Asteroseismology of solar-type stars with Kepler: III. Ground-based data

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We report on the ground-based follow-up program of spectroscopic and photometric observations of solar-like asteroseismic targets for the Kepler space mission. These stars constitute a large group of more than a thousand objects which are the subject of an intensive study by the Kepler Asteroseismic Science Consortium Working Group 1 (KASC WG-1). In the current work we will discuss the methods we use to determine the fundamental stellar atmospheric parameters using high-quality stellar spectra. These provide essential constraints for the asteroseismic modelling and make it possible to verify the parameters in the Kepler Input Catalogue (KIC).

1 Introduction

Kepler1 is a NASA Discovery mission searching for planets of the size of the Earth orbiting stars similar to the Sun. Another goal of the Kepler mission is the asteroseismic study of planet-hosting stars. That investigation can yield the stellar radii and as a result, radii of the transiting planets.

The asteroseismic part of the Kepler mission is being realized by the Kepler Asteroseismic Science Consortium2 (KASC) which has been established with the aim of making a full exploitation of the Kepler time-series space photometry. The main scientific goal of KASC is the study of stellar interiors by means of asteroseismic methods. To facilitate the research carried out in the KASC, 13 working groups have been established, each dedicated to the study of pulsating stars of a different kind. In working group number one (WG-1), stars expected to show solar-like oscillations are investigated; sub-group nine (SG-9) of WG-1 are in charge of the ground-based observations of solar-like Kepler asteroseismic targets.

Since the principal investigation of the KASC aims at deriving properties of planet-hosting stars selected for targets for the Kepler mission, the largest group of more than a thousand stars selected for the asteroseismic targets are main-sequence dwarfs similar to the Sun. These stars may show solar-like oscillations, the analysis of which yield the densities of the stars. The radii of the stars are then determined from comparison with the models of stellar evolution.

Unfortunately, the Kepler data do not provide the information which is crucial for the asteroseismic modelling, i.e., the stars’ effective temperature $T_{\text{eff}}$, surface gravity $\log g$, metallicity $[\text{Fe/H}]$, and projected rotational velocity $v \sin i$.

The Kepler Input Catalog3 (KIC) (Latham et al. 2005) provides values of $T_{\text{eff}}, \log g$ and $[\text{Fe/H}]$ for most Kepler targets derived from the Sloan griz filters and the narrow D51 filters of the Kepler Input Catalogue (KIC).

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1 http://kepler.nasa.gov/
2 Kepler Asteroseismic Science Consortium (KASC) is a group of collaborating scientists established to accomplish the activities of the Kepler Asteroseismic Investigation (KAI), represented by Ronald Gilliland (see http://astro.phys.au.dk/KASC).
filter. The uncertainties of these parameters are too large for the asteroseismic modelling, since they reach ±200 K in $T_{\text{eff}}$, and ±0.5 dex for both $\log g$ and [Fe/H]. Nevertheless, the information from the KIC is very useful for distinguishing giants from main-sequence stars, and for finding stars similar to the Sun.

Finally, only a small fraction of the Kepler asteroseismic targets has been studied in the literature. $T_{\text{eff}}$ has been derived either from spectroscopy or photometry only for 15% of the solar-like Kepler asteroseismic targets, $\log g$ for about 10%, and 5% have the measured [Fe/H].

In Fig. 1 we show the differences between $T_{\text{eff}}$, $\log g$, and [Fe/H] of the solar-like oscillators in the KIC and in the literature. As can be seen in the figure, for stars hotter than 6500 K, the differences between $T_{\text{eff}}$ in the KIC and in the literature can be very large. The reason is that KIC has been designed to help find stars similar to the Sun, and to distinguish them from hotter objects. As a result, the values of $T_{\text{eff}}$ given in the KIC for stars cooler than around 6500 K can be trusted, while those given for hot stars should only be used as a rough indication of the spectral type.

The comparison of $\log g$ in the KIC and in the literature is difficult because the uncertainties of this parameter in the KIC is very high (0.5 dex). The values listed in the KIC allow to distinguish dwarfs from giants, as they were expected to, but can not be used as constraints in asteroseismic modelling.

The same concerns [Fe/H] from the KIC which was supposed to help find stars of solar metallicity, and for such stars the agreement with the literature is quite good. Anyhow, we note that there is a trend in the differences between [Fe/H] in the KIC and in the literature, which we will investigate in more detail in the future. The stated trend exists both for the spectroscopic and photometric derivations, and shows that in the KIC the metal-deficient stars are found to be more metal-poor, and the metal-rich ones, generally more metal-abundant than in the literature.

2 Ground-based observations

For the reasons outlined in the previous section, the KASC WG-1/SG-9 organized a large coordinated programme of ground-based observations which aims at the determination of $T_{\text{eff}}$, $\log g$, [Fe/H], and $v \sin i$ of all the solar-like asteroseismic targets of Kepler. This concerns multi-colour photometric CCD photometry, high and medium resolution spectroscopic observations, and interferometric measurements.

We list the on-going programmes to obtain ground-based observations of solar-like Kepler asteroseismic targets in Table 1. This Table provides the information about the observatory at which the programmes are realized, the telescope and the instrument used, the type of the observing programme (spectroscopy, photometry or interferometry), the number of the nights, and the initials of the principal investigator of the proposal. The list of more than 170 solar-like targets, which have been already observed, will be soon put on the webpage of the KASC.

Many of the listed research programmes include targets of different KASC working groups. For the additional information, we refer to Uytterhoeven et al. (2010).

2.1 Spectroscopy

The spectroscopic investigation of the Kepler asteroseismic targets aims at deriving the atmospheric parameters of the stars and the value of the microturbulence in their atmospheres, as well as the projected rotational velocity and the radial velocity (see Molenda-Zakowicz et al. 2007, 2008, 2010; Catanzaro et al. 2010; Frasca et al. 2010.)

The observatories involved in this research include the Osservatorio Astrofisico di Catania (OACi) in Italy, the Observatorio del Roque de los Muchachos in Spain, the Mauna
A summary of the programmes of ground-based observations of solar-like Kepler asteroseismic targets.

| Observatory | Telescope/Instrument | Type of Programme | Number of Nights | P.I. |
|-------------|-----------------------|-------------------|------------------|------|
| Osservatorio Astrofisico di Catania, Italy | 91-cm FRESCO | Spectroscopy | 92 | J.M-Z |
| | 91-cm photometer | Photometry | 11 | J.M-Z |
| Observatorio del Roque de los Muchachos, La Palma, Spain | 2.54-m INT WFC | Spectroscopy | 5 | K.U. |
| | 2.56-m NOT FIES | Spectroscopy | 3 | K.U. |
| | 1.2-m Mercator HERMES | Spectroscopy | 7 | M.B. |
| | 3.58-m TNG SARG | Spectroscopy | 12 | G.C. |
| Calar Alto, Spain | 2.2-m BUSCA | Photometry | 5 | K.U. |
| Observatorio del Teide, Tenerife, Spain | 0.8-m IAC-80 CAMELOT | Photometry | 14 | K.U. |
| Mauna Kea, USA | 3.6-m CFHT ESPaDOnS | Spectroscopy | 10 hrs | H.B. |
| Pic du Midi, France | 2-m NARVAL | Spectroscopy | 40 hrs | H.B. |
| Xinglong, China (proposal submitted, under consideration) | 4-m LAMOST | Spectroscopy | 13 | P.D.C. |
| Center for High Angular Resolution Astronomy, USA | CHARA PAVO | Interferometry | 6 | D.H. |

Kea Observatory in the USA, the Pic du Midi Observatory in France, and the Xinglong Observatory in China.

We note that the observing proposal submitted by P.D.C. for the multi-fiber, multi-object spectrograph LAMOST at the 4-m telescope at Xinglong is particularly interesting because, if accepted, it will allow us to acquire low and/or medium resolution spectra of 6759 stars, i.e., 95% of all Kepler asteroseismic targets.

A separate spectroscopic investigation of late-type main sequence stars is carried out by C.K. (see Karoff et al. 2009). The aim of their research is to understand the relation between the changes in the chromospheric activity of stars and the changes in the eigenmodes of their oscillations. This can improve our understanding of the physics of convection and the cycles of stellar activity.

Finally, an investigation dedicated to giant stars in the Kepler field is conducted by S.F., D.S. and H.B. who have been awarded time to acquire high resolution spectra of the 4-m telescope at Xinglong is particularly interesting because, if accepted, it will allow us to acquire low and/or medium resolution spectra of 6759 stars, i.e., 95% of all Kepler asteroseismic targets.

2.3 Interferometry

The interferometric measurements performed by M.I., D.H., T.B., and D.S. using the Center for High Angular Resolution Astronomy (CHARA, ten Brummelaar et al. 2005) array at Mt. Wilson Observatory, California, USA, aim at deriving the angular diameters, $\theta$, of the brightest Kepler stars ($V=7-9$). Observations are performed using the Precision Astronomical Visible Observations (PAVO) beam combiner (Ireland et al. 2008).

Using the longest CHARA baselines (330 m) at a central wavelength of 0.75 $\mu$m, PAVO is able to resolve stars as small as 0.3 mas, which will allow precise angular diameter measurements of main-sequence stars observed by Kepler. Combining $\theta$ measured with the relative precision of, e.g., 2% with the parallax measured with the same relative precision yields the linear radius of the star with an uncertainty of 3%, which is comparable to the precision available from the asteroseismic analysis.

These numbers are representative for the analysed sample. The precision of the Hipparcos parallax for three Kepler short-cadence targets selected for observations with PAVO is 1–2% while for the more evolved stars it is 4–10%.

Combining $\theta$ with the observed bolometric flux gives a direct measurement of the effective temperature precise to around 1% (see, e.g., North et al. 2009.)

3 Atmospheric parameters

The atmospheric parameters of solar-like Kepler asteroseismic targets are the most important result of the research conducted by KASC WG-1/SG-9 since their values are crucial for asteroseismic modelling. In order to find accurate values of these parameters and to estimate realistic uncertainties,
we use different analysis methods applied to the same data, as well as to the data acquired by various instruments or by different methods, i.e., spectroscopic or photometric.

For the derivation of the atmospheric parameters of stars from spectroscopic observations, we use the VWA software developed by H.B. (see Bruntt et al. 2004, 2010), the ARES software developed by S.S. (Sousa et al. 2007), the MOOG code developed by Sneden (1973), the ROTFIT code developed by A.F. (Frasca et al. 2003, 2006), and the TLUSTY/SYNSPEC developed by Hubeny (1995).

Metcalfe et al. (2010) presented a detailed asteroseismic analysis of the solar-type Kepler target KIC 11026764. Their work relied on the constraints from the analysis of a high-quality spectrum using the methods mentioned here. The atmospheric parameters derived by the different methods agree quite well, but the estimates of the uncertainties are different by factors of 3–4, although the same spectrum was used. In the near future, we will conduct a systematic assessment of the uncertainties on the atmospheric parameters, which is a vital ingredient when constraining the asteroseismic modelling.

We estimate that for a good spectrum (SN > 80, R > 40000) covering a wide wavelength range, the uncertainty including systematic errors on $T_{\text{eff}}$ is about ±100 K, while for $\log g$ and [Fe/H] the uncertainties are 0.1 dex.

Molenda-Żakowicz et al. (2009) found significant disagreement for $T_{\text{eff}}$ derived from Strömgren photometry and from spectroscopy. For stars in the range of 6500–7500 K, spectroscopic temperatures are systematically cooler by about 300 K. We will investigate this further as more spectroscopic and photometric observations of Kepler asteroseismic targets are acquired.

4 Future observations

In the future, we will not restrict the ground-based spectroscopic and photometric follow-up observations to large telescopes. We intend to include also small and medium-sized telescopes, since many Kepler asteroseismic targets are bright enough for such instruments. Additionally, at the sites hosting these instruments it is often possible to perform long and dedicated observing runs that our observing program requires.

For these reasons, we strongly encourage the astronomical community to use the small and medium-size Northern telescopes for the photometric and spectroscopic research of Kepler asteroseismic targets. We stress that the participation in this programme is beneficial also for the sites hosting small telescopes.

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