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# Asteroseismology of Solar-type stars with Kepler III. Ground-based Data

**J. Molenda-Żakowicz[1,⋆], H. Bruntt[2], S. Sousa[3], A. Frasca[4], K. Biazzo[5], D. Huber[6], M. Ireland[6], T. Bedding[6], D. Stello[6], K. Uytterhoeven[7], S. Dreizler[8], P. De Cat[9], M. Briquet[10], G. Catanzaro[4], C. Karoff[11,12], S. Frandsen[12], L. Spezzi[13], and C. Catala[2]**

[1] Instytut Astronomiczny Uniwersytetu Wrocławskiego, ul. Kopernika 11, 51-622 Wrocław, Poland
[2] LESIA, UMR 8109, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon, France
[3] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762, Portugal
[4] INAF–Osservatorio Astrofisico di Catania, Via Sofia 78, 95123 Catania, Italy
[5] INAF–Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[6] Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
[7] Laboratoire AIM, CEA/DSM-CNRS-Universit Paris Diderot-IRFU/SAp, 91191 Gif-sur-Yvette Cedex, France
[8] Georg-August Universität, Institut für Astrophysik, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany
[9] Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium
[10] Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
[11] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[12] Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
[13] European Space Agency (ESTEC), P.O. Box 299, 2200 AG Noordwijk, The Netherlands

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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 thousand objects which are the subject of an intensive study of the Kepler Asteroseismic Science Consortium Working Group 1 (KASC WG-1). The main goal of this coordinated research is the determination of the fundamental stellar atmospheric parameters, which are used for the computing of their asteroseismic models, as well as for the verification of the Kepler Input Catalogue (KIC).



## 1 Introduction

The Kepler Asteroseismic Science Consortium KASC[1] has been established with the aim of making a full exploitation of the Kepler time-series space photometry. The main goal of KASC is the study of stellar interiors by means of asteroseismic methods.

The largest group of stars selected for asteroseismic targets for Kepler are those which are expected to show solar-like oscillations. Unfortunately, the Kepler data do not provide information on the effective temperature $(T_{\rm eff})$ surface gravity, $(\log g)$, metallicity, and projected rotational velocity, $(v \sin i)$, of these stars, which are crucial data for asteroseismic modeling. Only a small fraction of Kepler asteroseismic targets has been studied in the literature. The effective temperature has been derived either from spectroscopy or photometry only for 15% of the solar-like Kepler asteroseismic targets, the surface gravity, for 10%, and 5% have a measured metallicity.

The Kepler Input Catalog[2] (KIC) (Latham et al. 2005) provides values of $T_{\rm eff}$, $\log g$ and [Fe/H] derived from Sloan photometry for many Kepler targets. However, the uncertainties of $T_{\rm eff}$, $\log g$ and [Fe/H] in the KIC are too large for asteroseismic modeling since they reach $\pm 200$ K in $T_{\rm eff}$, and $\pm 0.5$ dex, both in $\log g$ and [Fe/H].

In Fig. 1 we show the differences between $T_{\rm eff}$, $\log g$ and [Fe/H] of the solar-like oscillators in the KIC and in the literature. As can be seen from the figure, the discrepancies can be as high as 1000 K, especially for stars hotter than 5500 K. The agreement in $\log g$ and [Fe/H] is slightly better but still poor. Their values agree to within the error bars, but the latter are so large that they do not allow any meaningful comparison.

Moreover, we note that there is a trend in the differences between [Fe/H] in the KIC and in the literature, which exists both for the spectroscopic and photometric derivations,

⋆ e-mail: molenda@astro.uni.wroc.pl

[1] 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).

[2] http://archive.stsci.edu/kepler/kepler_fov/search.php

and which shows that the metal-deficient stars are found to be more metal-poor, and the metal-rich stars, more metal-abundant in the KIC than in the literature.

## 2 Programmes of Ground-Based Observations

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

In Table 1, we list the on-going programmes of ground-based observations of solar-like Kepler asteroseismic targets, including the information on 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.

We note that 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 derivation of the atmospheric parameters of the stars and the value of the micro-turbulence in their atmospheres, as well as the projected rotational velocity and the radial velocity (see Molenda-Żakowicz 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 (OACt) in Italy, the Observatorio del Roque de los Muchachos in Spain, the Mauna 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 to acquire low and/or medium-resolution spectra of 95% of all the Kepler asteroseismic targets.

A separate spectroscopic investigation of late-type main sequence stars selected for being observed by Kepler for the entire life-time of the mission is carried out by C.K. (Karoff et al. 2009). The aim of the research of these authors is to understand the relation between the changes in the chromospheric activity of the stars and the changes in the eigenmodes of their oscillations, which can lead to the improvement of the models of stellar evolution.

An investigation of giant stars from the Kepler field of view is conducted by S.F., D.S. and H.B. who have been awarded time to acquire high resolution spectra (R=60 000) of these stars with FIES at the NOT. The aim is to get a signal-to-noise ratio (S/N) of 100 for about 60-80 giant stars. C.C and H.B. have been awarded time to observe 300 solar-type stars at Pic du Midi and CFHT. Their aim is to get S/N = 100-200 with a resolution of R=80 000. With these data, they will be able to derive $T_{\rm eff}$, $\log g$, and [Fe/H] of the targets with a $1\,\sigma$ uncertainty of 100K in Teff, and 0.1 dex in both log g and [Fe/H].

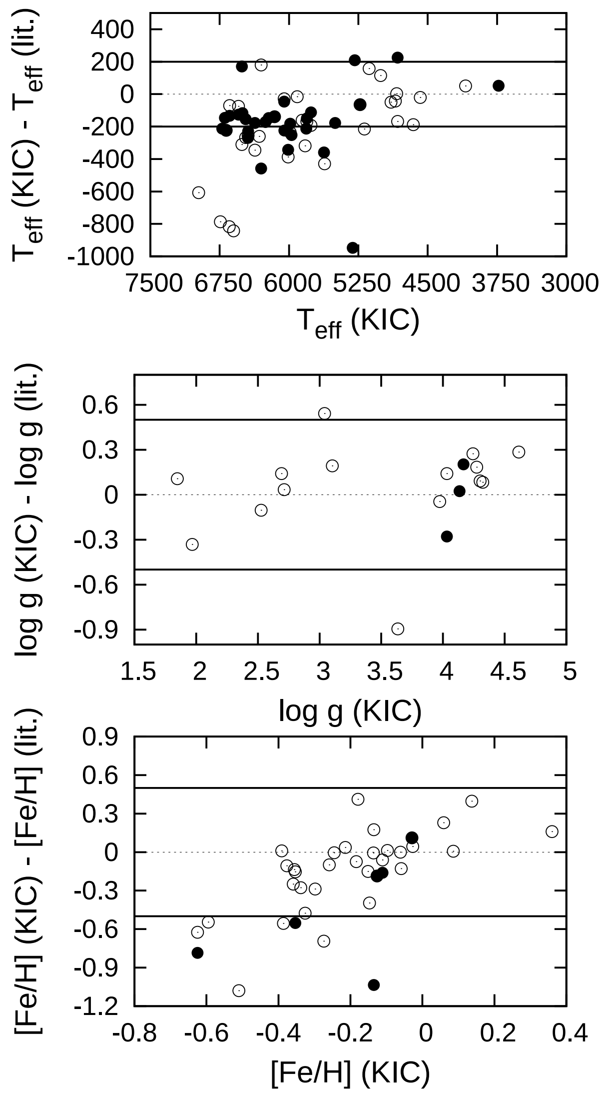


**Fig. 1** The differences between $T_{\rm eff}$, $\log g$ and [Fe/H] given in the KIC and in the literature. Solid and open symbols indicate literature values from photometry and spectroscopy, respectively. The $1\sigma$ uncertainty ranges of the determinations provided in the KIC are indicated with solid lines.

**Table 1** 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-Ż |
| 〃 | 91-cm photometer | photometry | 11 | J.M-Ż |
| Observatorio del Roque de los Muchachos, La Palma, Spain | 2.54-m INT WFC | photometry | 5 | K.U. |
| 〃 | 2.56-m NOT FIES | spectroscopy | 3 | K.U. |
| 〃 | 〃 | spectroscopy | 7 | S.F. |
| 〃 | 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. |
| Observatory of Izaña, 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. |

## 2.2 Photometry

The photometric research realized at the OACt in Italy, the Observatory of Izaña and Calar Alto Observatory in Spain also allows to determine the stellar atmospheric parameters from the Johnson and Strömgren magnitudes. These data, when combined with 2MASS JHK magnitudes (Cutri et al. 2003), can be used for computing the spectral energy distribution of the stars and deriving their atmospheric parameters. Additionally, photometric observations allow to measure the reddening of the stars and their absolute magnitude (see Molenda-Żakowicz, Jerzykiewicz & Frasca 2009; Frasca et al. 2009; Kupka & Bruntt 2001.)

## 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 mag). Observations are performed at visible wavelengths using the Precision Astronomical Visible Observations (PAVO) beam combiner (Ireland et al. 2008).

Using the longest CHARA baselines (330m) 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 $\theta$ with the parallax yields a measurement of the linear radius, while a combination of $\theta$ with the bolometric flux yields a direct measurement of the effective temperature.

Fig. 2 shows an example of preliminary PAVO data obtained in July 2009 (Huber et al. in preparation) of a metal-poor sub-giant observed by Kepler.

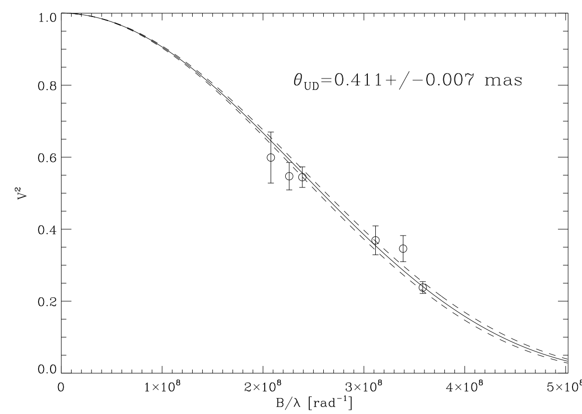


**Fig. 2** Squared visibility versus spatial frequency of a metal-poor sub-giant in the Kepler target list obtained using the PAVO beam combiner at the CHARA array. The solid line shows a uniform-disc diameter fit with 1-sigma uncertainties (dashed lines).

# 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 modeling. In order to find precise values of these parameters and to estimate their external errors 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[3] software developed by H.B. (see Bruntt et al. 2004, 2010), the ARES[4] software developed by S.S. (Sousa et al. 2007), the MOOG code developed by Sneden (1973)[5], the ROTFIT

[3] http://physics.usyd.edu.au/ bruntt/vwa/
[4] http://www.astro.up.pt/ sousasag/ares/
[5] http://verdi.as.utexas.edu/

code developed by A.F. (Frasca et al. 2003, 2006), and the TLUSTY/SYNSPEC developed by Hubeny (1995).

As shown by Metcalfe et al. (in preparation) who discuss KIC 11026764 observed at the NOT with the FIES instrument, the atmospheric parameters derived by means of the methods listed above agree well to within $1\sigma$ of their error bars. Nevertheless, the external uncertainty of the derivation of $T_{\rm eff}$ remains $\pm 200$ K while for $\log g$ and [Fe/H] it has been reduced to $\pm 0.25$ and $\pm 0.1$ dex, respectively.

Another kind of disagreement in $T_{\rm eff}$ derived from spectroscopy and from Strömgren photometry has been noticed by Molenda-Żakowicz et al. (2009) who show that stars from the temperture range 6500 – 7500 K in photometry are found systematically cooler by about 300 K in spectroscopy. This effect is of particular significance since it affects the process of the asteroseismic modeling of the stars, and as such should be explained. This will be done when 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, but we intend to additionally include small and medium-size telescopes because many Kepler targets that 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 will be beneficial also for the sites hosting small telescopes.

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