Stars and their variability observed from space
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THE BRITE-SONG OF ALDEBARAN – STELLAR MUSIC IN THREE VOICES

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Abstract. Solar-like oscillations in red-giant stars are now commonly detected in thousands of stars with space telescopes such as *Kepler.* Parallel radial-velocity and photometric measurements would help us understand better the physics governing the amplitudes of solar-like oscillators, but most stars targetted for space photometry are too faint for light-demanding ground-based spectroscopy. The *BRITE*-Constellation provides a unique opportunity of monitoring in two colours the flux variations of bright luminous red giants. Those stars are also bright enough to be monitored with high-resolution spectrographs on small telescopes, such as the *SONG* Network. This contribution provided a first overview of our comprehensive, multi-year campaign to use both *BRITE* and *SONG* to characterize Aldebaran (one of the brightest red giants in the sky) seismically. Because luminous red giants can be seen at large distances, when characterized well they will serve as valuable benchmark stars for Galactic archeology.

Keywords: stars: pulsation, evolution, individual: Aldebaran

1 Introduction

Space missions such as NASA's *Kepler* or *TESS* (Borucki et al. 2010; Ricker et al. 2015, respectively) have enabled the detection of solar-like oscillations in tens of thousands of main-sequence and red-giant stars (e.g. Hon et al. 2018; García & Ballot 2019; SilvaAguirre et al. 2019). While such satellites can provide ultra-precise monochromatic photometry, typical target stars are too faint for light-demanding ground-based complementary techniques. Simultaneous multi-colour photometry and parallel radial-velocity (RV) monitoring of solar-like oscillating stars would provide crucial information for understanding the physics governing the oscillations and their amplitudes. So far, the only solar-like oscillators for which such simultaneous data have been acquired and analysed are the Sun itself (Jiménez et al. 1999) and the mid-F sub-giant Procyon (Arentoft et al. 2008).

The 3-cm telescopes of the five *BRITE*-Constellation satellites (BRIght Target Explorer, Weiss et al. 2014), with their blue and red photometric filters, have enabled multi-colour space photometry of very bright targets since the launch of the the first pair in 2013. While the primary science case for BRITE satellites does not include solar-like oscillations on the main sequence, or evolved stars, it was shown by Kallinger et al. (2019) that red-giant stars with oscillation frequencies below 10 μHz ($R_\star > \sim 25 R_\odot$) exhibit oscillation amplitudes that are large enough to be detected by the *BRITE* satellites. Such targets are also accessible by spectrographs mounted on 1-m-class telescopes, such as SONG (Stellar Observations Network Group, Grundahl et al. 2017), which was designed for the acquisition of high-quality spectroscopic time-series for asteroseismology. The first telescope of that telescope network was commissioned in 2014 and is installed at the Teide observatory (Tenerife). It is

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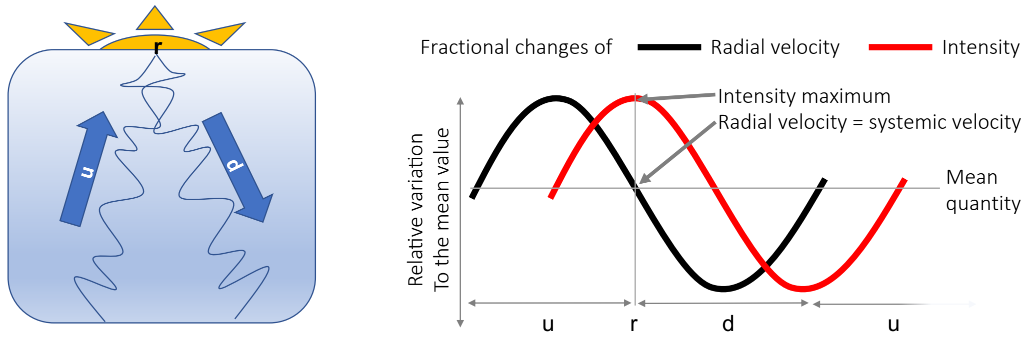

Fig. 1. Conceptual illustration of the behaviour of an oscillation mode near the surface of a star. **Left panel:** A wave coming from the interior (u) reaches regions of lower density and gets reflected back (r) into the deeper and denser layers again (d). **Right panel:** Two sine curves approximate the variations in radial velocity and intensity field (black and red, respectively). This sketch assumes ideal adiabatic conditions in the outer atmosphere, with the velocity field leading to an intensity variation shifted by 90^o.

equipped with a high-resolution spectrograph (with a resolving power of $77000 \leq \mathrm{R} \leq 112000$) and is capable of simultaneous wavelength calibration providing metre/sec RV precision.

This project is using a combination of multi-colour *BRITE* photometry and *SONG* spectroscopy to investigate solar-like oscillations in the luminous red-giant star Aldebaran (α Tau) wwhich has a visual brightness of +0.9 mag and a luminosity of $439\pm17\,\mathrm{L}_\odot$ (Heiter et al. 2015). Photometry obtained for Aldebaran by Farr et al. (2018) with *Kepler* shows intensity variations of ~5.7days, corresponding to an oscillation frequency of ~2 μHz. They concluded that the star has a mass of $1.16\pm0.07\,\mathrm{M}_\odot$. Interferometric radii are also available (Richichi & Roccatagliata 2005), thus providing an opportunity to test seismic scaling relations for luminous RGBs, which are suspected to depart significantly from well-established seismic scaling relations (Yu et al. 2020). More technical details are provided in Section 3. More than three decades of RV measurements (Hatzes et al. 2015) have revealed the presence a quasi-periodic modulation with a period of ~700 days, which is not reflected in the variation of the strength of the emission lines in the cores of the Ca II H & K lines, which are a classic activity indicator in cool stars. The authors suggested that this signal could originate from a planetary companion of 6 Jupiter masses, but also urged caution as the signal is not stable over decades as expected for a planet, and over-stable convection could serve as an alternative explanation. As is discussed further in Section 4, this candidate planet has been debated heavily in the literature.

2 Variations in the intensity *vs.* velocity field

When an oscillation mode reaches the near surface layers, it is reflected back to deeper, denser layers. Such modes at the surface lead to periodic distortions of the surface temperature and velocity field, described typically by the degree ℓ of the spherical harmonics (see Aerts et al. 2010, and references therein). The surface temperature variations lead to fractional variations of the stellar luminosity. Spectroscopy measures the surface field component along the line of sight. Oscillation modes therefore manifest themselves observationally as variations in the mean brightness and the systemic radial velocity of the star, respectively. At the point of reflection an oscillation mode exhibits its maximum brightness, as it is then least obscured by overlying layers. Coincidentally, the perturbation of the velocity field is changing its direction of propagation. The velocity field for a given mode therefore shows no perturbation and is equal to the systemic radial velocity of the star. As illustrated in Fig. 1, that leads to a phase shift of –90 deg in the ideal case.

The two parameters describing the differences between the velocity and intensity variations in Fourier space are (i) amplitude ratio and (ii) the phase difference. The quantities provide two important diagnostic constraints. The information contained in these parameters allows us to test stellar oscillation and atmospheric models beyond the possibilities of classic asteroseismology. Nevertheless, owing to the lack of appropriate simultaneous data, such studies have only been carried out for two solar-like oscillators.

As demonstrated by Houdek & Gough (2002) and Houdek (2010), a calibrated amplitude ratio between intensity and velocity variations provides strong constraints on the stellar atmosphere that are independent of the excitation model. While the RV amplitude is determined by the velocity fluctuations from oscillations and granulation along the line of sight, and therefore enables a direct comparison with models, the case of photometric variations remains challenging Kjeldsen & Bedding (2011). The intensity variations correspond primarily to the temperature fluctuations of the atmosphere over the whole oscillation cycle, but need to be

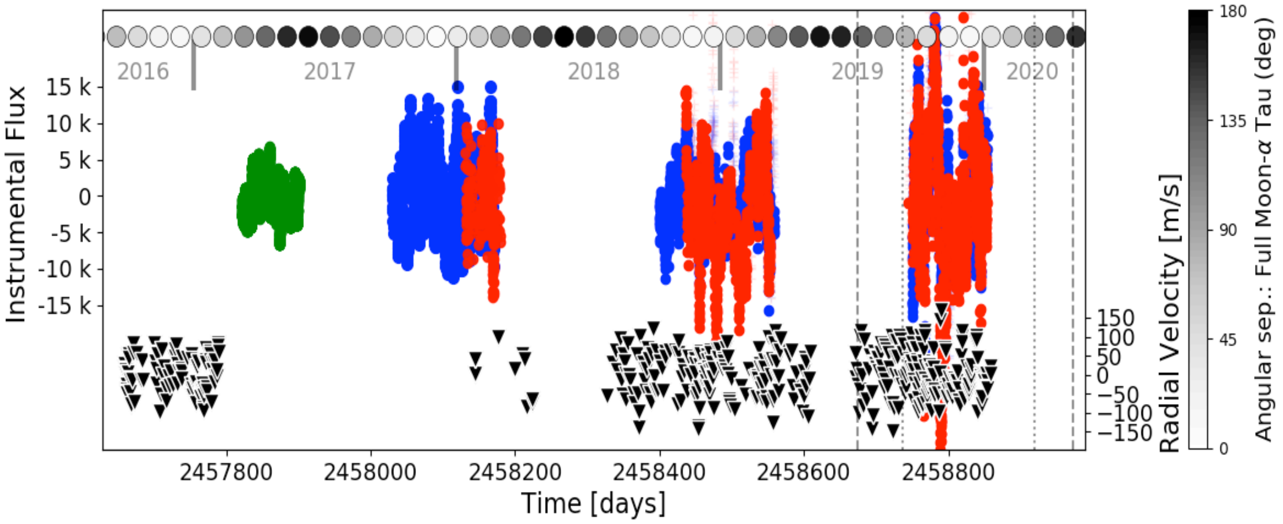

Fig. 2. Data from the ongoing observing campaign on Aldebaran. The red and blue points depict the mean orbital values of the photometric flux measured by *BRITE*/Lem (blue filter) and *BRITE*/Toronto (red filter), respectively. The 80 days of *K2* photometry (Farr et al. 2018) are shown in green. Radial velocities measured with SONG are depicted as black triangles; the long-period trend has been removed. The duration of the ongoing *SONG* and *BRITE* observations in the 2019/20 season are indicated by dashed and dotted lines, respectively. Years are noted at the top, and are juxtaposed with measures of the angular distance between the star and the Moon at the moment of full moon (indicated in the grey scale on the right). Owing to stray-light contamination, data points taken with the Moon closer than 35 degrees are shown as semi-transparent plusses.

translated into fractional changes of the bolometric luminosity. However, to compare observations and models, observational aspects such as the photometric passband and the colour-dependent quantum efficiency of the detector of the space telescope need to be taken into account. In that respect, simultaneous multi-colour photometry provides different measures of the same quantity and increases the robustness of the experiment.

The phase shift between oscillation modes seen in these two observables is a relevant parameter for constraining pulsation eigenfunctions and eventually models of stochastic excitation (Houdek 2010). Were the oscillations purely adiabatic, the RVs would be expected to lead the intensity variations with a phase shift of −90 deg when normalised by the oscillation period. The solar case has been found to be close to this value (Jiménez et al. 1999). Any departure from it reveals heat transfer between the stellar background and the oscillation modes (Christensen-Dalsgaard & Frandsen 1984; Jiménez et al. 1999), with a maximal lag of −180 deg in the isothermal case.

3 Experimental data: 2016–2020

The multi-technique campaign described in this contribution (see Fig. 2) was started in the visibility season 2017/18 of Aldebaran, with observations from *BRITE*/Lem, which is equipped with a blue photometric filter (λ 4000–4500 AA). At the end of the same observing season, Aldebaran was added to the observing programme of *BRITE*/Toronto, which is equipped with a red filter (λ 5000–7000 AA). Each data point shown in Fig. 2 represents the mean of all the individual measurements obtained during a satellite orbit; we discard orbits with less than 15 individual measurements. The orbital period of the *BRITE* satellites is about 90 minutes, resulting in 14–15 photometric measurements per day.

Towards the end of that season we also attempted simultaneous spectroscopic observations with *SONG*. The standard observing programme was comprised of 1 or 2 pointings a night, taking three consecutive spectra with a resolving power of 90,000 and an iodine cell for simultaneous wavelength calibration. However, unfortunately we experienced adverse weather conditions that were extreme in both intensity and duration for Tenerife.

Since observing season 2018/19, all three instruments have become well coordinated. A typical observing season with *BRITE* lasts for about 140 days (September–March), while *SONG* can obtain at least one set of spectra per night for about 300 consecutive days; That time series is only interrupted between May and July, though periodic gaps are introduced into the dataset by the Moon. Given the low ecliptic latitude of Aldebaran of about 5 deg, photometric observations are contaminated by, and eventually interrupted by, the full moon once every ∼28 days. Scattered light from the Moon is not an issue for spectroscopic observations.

The complete dataset of the ongoing campaign is depicted in Fig. 2. It also shows the complementary dataset of 80 days of *K2* photometry, obtained by Farr et al. (2018) using the photometric technique of Halo-photometry to counteract the effects of partial saturation White et al. (2017). In 2016 and prior to *K2* photometry, Farr et al. (2018) obtained 125 days of RV with *SONG*, which is also included in our analysis.

4 The controversy over the planet orbiting Aldebaran

The possibility of the presence of a planetary companion around Aldebaran was originally proposed by Hatzes et al. (2015), who interpreted the long-period trend present in the RV signal as a possible indication of a massive Jupiter-like planetary companion. However, they were cautious about declaring it firmly as a planet, as the RV signal was not as stable as would be expected from an exoplanet. They also considered an alternative possibility that the signal originated from overstable convection, which can occur under extreme non-adiabatic conditions in a stellar atmosphere (Saio et al. 2015).

Three years later (and parallel to the start of our campaign), numerous studies on Aldebaran or the nature of the long-period variations were published. First, Hatzes et al. (2018) showed that the RV in the luminous red giant γ Draconis initially exhibited a similar behaviour. However, the RV signals disappeared in 2013–16 and then reappeared with a phase-shift, so were not compatible with a planetary origin. The authors concluded that the finding also supported a non-planetary explanation for the long-period signal in Aldebaran. Farr et al. (2018), who presented a first seismic analysis based on *K2* photometry and *SONG* RVs, used their results to improve the parameters of the planetary companion. In addition, they argued that both Aldebaran b and γ Draconis b must be planets, stating that: *"it would be a cruel conspiracy of nature if red giants support a type of oscillation that is common and closely resembles a planetary signal. We believe this cannot be the case"*, (Farr et al. 2018, incipit of paragraph 3, Appendix D). Reichert et al. (2019) then presented an analysis of the stability of the dataset of Hatzes et al. (2015), complemented with their own spectroscopic observations from Lick Observatory. They tested a two-planet model, which reduced significantly the large RV scatter in the residuals, but found that such solution was very unlikely to be stable dynamically.

5 Current status of the analysis, conclusions & Outlook

The ongoing photometric and spectroscopic observations obtained by the *BRITE* satellites and the *SONG* telescope are building a unique, multi-year data set for studying amplitude and phase differences between velocity and intensity variations. Combining the RV from *SONG* with multi-colour space photometry from *BRITE* offers a rare possibility to characterise the outermost layers of luminous red giants and to provide crucial diagnostics to test the physics of the stellar atmosphere. Those parameters give access to layers in the star that are not well probed by normal oscillation modes. Luminous red giants like Aldebaran are of added interest in that they enable us to study the asteroseismic scaling relations and the stellar structure of objects with increasing departure from the adiabatic conditions in the atmosphere (Yu et al. 2020; Kallinger et al. 2018).

As is visible in Fig. 2, the observing project is still ongoing and the data we have shown for analysis are only preliminary. That affectsthe photometric amplitudes in particular We therefore refrain from quantifying the parameters discussed above.

The comparison of photometric and spectroscopic datasets shows clearly that the variation in RV is leading the variation in intensity. Visual inspection in the time domain suggests a phase difference which is much larger than the −90 degrees predicted in the adiabatic case. This is not surprising, but one needs to be cautious because the interference from granulation, which has amplitudes and periods comparabe to the oscillation signal of Aldebaran, could lead to an overestimated phase difference. The final value will therefore be determined from the frequency domain. However, the frequency resolution of a full season of *BRITE* observations is not sufficient to resolve individual oscillation modes.

The long-period modulations previously reported in the literature are also present in the *SONG* dataset. However, it is too early to arrive at concrete conclusions about their origin. The long time-base and the high sampling rate of the RV measurements will help us decide if those variations are caused by a planetary companion or by an unidentified physical process. We note that they are on different times-scales than were found for secondary clump stars of the Hyades and which were likely to originate from rotational modulation (Beck et al. 2015; Arentoft et al. 2019).

Constraining the origin of the signal is essential for disentangling actual planets around red giants from spurious detections due to intrinsic effects and activity. The observations reported clearly demonstrate that a firm detection of planets around red giants requires RV monitoring that extends over at least several decades.

Understanding benchmark stars like Aldebaran, γ Draconis or Arcturus is of high importance, since luminous red giants can also be seen at greater distances in the Milky Way (e.g. Mathur et al. 2016). Such stars can therefore serve as highly-needed probes for understanding extreme phases of stellar evolution, the distribution of exoplanets, and (eventually) the evolutionary history of our Galaxy.

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