Satellite Observations of Pulsating Stars

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Presented are the impact of satellite observations on asteroseismic investigation and the programmes of ground-based follow-up observations dedicated to different space missions.

1 Asteroseismology from Space

The second half of the XX$^{\rm th}$ century provided astronomers with an invaluable opportunity to observe stars from space. Since the satellite observatories are located above the Earth's atmosphere, data obtained with them do not suffer from distorting effects of the atmosphere and their acquisition is not limited by the weather conditions or the day-and-night cycle (but see Gadimova & Haubold, 2014, who discuss how the space weather affects satellite observations). As a result, space telescopes can obtain long, uninterrupted time-series of observations of a selected target or perform continuous mapping of the entire sky. Another important advantage of space missions is an opportunity to observe stars in these parts of the electromagnetic spectrum which does not reach the Earth's surface such as γ-rays, X-rays, far ultraviolet, and large parts of the infrared spectrum.

The list of space telescopes which improved our understanding of the properties of pulsating stars is long. Among the most important ones there are: the astrometric space mission Hipparcos (Lacroute, 1981), the Hubble Space Telescope (HST, Bahcall, 1986), the Wide Field Infrared Explorer (WIRE, Hacking & Werner, 1995), the Microvariability and Oscillations of STars telescope (MOST, Walker et al., 2003; Matthews, 2003), the *Kepler* space telescope and its continuation the K2 mission (Koch et al., 2004; Gilliland et al., 2010; Howell et al., 2014), the COnvection ROtation and planetary Transits space mission (CoRoT, Baglin et al., 2006), and the BRIght Target Explorer (BRITE-Constellation, Weiss et al., 2014).

For some of those instruments, like for MOST or BRITE, asteroseismology has been selected for the primary scientific aim. For other missions, like *Kepler*, K2, or CoRoT, studies of pulsating stars have been a significant but not a fundamental part of research. There were also instruments like Hipparcos, which delivered data valuable in asteroseismic studies as a by-product of its original scientific programme, telescopes like HST, which in its plenitude of the research topics allowed to carry out only a limited number of projects dedicated to pulsating stars, and finally missions like WIRE which was intended to be a four-month infrared survey observing starburst galaxies and luminous protogalaxies but which suffered from a failure shortly after launch and eventually has been used for a successful photometric monitoring of bright stars in various asteroseismic projects (Bruntt, 2007).

Each of those instruments helped us widen our horizons and understand pulsating stars in more detail. Thanks to Hipparcos we learnt that the number of Slowly Pulsating B-type stars (SPBs) and γ Dor-type stars is significantly higher comparing to what was known from the analysis of ground-based data (Waelkens et al., 1998; Aerts et al., 1998; Molenda-Żakowicz, 2000). That was due to the fact that the length of periods of pulsations in SPB and γ Dor-type stars is close to one day and as such can be easily interpreted as daily aliases when analysing the periodograms of ground-based observations.

It is important to keep in mind that satellite observations of individual stars can allow a detailed insight in the stellar structure especially if they are complemented with ground-based data. Interesting case studies include ζ Oph, an Oe-type star for which the MOST photometry combined with ground-based spectroscopy allowed a detailed asteroseismic analysis (Walker et al., 2005), μ Eri, a B-type eclipsing binary for which it was possible to measure the mean density and clearly detect the SPB frequencies in the WIRE and MOST photometry (Buzasi et al., 2004; Jerzykiewicz et al., 2013), HD 163899 B2Ib/II observed with MOST which has been discovered by Saio et al. (2006) to be a prototype of a new class of slowly pulsating B-type supergiants (SPBsg) distinct from α Cyg-type variables, or the brightest roAp star α Cir for which the period of rotation has been measured in the WIRE photometry by Bruntt et al. (2009).

Very interesting results have been obtained for B-type stars with the CoRoT telescope. These include detection of solar-like oscillations in a β Cep type star V1449 Aql (Belkacem et al., 2009), the first detection of a deviation from a constant period spacing in gravity modes in an SPB star (Degroote et al., 2010), or monitoring the time-evolution of the frequency spectrum of a B0.5IVe star HD 49330 during an outburst (Huat et al., 2009). Interesting results for massive stars are expected also from the BRITE-Constellation which targets are mainly the most intrinsically luminous stars selected for a thorough asteroseismic analysis which aims at probing the stars' interiors and measuring their ages.

Moving to lower effective temperatures and to δ Sct-type stars we learnt from the CoRoT photometry that frequency spectra of these stars can show hundreds of peaks (Poretti et al., 2009) which has never been observed from the ground and which exceeded even the amount of frequencies detected with the *Kepler* telescope for other pulsating stars (see, e.g., the results obtained by Balona et al., 2011, for B-type stars).

Another surprise was that the δ Sct and γ Dor-type stars discovered with *Kepler* seemed to cover uniformly a large area of the HR diagram (Grigahcène et al., 2010; Uytterhoeven et al., 2011) instead of falling into the regions of instability known from theoretical models and ground-based observations (Rodríguez & Breger, 2001; Handler & Shobbrook, 2002). We learnt also that some δ Sct-type stars, like HD 187547 which was studied by Antoci et al. (2011), show frequency patterns similar to solar-like oscillations that are not expected in stars with so shallow convection zones (see also Michel et al., 2008), while other stars seem to be constant even though they fall into the δ Sct or γ Dor instability regions (Guzik, in prep.)

The most spectacular discoveries with space missions have been made for solar-type stars, though. These stars display solar-like oscillations which allow to probe stellar interiors (Christensen-Dalsgaard, 2004) but which amplitudes are so tiny that it is almost impossible to detected them from the ground. The first clear detection of such oscillations in a star other than the Sun was obtained with the WIRE satellite for α Cen (Schou & Buzasi, 2001). Very interesting results have been obtained also Procyon. That star in the MOST photometry turned to not show solar-like oscillations to the extent that had been expected (Matthews et al., 2004) which resulted in a very eager scientific discussion (see e.g. Christensen-Dalsgaard & Kjeldsen, 2004; Bedding et al., 2005).

Those results were obtained mostly for individual stars but it was only the *Kepler* mission which revolutionised asteroseismology by increasing the number of stars with detected oscillations by nearly two orders of magnitude and delivered data with unprecedented signal-to-noise ratio of several parts per million (ppm). The thousands of stars showing solar-like oscillations discovered with *Kepler* allowed statistical analysis of their properties (mass, radius, and age) and to test present theories of stellar evolution and pulsations (Huber et al., 2010, 2014; Chaplin et al., 2011; Silva Aguirre et al., 2011). Asteroseismic investigation has been recognised as crucial tool of analysis also for planet-hosting stars which are the primary scientific goals of the *Kepler* and the K2 missions. A good example is HAT-P-7 for which the value of the radius was derived with a precision of 1% by Christensen-Dalsgaard et al. (2010).

Finally, space missions provided valuable insight in properties of pulsating stars which are significantly cooler or much more evolutionary advanced than the Sun. Among them there are, e.g., Mira-type pulsating stars which angular diameters were measured by Lattanzi et al. (1997) with the HST, or pulsating white dwarfs for which the instability strip has been found by Szkody et al. (2010) by means of the same telescope.

2 Ground-Based Follow-Up

Even though space telescopes deliver data which are not possible to be obtained from the ground, their proper interpretation strongly depend on the accessibility of ground-based observations. The latter are obtained by individual researchers who often are members of different scientific organisations which facilitate collaboration on follow-up observing projects. One of the first, large organisation which aimed at facilitating the process of collecting ground-based observations was the *Kepler* Asteroseismic Science Consortium (KASC). KASC was set up in summer 2009. It is a large team of over 400 scientists who contribute to different parts of the data analysis and interpretation of the *Kepler* asteroseismic targets. The work in the KASC is divided between several working groups (WGs), each focusing on a special type of pulsations and one dedicated to ground-based follow-up observations. An overview of the observing programmes realized in the framework of the KASC can be found in Molenda-Żakowicz et al. (2010); Molenda-Żakowicz (2013); Uytterhoeven et al. (2010).

Another large observing project is the Apache Point Observatory Galactic Evolution Experiment (APOGEE, Epstein et al., 2014) which cooperates with the KASC to characterise the fundamental properties of thousands of red giants in the *Kepler* field. It is important to mention also the *Kepler* Community Follow-up Observing Program (CFOP) which is a web site that contains information about observing projects related to the *Kepler* Objects of Interest (KOIs). A similar initiative is the GAIA-ESO Public Spectroscopic Survey (Gilmore et al., 2012) which aims at obtaining high quality spectroscopy of $\sim 100,000$ stars in the Milky Way as a ground-based support for the ESA space mission GAIA which will observe also variable stars (Eyer et al., 2009).

One of the recent projects of ground-based follow-up observations which is being realized in the framework of the KASC and which is dedicated to the *Kepler* mission is the LAMOST-Kepler project (L-K project). That project started in 2010 (De Cat et al. in preparation) and has been continued through 2014. It makes use of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, Zhao et al., 2012) which allows to acquire simultaneously thousands of low-resolution spectra of objects

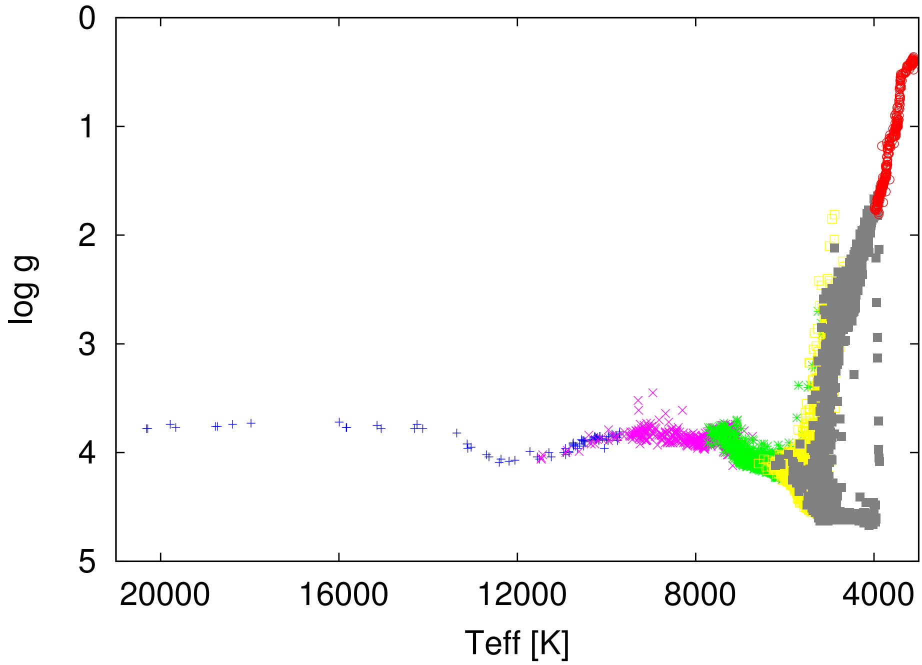

Fig. 1: $T_{\rm eff}$-log g diagram for 10,211 stars in the *Kepler* field of view which were observed with the LAMOST facility in 2010 and 2012 and analysed with the code ROTFIT. The colour-coded symbols indicate the spectral type classification delivered by the ROTFIT code: blue for B, violet for A, green for F, yellow for G, gray for K, and red for M-type stars.

as faint as 20.5 mag and as such is a very good instrument to perform spectroscopic follow-up observations for targets in the *Kepler* field of view. The L-K project focuses on those stars in the *Kepler* field of view which are too faint for high-resolution spectrographs or for which there are no atmospheric parameters reported in the literature. The target selection procedure, the details of the observing programme, and an outline of the methods of analysis of the collected spectrograms will be described by De Cat et al. (in preparation). The results of analysis of observations acquired in the framework of the L-K Project will be published soon by Frasca et al. (in preparation). In order to illustrate the sample which has been observed in 2011 and 2012, in Fig. 1 we show the $T_{\rm eff}$-log g diagram for 10,211 stars for which the atmospheric parameters have been derived by Frasca et al. (in preparation) with the code ROTFIT (Frasca et al., 2003, 2006; Molenda-Żakowicz et al., 2013).

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