KEPLER TELESCOPE AND SOLAR-LIKE PULSATORS

J. Molenda–Żakowicz¹, T. Arentoft²,³, H. Kjeldsen²,³, and A. Bonanno⁴

¹Instytut Astronomiczny Uniwersytetu Wrocławskiego, Kopernika 11, 51-622 Wrocław, Poland
²Institute of Physisc and Astronomy, University of Aarhus, Bldg. 1520, DK-8000 Aarhus, Denmark
³Danish Asteroseismology Centre (DASC), University of Aarhus, Bldg. 1520, DK-8000 Aarhus, Denmark
⁴Osservatorio Astrofisico di Catania, Via S.Sofia 78, 95123 Catania, Italy

ABSTRACT

We present 104 stars selected for a long-time monitoring for Kepler, a new NASA space telescope. 30 of these stars are primary asteroseismological targets for Kepler, the remaining 74, secondary asteroseismological targets for the telescope. They are mostly F–K stars that we expect to show solar–like oscillations.

We determine fundamental astrophysical parameters and estimate pulsational properties of the selected targets. Then, we use simulations to present Kepler’s ability of detection oscillations with frequencies and amplitudes typical for solar-like pulsators.

Key words: Stars: variables: solar–like; Stars: variables: other; Space missions: Kepler.

1. INTRODUCTION

Kepler is a new NASA space telescope designed for detection of Earth–size and larger planets with the method of photometric transits (Borucki et al. [6]). Kepler instrument is a 0.95–m Schmidt telescope with a 105 deg² field of view centered in the Cygnus–Lyra region at α₂₀₀₀ = 19h22m40s, δ₂₀₀₀ = +44°30’’. The telescope will be launched in October 2008. The mission is planned to last for four years and then continue for another two years. For the entire life–time of the mission, Kepler will perform continuous and simultaneous observations of more than 200 000 stars (according to the estimations of the Kepler team) that fall into Kepler field of view and into its nominal magnitude range that is V = 9–14 mag.

We present 104 most promising targets for an asteroseismic study that can be performed with the use of the Kepler telescope. Our list includes stars that may show variability of different type including SPB, δ Scuti, ro–Ap, γ Doradus and solar–like pulsators. We focus on the last type of pulsators and we discuss the Kepler mission in the context of discovery of new variables of this kind.

Figure 1. Histogram of spectral types for 91 of 104 Kepler asteroseismic targets that have spectral classification.

2. TARGET SELECTION

In the process of selection the most promising asteroseismic targets for Kepler, we focused on stars for which fundamental astrophysical parameters, i.e., luminosity, effective temperature, gravity, metalicity, etc., can be determined and precise pulsational models computed. We searched the Hipparcos Catalogue (ESA [16]) and selected 104 stars from the magnitude range V = 9–11 mag. We selected the brightest stars from the Kepler nominal magnitude range because they will have the highest signal–to–noise, S/N, ratio in the Kepler photometry. We used the pixel calculator C–code kindly provided by D. Koch to check the position of these stars on Kepler CCD panels. We found 87 stars to fall onto active CCD panels and 17, into the star tracker corner. In Fig. 2, we show the finding chart with Kepler asteroseismic targets (dots) and other stars brighter than V = 6 mag (circles). Due to the clarity of the plot, we do not show stars from the magnitude range V = 7–8 mag.

The total selected sample contains five stars classified as B, 22, as A, 19, as F, 16, as G, 24, as K and five, as M. The remaining 13 stars do not have spectral classification. In Fig. 1, we show a histogram of spectral types of 91 of the selected targets that have assigned a spectral type.
Figure 2. The finding chart for 104 Kepler asteroseismic targets. Dots, $V = 9–11$ mag Kepler asteroseismic targets labeled with Hipparcos HIP numbers, circles, other stars brighter than $V = 6$ mag.
3. ASTROPHYSICAL PARAMETERS

We derived effective temperatures of the 104 stars using either Strömgren uvbyβ, Johnson UBV or 2MASS JHK photometry (Cutri et al. [13]). For HIP 92937, 94012, 94748, 95092, 95495, 96061, 96343, 96776, 97486, 97582, 97724 and 98486, we used JHK photometry and the calibration of Kinman & Castelli [21]. For the remaining stars, we used JHK photometry and the calibration of Alonso et al. [1] or Alonso et al. [2]. Finally, for both components of HIP 94335, a eclipsing binary of Algol-type, we adopted the log $T_{\text{eff}}$ values listed by Ribas et al. [30].

Computing $T_{\text{eff}}$ from the metallicity–dependent calibrations of Kinman & Castelli [21], Alonso et al. [1] or Alonso et al. [2], we used the values of metalicity published by Pilachowski et al. [28], Reid et al. [29], Carney et al. [10], Feltzing & Gustafsson [17] and Zhang & Zhao [33] for HIP 92775, 94704, 95184, 95631, 95638, 95733, 96146, 96634, 96735, 96938, 97168, 97337, 97657, 97829, 98381, 98829, 99267, respectively. For the remaining stars we used the solar value.

Then, we used the photometric errors to compute the standard deviations of log $T_{\text{eff}}$. The computed values increase with log $T_{\text{eff}}$ that is partly due the the internal precision of the applied calibration, partly to the increase of photometric errors. For FGK stars for which we used 2MASS photometry, as well as for early–type stars for which we used Strömgren photometry, the average error in log $T_{\text{eff}}$ is equal to 0.02. For A–type stars for which we used 2MASS photometry, the average error in log $T_{\text{eff}}$ is equal to 0.006. The highest errors occur for B–type stars for which we used $(B - V)$ indices from the Hipparcos Catalogue. The typical errors of this index is equal to 0.03 mag. This results in a high uncertainty in the effective temperature, that is on the average equal to 0.10.

The average scatter on the effective temperature, however, is low since it does not include systematic errors of the calibration that are in general larger that the internal scatter. The main source of such systematic errors is $E(B - V)$ that is not directly measured but either calculated from the formula of di Benedetto [15] or derived from the dust maps of Schlegel et al. [31]. Therefore, the possible systematic errors of this parameter can influence the effective temperature and luminosity. Another source of systematic errors is the metallicity that has been measured for most of the studied stars and therefore assumed to be equal to the solar value.

30 of the 104 targets, mainly F–K stars, have the ratio of $\sigma_\pi/\pi$ lower than 0.175 (see the Hipparcos Catalogue, ESA [16]). In Fig. 3, we show the histogram of spectral types of 27 of these stars. We computed log $L/L_\odot$ for these stars using the formula of Smith [32] that includes the Lutz–Kelker bias (Lutz & Kelker [24]) in computations of $M_V$. Computing the bolometric magnitudes, $M_{\text{bol}}$, we used the values of bolometric corrections, $BC$, listed by Flower [18] and the solar bolometric magnitude, $M_{\text{bol}}$, equal to 4.74 mag. We calculated the standard deviation of log $L/L_\odot$ using the photometric errors, the parallax errors and the uncertainty of $BC$. We list these 30 stars, hereafter Kepler primary targets, their spectral types, de–reddened $V$ magnitudes, and computed log $T_{\text{eff}}$ and log $L/L_\odot$ in Table 1. We plot them on the log $T_{\text{eff}}$ – log $L/L_\odot$ diagram in Fig. 4. The results obtained for the remaining 74 stars, hereafter secondary targets, we list in Table 2.

4. SOLAR-LIKE VARIABILITY IN KEPLER PHOTOMETRY

The sample presented in the previous sections is perfect for an extended study of solar–like oscillations in stars of
Table 2. Effective temperatures of 74 Kepler secondary asteroseismic targets. The standard deviation of $T_{\text{eff}}$ is expressed as $\sigma \times 10^{-3}$.

<table>
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<th>$\log T_{\text{eff}} \pm \sigma$</th>
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Figure 3. Histogram of spectral types for 27 of 30 Kepler primary asteroseismic targets that have spectral classification.

Figure 4. $\log T_{\text{eff}} - \log L/L_\odot$ diagram for 30 Kepler primary asteroseismic targets.
different evolutionary status and different astrophysical parameters. With the use of asteroseismology, the interior of these stars can be examined (Christensen–Dalsgaard [12]) allowing detailed tests of pulsational and evolutionary models.

The solar–like oscillations are driven stochastically by convection in the outer layers of the stellar atmosphere. They are characterized by high regularity. At least for low-degree modes, the p-mode frequencies of radial order n and angular degree l, follow approximately the asymptotic relation, (see, e.g., Bedding & Kjeldsen [5]):

\[
\nu_{n,l} = \Delta \nu (n + \frac{1}{2} l + \epsilon) - l(l + 1) D_0. \tag{1}
\]

Modes of same l but adjacent radial order, n, are separated by the large separation, \( \Delta \nu \), while modes of the same n but adjacent l are separated by \( \sim \frac{1}{2} \Delta \nu \). The large separation is sensitive to the mean density of the star, while \( \epsilon \) is sensitive to conditions at the surface, and \( D_0 \) to conditions near the center. The advantage of this regularity is that information about the star (the mean density) can be derived even from low signal-to-noise observations, e.g., by autocorrelation analysis of the amplitude spectrum, using all modes simultaneously to derive the large separation.

These stars, however, show very tiny amplitudes which can be detected either in precise Doppler measurements or in space photometry (see Kjeldsen & Bedding [23]). Kepler, although it is a planet finding mission, will provide photometric measurements that will be suitable for observing pulsating stars, including so low–amplitude variables as solar-like pulsators. We used the scaling relations from Brown et al. [8] and Kjeldsen & Bedding [22] to compute the acoustic cut–off frequencies and amplitudes of solar–like oscillations that can be estimated as functions of mass, luminosity and effective temperature:

\[
\nu_{ac} = \frac{M/M_\odot}{(R/R_\odot)^2 \times \sqrt{T_{eff}/5777}} \times 5.5 \text{ mHz} \tag{2}
\]

\[
dL/L = \frac{L/L_\odot}{(M/M_\odot) \times (T_{eff}/5777)^2} \times 4.7 \text{ ppm} \tag{3}
\]

and we compared those values to the time sampling and noise levels of Kepler. We compared the Nyquist frequencies of Kepler (8333 and 278\( \mu \)Hz, for the 1 and 30-min cadence planned for the Kepler mission, respectively) with the upper frequency limit of solar-like oscillations, i.e., the acoustic cut–off frequency, expected for stars across the HR-diagram. We based our computations on models of Christensen–Dalsgaard [11]. We show our results in Fig. 5, where we use dashed and dotted lines to indicate stars have periods sufficiently long to be resolved with the 1 or 30 minute cadence, respectively. We show that with respect to time resolution, in most stars oscillations can be observed with the 1-min cadence. The 30-min cadence may be used only for evolved stars.

In a similar way we compared expected amplitudes of solar–like oscillation to the Kepler noise level for stars across the HR-diagram. Requiring a signal-to-noise of 3 after one month of observations we obtained the plot shown in Fig. 6. The different lines show the smallest \( L/M \)-values for which the 3\( \sigma \) criterion is fulfilled. This plot concerns stars of magnitudes \( V = 10 \) to \( V = 14 \) and was obtained with the use of the noise levels stated in the caption of the Figure. We found that for a \( V = 11 \), all stars more massive or more evolved than the Sun, will have amplitudes sufficiently high to be detected at the 3\( \sigma \) level after one month of observations at the 1-min cadence. After 3 months, solar amplitudes can be detected in stars slightly fainter than \( V = 12 \). We stress, however, that these estimations do not take into account the finite life–time of the modes and also that results on Procyon and on stars in M67 indicate that the \( L/M \) scaling relation for the amplitudes overestimates the amplitudes for F–type stars (e.g., Bedding & Kjeldsen [5]).

In order to assess what can actually be obtained from Kepler observations of solar–like stars, we prepared simulations of the stochastically excited modes carried out with the aim of estimating the precision to which stellar radii can be determined from seismic data. The simulations were done using algorithms described in De Ridder et al. [14]. The idea is that stellar radii can be obtained from the large frequency separation of solar-like oscillations, as it depends on the mean sound speed of the star. This possibility is of potentially great importance for characterizing planet-hosting stars detected with Kepler.
Figure 6. Lines of S/N>3 for stars across the HR-diagram at distances corresponding to \( V = 10 \) to \( V = 14 \), using the scaling relation for estimating amplitudes and assuming noise-levels in the amplitude spectrum of 0.96, 1.5, 2.41, 3.83 and 6.06 ppm in one month for \( V = 10 - 14 \), respectively.

Figure 7. Amplitude spectra for two of the simulated stars (simulations #8,10), after 30 and 90 days of observations at the one-minute cadence, respectively. Ordinate scales differ from panel to panel.

We simulated time series of 10 stars of different brightness and pulsational periods, amplitudes and mode lifetimes. Noise levels were scaled according to Table 1 in Borucki et al. [7], assuming a white-noise level of 71 ppm/min in the time series of a \( V = 9 \) star (0.61 ppm per month in the amplitude spectrum). We show amplitude spectra for two of the simulated stars in Fig. 7. We found that for all 10 simulations, the large separation could readily be obtained, even in cases of low signal-to-noise in the amplitude spectra (cf. Fig. 7, upper panels). Autocorrelations for the two stars in Fig. 7 are shown in Fig. 8. As above, input was the part of the amplitude spectrum where the signal is (about 2–4 mHz depending on the specific simulation), including only peaks above 1.5\( \sigma \) (the noise at high frequency). The autocorrelations show clear, regular spaced peaks at integer and half-integer values of the large separation as expected from the asymptotic relation. For all 10 stars, subsequent comparison with the input frequencies showed that the large separations derived from the data were correct.

We estimated also the precision of derivation of the large separations from our simulated data. We found that the separations extracted from the data of different chunks of months are consistent within a few tens of a \( \mu \)Hz. We found that the large separations found in the individual bins typically fall within 0.2\( \mu \)Hz with the scatter equal to 0.04\( \mu \)Hz. Therefore, we conclude that on the average the large separation can be determined to an estimated precision of better than at least 0.5\( \mu \)Hz.

5. SUMMARY

We presented a list of 30 primary and 74 secondary asteroseismic targets for the Kepler space telescope. We computed effective temperatures for all the targets and also luminosities, for the primary ones. In most cases, \( \log T_{\text{eff}} \) computed by us is the first determination of this parameter. The obtained values slightly differ from the preliminary \( \log T_{\text{eff}} \), \( \log L/L_\odot \) listed in Molenda–Żakowicz [26] because of more precise de-reddening procedure and slightly different approach to estimation \( E(B-V) \). For stars with effective temperatures derived also by other authors, i.e., HIP 96146, 97219 and 99267 Masana et al. [25], HIP 92775 Pilachowski et al. [28], HIP 95184 Carney et al. [10], HIP 98814 Budding [9] and 18 other stars from our sample listed by Ammons et al. [3], our values agree well with those from the literature.

We showed that both the Kepler 1–min (high) cadence and the 30-min (low) cadence modes can be used for detection of solar–like oscillations and for precise determination of seismic parameters in a wide range of HR diagram. Finally, we show that this detection, i.e., discovery of new solar–like pulsators, can be made in a short time after the start of the mission.
Figure 8. Autocorrelations for the data shown in Fig. 7. The dotted lines show the large separations found for the two simulations. Ordinate scales differ from panel to panel.

REFERENCES