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WET stars and planets: telescope network observations of mCP stars and exoplanets

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Abstract. The Whole Earth Telescope (WET) and similar global telescope networks are discussed. In particular this work focuses on the recent contribution of such networks to the study of magnetic A-type stars with particular attention given to pulsating variable stars. In addition, telescopes that are part of such networks have the ability to provide similar observations for the study of multi-planetary systems.

Key words: asteroseismology – stars: chemically peculiar – planets and satellites: general

1. Introduction

The Whole Earth Telescope (WET) is an international collaboration between 45 observatories which aims to to provide near-continuous photometric observations of variable stars. The broad longitudinal coverage of the network, a shown in Fig. 1, allows a star to be monitored by one site in the east, then picked up by a more westerly observatory as it starts to set at the first location. This system, in principle, allows for uninterrupted observations leading to a 100 % duty cycle which would otherwise be unobtainable from the ground.

The WET was founded in the 1980s with the primary goal of observing pulsating white dwarf stars. Although multi-site campaigns had successfully observed variable stars before the foundation of the WET, the WET is unique as it works as a single instrument. During observations at each site, information is continuously fed-back to headquarters (HQ) at Mt. Cuba Observatory and the University of Delaware (see `http://www.physics.udel.edu/gp/darc/2015new/index.html` for details) so that if an observatory site monitoring the primary star is clouded over, a second over-lapping site can switch from a secondary target to the primary to obtain continuous coverage.

At the end of each night, the data are sent back to HQ for uniform reduction and analysis with the in-house data reduction packages MAESTRO and WQED (with details available on the WET web pages). Standard data reduction steps are applied, as well as correction for primary extinction. The final light curves consist of differential photometry, with time stamps in BJD.

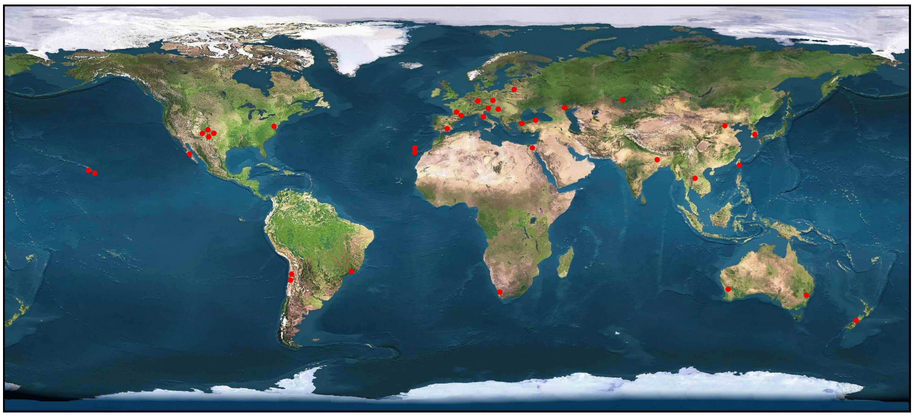

Figure 1. The locations of the observatories, marked by red circles, that have agreed to contribute to Whole Earth Telescope observations.

For a more detailed discussion of the WET, I refer the reader to Sullivan (2001) and Provencal et al. (2014).

2. Observations of magnetic chemically peculiar stars

The magnetic chemically peculiar (mCP) stars span the spectral types of late B to early F. They are characterised by slow rotation, strong global magnetic fields and over-abundances of elements such as Sr, Eu, Cr and rare earth elements whose abundances can be up to one million times that of the Sun (Ryabchikova et al., 2004). The magnetic field in these stars confines the chemical abundances in spots, typically around the magnetic poles, which leads to a light curve modulated with the rotation period of the star. This modulation is evident as the magnetic axis is misaligned with the rotational axis resulting in oblique rotation (Stibbs, 1950).

The rotation periods of the mCP stars have a broad range, from less than a day to, potentially, hundreds of years (Mathys, 2017). The cause for these short rotation periods, when compared to their non-magnetic counterparts, is thought to be magnetic breaking (Abt & Morrell, 1995; Stępień, 2000).

In the late 1970s, Kurtz (1978) observed rapid oscillations in the very peculiar Przybylski's star (HD 101065). With further exploration of other mCP stars, he was able to define the class of rapidly oscilllating Ap (roAp) stars (Kurtz, 1982). The pulsations in these stars are thought to be driven by the κ-mechanism acting in the H I ionisation zone causing the excitation of high-overtone, low degree, pressure (p-) modes (Balmforth et al., 2001; Saio, 2005). However, it is also possible that turbulent pressure in the atmospheres of these stars can also excite pulsations (Cunha et al., 2013), which helps to explain the observed frequencies which cannot be driven by the κ-mechanism. The pulsation periods of the roAp range from $5-24$ min, with peak-to-peak amplitudes up to 34 mmag in B-band observations (Smalley et al., 2015; Joshi et al., 2016; Holdsworth et al., 2018a). It is thought that the magnetic field suppresses low-frequency pulsations in Ap stars (Saio, 2005), although recent K2 observations analysed by Bowman et al. (2018) suggest that this might not be the case.

The pulsation axis in the roAp stars is closely aligned with the magnetic one which leads to a modulation of the pulsation amplitude as the star rotates. This is evident in Fig. 2. This modulation in the amplitude causes a frequency multiplet in the amplitude spectrum of the light curve, and holds information on the geometry of the mode. For a non-distorted mode, a modulated dipole pulsation (i.e. $\ell = 1$) results in a frequency triplet, and a quadrupole ($\ell = 2$) mode shows a quintuplet in the amplitude spectrum.

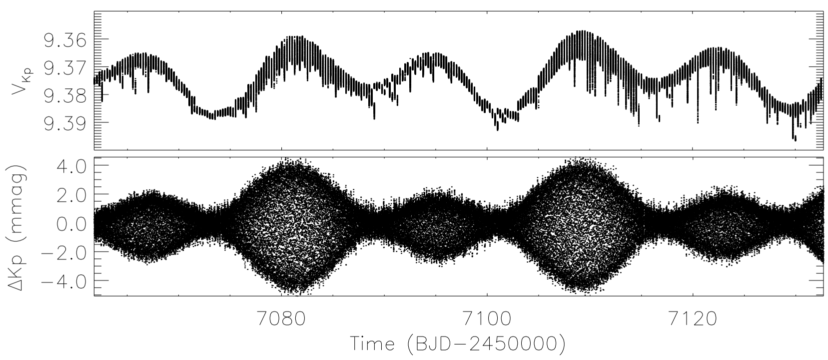

Figure 2. K2 observations of the roAp star HD 24355. The top panel shows the light curve. Evident is the rotational modulation due to surface spots (with a period of about 28 d) and also the $\sim$ 6 h drift in the spacecraft pointing. The lower panel shows the light curve with the low-frequency signals removed. The modulation seen is that of the pulsation envelope which coincides with the spot modulation. Figure from Holdsworth et al. (2016).

If the amplitude of the pulsation goes to zero over the rotation cycle, the line of sight to the star coincides with a pulsation node. When this occurs, we expect a phase change of the pulsation by π-rad as we are now observing the opposite pulsation pole. This is, again, the expected case for a non-distorted mode. Fig. 3 shows examples of the non-distorted case (lower three panels) along side that of a distorted quadrupole pulsation (top panel; HD 24355).

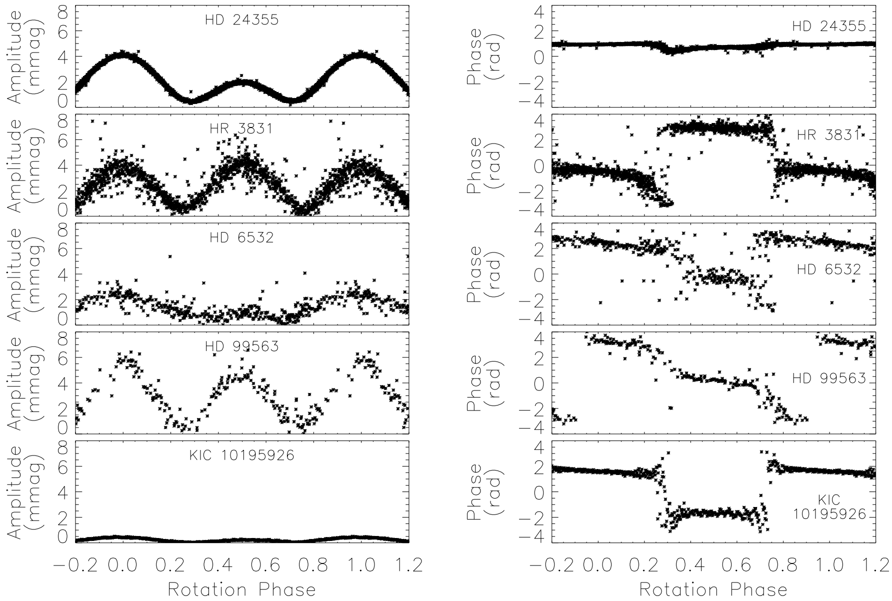

Figure 3. A comparison of non-distorted pulsations in roAp stars (bottom 4 panels), and the distorted mode in HD 24355. The amplidue modulation is as expected, but the lack of a π-rad phase change allows us to conclude that the mode in HD 24355 is distorted. Figure from Holdsworth et al. (2016).

2.1. WET observations of roAp stars

Although the Whole Earth Telescope was primarily designed for the observations of pulsating white dwarf stars (e.g. Kepler et al., 1995; Sullivan et al., 2008; Provencal et al., 2012), it is well suited for the study of pulsations in Ap stars. The need for continuos observations to reduce (or ideally remove) the effects of aliases in an amplitude spectrum is key to identifying real frequencies which are not perturbed by cross talk with the spectral window. The roAp stars can have a rich spectrum of closely spaced modes (cf. HR 1217; Kurtz et al., 2005) representing the large and small frequency separation, thus allowing for a full asteroseismic model of the star.

The most extensively studied (from the ground) roAp star is HD 1217. This star was the first roAp star targeted with the WET in 2000 after observation in 1986 showed this to be a promising star to perform asteroseismology on. The campaign lasted a total of 35 d, achieved a duty cycle of 36 % and provided the most precise ground-based measurements of the amplitudes in roAp stars, reaching a precision of 14 μmag (see Fig. 4 Kurtz et al., 2005). With such precise data, predictions by Cunha (2001) of a missing mode in the 1986 data were proven to be true, allowing for a complete asteroseismic model of the star to be computed.

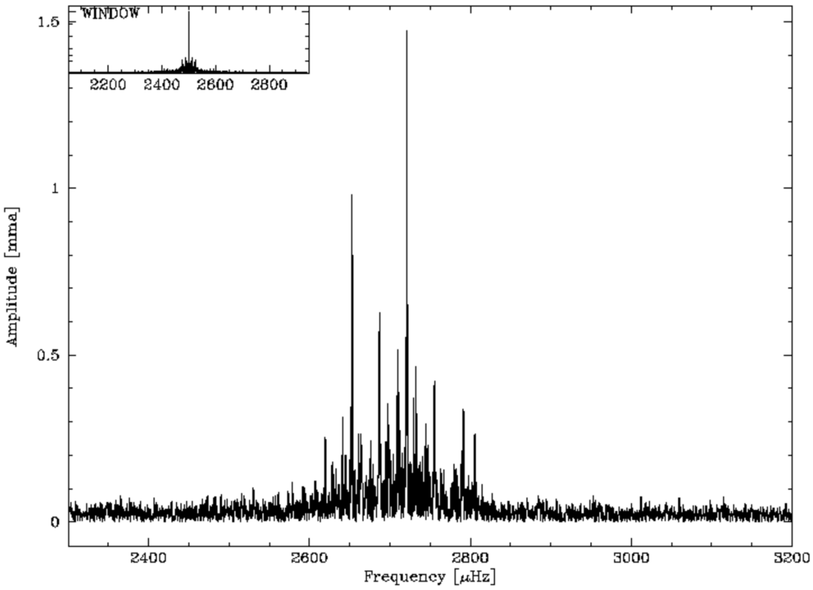

Figure 4. The amplitude spectrum of WET data for HR 1217. The high duty cycle (for ground-based observations) led to a suppression of aliases, and the data length provided high frequency precision. Most of the structure seen in the frequency range $2600 - 2800\,\mu$mag is real. The amplitude unit, milli-modulation amplitude, converts to milli-magnitude as 1 mma=1.086 mmag. Figure from the WET team.

More recently, the WET targeted the largest amplitude roAp star known: J1940 (Holdsworth et al., 2014, 2018a). Although only achieving a duty cycle of 21 %, the multi-site observations revealed that J1940 pulsates in a very distorted quadrupole mode. Through modelling the pulsational phase variations (after the method of Saio 2005), which are sensitive to mass and the polar magnetic field strength, it was shown that the pulsation frequency is much higher than the theoretical cut-off frequency i.e. the pulsation frequency cannot be recreated with the κ-mechanism alone.

Other multi-site campaigns of roAp stars have also unveiled stars which show a suppression of the pulsation phase. Holdsworth et al. (2018b) collected data from three observatory sites (Siding Springs, Australia; Sutherland, South Africa; Cerro Tololo Inter-American Observatory, Chile) to study J1640, while Holdsworth et al. (2018c) utilised the Las Cumbres Observatory's 0.4-m telescopes to observe J0855. Both projects aimed to obtain continuous observations in the same way as the WET, but through independent means. These multi-site campaigns, coupled with results from the *Kepler* Space Telescope, have identified many roAp stars that pulsate with frequencies greater than their respective acoustic cut-off frequencies (Fig. 5). All of these stars show suppressed phase variations, with the modes being strongly distorted by the star's magnetic field.

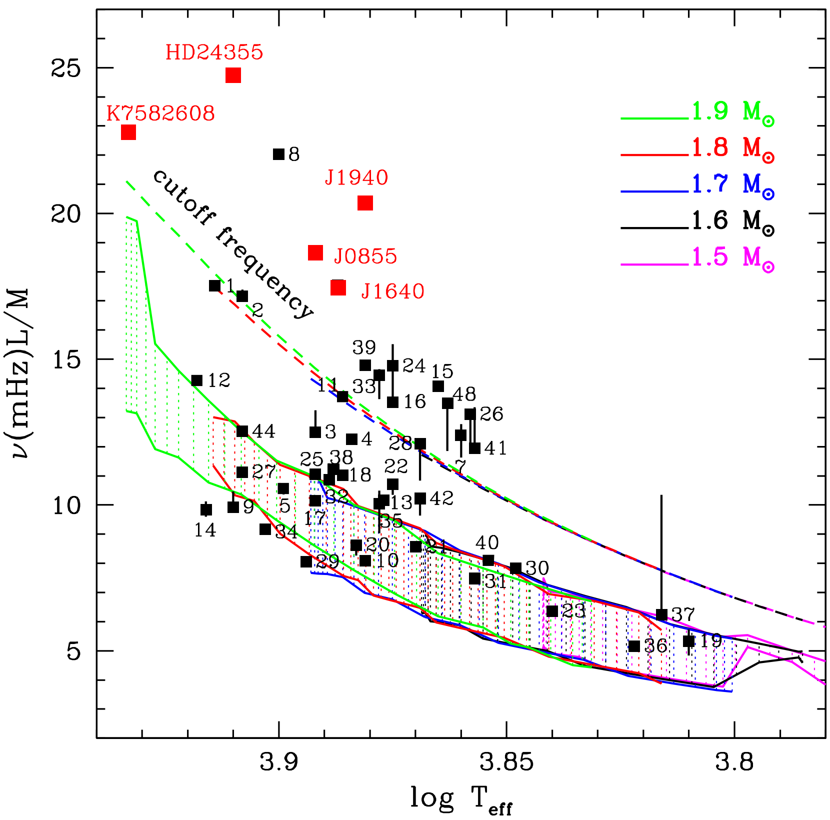

Figure 5. The $\log T_{\rm eff} - \nu L/M$ plane showing the positions of the roAp stars. The squares represent the principal pulsation frequency, with vertical bars showing the range of frequencies for multi-periodic stars. The hatched region represents where high-order p modes are excited by the κ-mechanism in the H-ionization zone in non–magnetic models. Acoustic cutoff frequencies are represented by the dashed lines. The stars shown in red are those which show suppressed phase variations. The numerical labels correspond to the stars in table A1 of Holdsworth et al. (2018b). Figure from Holdsworth et al. (2018c), after Saio (2014).

3. Observations of exoplanets

It is not just asteroseismology that benefits from continuous observations; the study of transiting exoplanets can make good use of uninterrupted data sets. A prime example of this is the TRAPPIST-1 planetary system (Gillon et al., 2017). The presence of three transiting planets were well established not long after discovery of the system, however the precise period of the (then) outer most planet was not known. A total of 10 telescopes were used to try and confirm the parameters of the system through near-continuous observations. However, it was not until the *Spitzer* space telescope observed the system, with complementary data from the ground, that the full extent of the planetary system was known. Uninterrupted data provides the opportunity to probe the full period range of planets without diurnal gaps.

A further point that should be mentioned is the power of multi-site spectroscopy. Although this is by far not a new concept, the Las Cumbres Observatory is installing 6 identical high-resolution spectrographs at a selection of their sites. With the use of identical instruments and telescopes, instrumental profiles become less of an issue so that the data require less processing to be analysed together. Since spectroscopy is also more sensitive to smaller planets (from the ground at least), continuous spectroscopic observations have the potential to provide many planetary systems with many terrestrial planets.

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