oscillations are to good approximation Lorentzian in shape, with the full width at half-maximum of the peaks given by $\Gamma = (\pi \tau)^{-1}$ (e.g. see Chaplin et al. 2002). Fig. 3 shows how a finite mode lifetime would affect the appearance of the aliased quintuplet from the bottom-left panel of Fig. 2. The different linestyles show the composite, aliased limit-spectrum profiles expected when the real mode has a lifetime (linewidth) of 73 d (0.1 $\mu$Hz; dashed line),....
Figure 2. Top-left panel: zoom of the peak due to the true frequency marked ‘a’ on the right-hand panel Fig. 1. Other panels: zooms of the aliases marked ‘b’, ‘c’ and ‘d’ on Fig. 1.

Figure 3. Impact of finite mode lifetimes on the aliased quintuplet from the bottom-left panel of Fig. 2. The different linestyles show the composite, aliased profiles expected when the real mode has a lifetime (linewidth) of 73 d (0.1 \( \mu \)Hz; dashed line), 123 d (0.05 \( \mu \)Hz; dotted line), 184 d (0.02 \( \mu \)Hz; dark solid line) and 1 yr (0.01 \( \mu \)Hz; grey solid line).

123 d (0.05 \( \mu \)Hz; dotted line), 184 d (0.02 \( \mu \)Hz; dark solid line) and 1 yr (0.01 \( \mu \)Hz; grey solid line).

Lifetimes of solar-like oscillations in main-sequence and subgiant stars are typically of the order of several days in length. The lifetimes of detected radial mode oscillations in red giants can be as long as the 73-d lifetime considered above (e.g. Corsaro et al. 2012). The corresponding dashed line in Fig. 3 would be barely indistinguishable from a Lorentzian profile in the presence of real noise. The same would of course be true for shorter mode lifetimes. The longer lifetimes modelled in Fig. 3 show much more significant departures from a Lorentzian appearance. Provided S/N levels in the observed modes are sufficiently high, it might therefore be possible to discriminate visually the sidebands of some long-lived modes. It is worth noting once more that amplitudes of solar-like oscillations are usually much lower than for coherent pulsators, making it harder to distinguish the sideband structure.

We conclude that an important consequence of the finite mode lifetimes is that in most cases one would no longer be able to distinguish aliased from true oscillation peaks on account of the sideband structure. However, for solar-like oscillators we are fortunate in that we do not need to rely on such discrimination alone.

4.2 Use of a priori information for solar-like oscillators

The rich spectra of overtones shown by solar-like oscillators provides the necessary, a priori information to allow us to select the true spectrum from the aliased spectra. We illustrate how with a real example, the low-luminosity red giant KIC 4351319. This target was observed in both long and short cadence during the nominal Kepler mission. Here, we have used data prepared using the PDC-MAP pipeline (Smith et al. 2012; Stumpe et al. 2012). The top panel
discriminate the true from the aliased spectrum. The lengths of the horizontal arrows in the bottom panel correspond to expected average separations, assuming a $v_{\text{max}}$ of $\pm 190$ µHz (peaks below $v_{\text{Nyq}}$) and $\pm 380$ µHz (peaks above $v_{\text{Nyq}}$). The shaded regions mark the locations of pairs of adjacent $l = 2$ and $l = 0$ modes. The frequency intervals between these regions provide a visual estimate of the observed large separation. Evidently, it is the spectrum above $v_{\text{Nyq}}$ that conforms with the expected average separation.

The second check relates to the relative power shown by adjacent $l = 2$ and $l = 0$ modes. Within each pair, the $l = 0$ mode lies at higher frequency. We expect to see more power in the $l = 0$ mode than in its $l = 2$ counterpart. Whilst predictions of the exact power ratios are rendered uncertain by the complexities of non-adiabatic calculations, observed ratios are usually not too far from the $\pm 2$-to-1 ratio expected from the assumption of energy equipartition and geometric cancellation of the perturbations on the visible stellar disc (when projected on to spherical harmonic functions, with an appropriate limb-darkening law; e.g. see Aerts, Christensen-Dalsgaard & Kurtz 2009). Unless the star is observed with the rotation axis along the line-of-sight, power shown by the $l = 2$ modes will be spread across several components (e.g. Gizon & Solanki 2003). The ratio in total power then tends to be exaggerated in the frequency-power spectrum because it is the maximum power spectral densities, i.e. the heights of the mode peaks, that are immediately apparent from a visual inspection.

Inspection of the mode pairs in the bottom panel of Fig. 3 again implies that the spectrum above $v_{\text{Nyq}}$ is the true one. The $l = 0$ modes, the higher frequency modes in each marked pair, have the higher observed powers.

4.3 Impact of signal attenuation and background aliasing

How far above $v_{\text{Nyq}}$ might we hope to detect solar-like oscillations in the LC Kepler data? A combination of several factors means that pushing the limit well above $v_{\text{Nyq}}$ is challenging. First, the sinc-function attenuation due to the finite integration time leads to significant reduction of the observed oscillation amplitudes at frequencies above $v_{\text{Nyq}}$. Secondly, the impact of the sinc attenuation is exacerbated by the fact that the intrinsic maximum amplitudes of solar-like oscillations decrease with increasing $v_{\text{max}}$. And thirdly, we must also contend with background power aliased from the region below $v_{\text{Nyq}}$, which has contributions from stellar granulation, stellar activity, shot and instrumental noise. Note that any non-white or ‘red’ noise component, such as the granulation, will also have a contribution above $v_{\text{Nyq}}$ that is sinc-function attenuated, just like the oscillations (e.g. see Kallinger et al., 2014).

We come back to the example of KIC 4351319 to help illustrate these points. The top panel of Fig. 4 shows clearly the attenuated power of the oscillations in the LC spectrum of KIC 4351319, relative to those observed in the SC spectrum. The impact of the sinc-function attenuation on the observed S/N is compounded in the LC spectrum because the background in the region of $v_{\text{max}}$ is the aliased background from lower frequencies, which is dominated by granulation and is much higher – by more than an order of magnitude – than the shot-noise background. The spectrum of the oscillations is in reality coincident in frequency with the lower power, higher frequency part of the granulation spectrum, as shown by the SC spectrum of KIC 4351319. A much higher S/N is therefore observed in the oscillations when using SC data, because we do not have to contend with aliasing of power from the lower frequency, higher power part of the granulation spectrum. Our tests indicate that it is only when $K_g$ is fainter than approximately 11–12 mag that
After the top-left panel of Fig. 6, the other panels show schematic representations of the limit (noise-free) power density spectra expected for LC (upper plots) and SC (lower plots) data, where we assumed each model was observed as a bright Kepler target having a Kepler apparent magnitude of $K_p = 9$. The composite SC spectra were constructed using the scaling relations and formulae in Chaplin et al. (2011b), with contributions from oscillations, granulation and shot noise included. We refer the reader to that paper for further details.

There was one ingredient missing from Chaplin et al. (2011b) that we needed to make the spectra, and that was the step to convert estimates of the maximum mode amplitudes, $A_{\text{max}}$, into maximum mode power spectral densities (peak heights) $H_{\text{max}}$. In this paper, we have used an appropriate formalism from Chaplin et al. (2008), i.e.

$$ H_{\text{max}} = \frac{2 A_{\text{max}}^2}{\pi T_G + 2}. $$

with mode peak linewidths $\Gamma$ estimated from Appourchaux et al. (2012) using the effective temperature $T_{\text{eff}}$ of the models. To avoid cluttering the plots, we only mark the predicted limit (noise-free) heights of the radial ($l=0$) modes; we do not plot the Lorentzian limit profiles or predictions for non-radial modes. The predicted oscillation lifetimes (Lorentzian peak linewidths) are in all cases short (large) enough that the timing sidebands would be unresolved (see Section 4.1), and so each range of $v_{\text{Nyq}}$ would essentially be a near identical, reflected copy.

The predicted SC spectra in Fig. 6 show where the true frequencies lie. Regarding the general appearance of the SC spectra: the power in, and the characteristic time-scale of, the granulation both increase with decreasing $v_{\text{max}}$; we also recall that the power in the oscillations increases with decreasing $v_{\text{max}}$. The nature of these changes is such that all composite SC spectra are, in their gross properties at least, approximately homologously scaled versions of one another.

The SC spectra were converted to predicted LC spectra by applying the sinc-squared attenuation filter, $\eta^2$. (Note we have not bothered to attempt to discriminate the white contribution due to shot noise, since it is very small compared to the other contributions.) The predicted LC power below $v_{\text{Nyq}}$ is given by adding the sub-Nyquist SC attenuated power to the aliased, super-Nyquist attenuated spectrum from above $v_{\text{Nyq}}$ (after reflecting the latter about $v_{\text{Nyq}}$). The predicted LC power above $v_{\text{Nyq}}$ is then just the reflected prediction from below $v_{\text{Nyq}}$. Fig. 5 shows the resulting prediction (lower plot), together with the LC spectrum from Fig. 4 (upper plot).

When the oscillations are undersampled, the appearance of the oscillations spectra in the super-Nyquist regime depends critically on the proximity of $v_{\text{max}}$ to the boundary at $2v_{\text{Nyq}}$. This boundary is where the first zero of the sinc-function attenuation lies, and is also where aliased background power – from granulation, activity and instrumental noise – is most severe, coming as it does from the very low frequency part of the spectrum. Fig. 6 is an idealized, visual guide to the changing appearance of spectra as $v_{\text{max}}$ is varied. The figure shows schematic frequency-power spectra made by applying suitable scaling relations (see below) to the properties of a sequence of 1 $M_\odot$ stellar evolutionary models computed by the Padova group (Marigo et al. 2008). The top-left panel of Fig. 6 plots tracks in the log $g$–$T_{\text{eff}}$ plane, with the selected models shown in red. All five models have a predicted frequency of maximum solar-like oscillations power, $v_{\text{max}}$, that lies above $v_{\text{Nyq}}$. The characteristic $v_{\text{max}}$ frequency was estimated from the fundamental stellar properties (Brown et al. 1991; Kjeldsen & Bedding 1995) using

$$ v_{\text{max}} = v_{\text{max}, \odot} \left( \frac{M}{M_\odot} \right) \left( \frac{R}{R_\odot} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff}, \odot}} \right)^{-0.5}, $$

where we have scaled against the solar values of $v_{\text{max}, \odot} = 3090$ μHz and $T_{\text{eff}, \odot} = 5777$ K. Loci of constant $v_{\text{Nyq}}$, and selected multiples thereof, are also marked in the top panel.

The signatures of the oscillations and granulation are also attenuated in the SC data, but since the SC Nyquist frequency is $\geq 8496$ μHz the impact in the frequency range of interest here is negligible.

Figure 5. Frequency-power spectrum of KIC 4351319: upper plot shows LC spectrum, lower plot predicted LC spectrum made from the available SC spectrum.

3 The signatures of the oscillations and granulation are also attenuated in the SC data, but since the SC Nyquist frequency is $\geq 8496$ μHz the impact in the frequency range of interest here is negligible.
with reference to the above, intrinsic stellar noise should remain the limiting factor for brighter targets. Taking $T = 75 \text{ d}$, the length of each K2 campaign, we estimate an absolute upper detection limit between $v_{\text{max}} \simeq 400$ and $\simeq 450 \mu\text{Hz}$.

### 4.4 Some real examples

Fig. 7 shows some more super-Nyquist examples from the Kepler archive. Five targets with Kepler LC and SC data have been selected that have undersampled oscillations in LC. The $v_{\text{max}}$ values range...
Figure 7. Demonstration, using real Kepler LC data on five stars, of undersampled solar-like oscillation spectra in the LC super-Nyquist regime. Each target also has some SC data available, in which the oscillations are oversampled. The top-left panel shows the locations of the stars in the log $g$–$T_{\text{eff}}$ plane. Other panels: main plots show the LC power spectra (oscillations undersampled), insets show power spectra computed from available SC data (oscillations oversampled).

From $\approx 320$ (just above $\nu_{\text{Nyq}}$) to $\approx 550$ $\mu$Hz (just below $2\nu_{\text{Nyq}}$). It is worth stressing that there are not many targets like this in the Kepler archive with SC data (in particular at the low end of the range). The top-left panel plots the locations of the stars in the log $g$–$T_{\text{eff}}$ plane, with stellar properties taken from Chaplin et al. (2014). The main plots of the other panels show zooms of the LC power spectra in the undersampled, super-Nyquist regions where the real oscillation frequencies lie. Note that we chose a slightly different layout compared to the previous figures to show more clearly the lower S/N cases at higher $\nu_{\text{max}}$. The insets show power spectra computed from available SC data. Note that, unlike KIC 4351319, the SC coverage was much more limited for some of these stars. Even though the SC and LC data are not necessarily contemporaneous, the insets show clearly where the real oscillations are.
From our model predictions above, we expect to have good sensitivity up to $v_{\text{max}} \approx 400$ $\mu$Hz, a conclusion that is borne out by these real data. At frequencies above this, detecting the modes becomes more difficult. Signatures of the oscillations are clearly apparent in the LC spectrum of KIC 6531928 ($v_{\text{max}} \approx 450$ $\mu$Hz) but at a much reduced S/N compared to the other targets. KIC 8038445 has a $v_{\text{max}}$ of 490 $\mu$Hz. Signatures of a few modes are just detectable in its LC spectrum. This case marks the approximate upper $v_{\text{max}}$ limit for making detections in the archival Kepler data.

Things become much more challenging as we move to higher frequencies, to the region where $v_{\text{max}}$ straddles or lies close to the boundary at $2v_{\text{Nyq}}$. Imposing a high-pass filter to suppress the very low frequency background power in the sub-Nyquist regime does not help to improve the S/N in the super-Nyquist regime: the filtering response is the same in each domain of $v_{\text{Nyq}}$ and so any oscillation signal is also filtered.

5 CONCLUSION

We have considered the prospects for detecting solar-like oscillations in the undersampled ‘super-Nyquist’ regime of LC Kepler data, i.e. above the LC Nyquist frequency of $\approx 283$ $\mu$Hz. We conclude that the LC data may be utilized for asteroseismic studies of targets whose dominant oscillation frequencies lie as high as $\approx 500$ $\mu$Hz. The frequency detection threshold for the shorter duration K2 science campaigns is lower. We estimate that the robust threshold will lie somewhere between $\approx 400$ and 450 $\mu$Hz.

These stars would usually be studied with Kepler SC data. The oscillations are then oversampled, since the associated Nyquist frequency of $\approx 8496$ $\mu$Hz lies well above the frequencies of the detectable oscillations. However, the number of SC available target slots is very limited: indeed, there are around only 50 targets of interest in the Kepler archive that have detected oscillations in SC data and $v_{\text{max}}$ between the LC $v_{\text{Nyq}}$ and $\approx 500$ $\mu$Hz. In most of these cases, there are only 1-month of data from the initial asteroseismic survey phase. This precludes very detailed studies of these targets, which demands high-frequency-resolution data sets for analyses of individual modes (including rotational frequency splittings).

The exploitation of the archival Kepler and new K2 data for LC super-Nyquist studies offers the prospect of increasing significantly the number of evolved subgiant and low-luminosity red giant targets available for asteroseismic study. By making use of the revised catalogue of Kepler star properties in Huber et al. (2014), we estimate that up to 400 targets may be available for study in the Kepler archive. Moreover, many of these targets will have data spanning the entire nominal mission, giving the frequency resolution needed for the above-mentioned analyses of individual modes.

The potential number of targets amenable to study with K2 data could run into the thousands, since new target lists will be generated for each campaign.

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