The power of heartbeats through the lens of ι Orionis

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O star asteroseismology is a relatively new field which has not been able to gain significant traction due in large part to the lack of known pulsators in addition to the relatively sparse number of frequencies detected in those pulsators. This is likely due to a combination of factors, chief among them long frequencies, on the order of days, and weak amplitudes ($\approx$ 1 mmag and below). Fortunately, through the discovery of the most massive heartbeat system ι Orionis and it's corresponding tidally induced oscillations with BRITE-Constellation there exists a new avenue with which to explore O star asteroseismology. In this paper we will give a prescription for using tidally induced oscillations to do asteroseismic analysis on O stars and present a list of candidate systems for this analysis within the BRITE sample.

1 Introduction

While stars are seen as relatively stable objects for the majority of their life, most have or at some point will exhibit oscillations. The study of such oscillations, known as asteroseismology, is a key to understanding the interior structure of these stars. In fact, determining the bulk pulsational properties for a given star can tell us it's mass, radius and even age (Christensen-Dalsgaard, 1993) to high precision. However, due to the small amplitudes associated with these pulsation modes along with the inherent aliasing of observing from the Earth, this field was limited mainly to stars with fast solar-like oscillations. This changed with the launching of spaced based missions such as MOST, CoRoT, and Kepler, where continuous long baseline photometry was available for the first time.

This allowed the field of asteroseismology to grow exponentially as it allowed for much higher precision on much longer frequencies. Now instead of tens of known pulsators of virtually any given type, there are now access to hundreds or even thousands of objects. This led to great strides in ensemble asteroseismology, using large numbers of modes to determine fundamental parameters. From there it was possible to learn more about stellar evolution by applying this analysis to red giant stars (Stello et al., 2013; Hekker et al., 2009). It was even used to look inside these stars, clearly distinguishing the envelope from the pre-WD core (Beck et al., 2012). Recently, this has been extended to the δ Scuti pulsators where for the first time ensemble asteroseismology is possible (García Hernández et al., 2013). Even, in the area of compact pulsators, where the total number of systems is still quite low, there has been a large leap forward in our understanding.

Our knowledge of massive stars, however, has not increased nearly as much. While there has been some progress on slowly pulsating B stars and β Cephei stars, the number of objects is still relatively small. What's more, O star asteroseismology has been virtually non-existent. Since 1998, where the number of confirmed photometric O star pulsators was effectively zero (Henrichs, 1999), the numbers have increased to a total of seven photometric pulsators (Buysschaert et al., 2015; Pablo et al., 2015). Even adding in the spectroscopic pulsators (e.g. de Jong et al., 1999) the number is still ≈ 10. The reason for this is two-fold. First, the number of O stars observed from space is small, around two dozen with MOST, six with CoRoT, and zero in the initial Kepler mission, though this is increasing with K2. Second, O stars seem to pulsate at low amplitude and periods on the order of days which require longer time-baselines to be able to identify more than a handful of modes.

Currently, there are two options for furthering our knowledge of O star asteroseismology: K2, and BRITE. K2 has sufficient precision but can only observe objects for a maximum of 75 days (Howell et al., 2014). While this will certainly increase the number of known O star pulsators, experience from MOST, which has similar observational time constraints, has shown that even in the best case mode identification will be difficult, and having enough modes for ensemble asteroseismology is unlikely (Howarth et al., 2014). The other possibility is BRITE-Constellation which can look at fields for up six months with excellent precision for its size (Weiss et al., 2014), but will never reach the precision of K2's 1-m telescope. This means, that while the baseline may be sufficiently long, the precision likely will not be sufficient modes. In theory, this means that the traditional methods of asteroseismology are closed to us at the present time. Fortunately, a new path has been opened to us recently with the discovery of a unique class of objects, known as heartbeat stars (Thompson et al., 2012).

These so called heartbeat stars are in reality highly eccentric binaries with relatively stable flux values except for at periastron, where the components are close enough that tidal distortion, otherwise known as ellipsoidal variation is present. For such stars, the shape of this phenomenon is strongly dependent on the inclination, which means that is is possible to determine fundamental parameters for such a system even in the absence of eclipses. This is especially useful for massive stars, where close binaries are highly likely to interact and give a skewed evolutionary picture. What is more important though, is that the proximity of these stars serves to induce tidal oscillations in their companions. This makes these objects ideal for the study of O star seismology because not only will they show several modes, but also because they have a built in check of theoretical asteroseismic models through binarity. In this paper, we will use results from the newly discovered and currently only O-star heartbeat ι Ori (Pablo et al., 2017, hereafter P17) to discuss the merits of heartbeats stars as probes of asteroseismology. We will also show that this should extend to all binaries which show tidally induced oscillations and we identify several candidate systems which either have or will be observed by BRITE.

2 Oscillation phasing

Tidal oscillations are g-mode oscillations which are induced either at harmonics of the orbital period (Willems, 2003), or by enforced frequency spacings at the objects orbital period (Hambleton et al., 2013). What makes them unique relative to normal oscillations modes, though, is that they are extremely stable in both frequency and phase. This means that when phased on the orbital period, these oscillations will persist and in many cases stand out stronger above the noise as show in P17. Additionally, they also tend to be stable in amplitude, with significant amplitude changes occurring only rarely (O'Leary & Burkart, 2014; Guo et al., 2017), and even when it does occur it is on the order of years. This is extremely important, because it means that by phasing on the orbital period, we can confirm the existence and properties of significantly more modes than would otherwise be possible.

While P17 did this only within one continuous observation, this same technique should also be applicable to all the data regardless of gaps. Using the same method as in P17 we phase fold all the observations taken in the blue filter across both the OrionI and Orion II fields. The results are shown in the top plot of Figure 1. Immediately, apparent are all the frequencies found in P17 plus two additional frequencies at the 19th and 22nd orbital harmonics. However, while this technique is useful in determining whether or not frequencies are indeed significant, it is somewhat limited because the frequency resolution is exactly the orbital frequency $f_{\rm orb}$, making it difficult to identify modes if they are too close together (see top panel of Fig. 1).

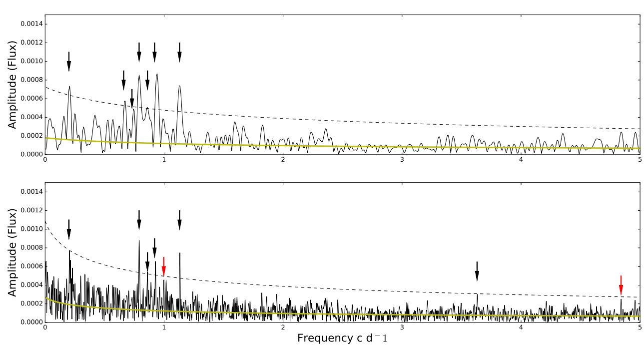

Fig. 1: Fourier transform of the phase-folded data (top) and gap subtracted data (bottom) of blue filtered data from Orion I and Orion II observations. Black arrows mark significant frequencies. The yellow line is the noise floor, where the dashed line represents the 3.6 sigma significance threshold. Red arrows mark orbital harmonics which are possible frequencies just below the significance.

However, there is another technique which can be used. The largest limitation with the BRITE data that exists now is that there will be a gap of at least six months in between consecutive observations of the same field. Normally, such gaps would make combining the datasets in the time domain impossible. In our case though, since the phase and frequency are stable we have the option of simply cutting out the gap. To do this we convert the observations into orbital phase and subtract an integer number of orbits from the second observation, creating a nearly continuous dataset. The results are shown in the bottom panel of Fig. 1. Again we find the five main frequencies, and one additional frequency at 3.63 d^{-1} (106th orbital harmonic) the highest harmonic we have currently been able to identify. While we were unable to determine any other frequencies our analysis does point to three additional frequencies just below the significance threshold (identified with red errors in the bottom panel of Fig. 1). With the addition of a third Orion run, and a 4th currently in progress (October, 2016), we should be able to increase the number of known peaks substantially.

3 Binary constraints

While tidally induced oscillations are a window into O star asteroseismology, the constraints which they put on stellar models is only as good as the precision to which the fundamental parameters of the pulsating star are known. Fortunately, any system in which the stars get close enough for oscillations to be induced is likely to exhibit strong photometric effects of the binary as well. Whether through eclipses or the heartbeat signal, it should be possible to derive masses and radii with the addition of one extra piece of data: radial velocities. While this is obvious for eclipsing systems, P17 has shown that it is possible to determine these parameters using the heartbeat signal to within a few percent.

Just the results in this one system have already shown some discrepancies between models and fundamental parameters, specifically through the existence of a tidally excited mode whose amplitude and frequency are anomalous given the stars fundamental parameters. While this is explained through the existence of Rossby modes in P17, these are currently not calculated in most theoretical models, though this system has shown that their inclusion is indeed necessary.

4 BRITE sample

At the present time, ι Ori is unique. It is the most massive heartbeat, the only O star in a heartbeat system, and the only O star which shows tidally induced pulsations. However, there is no reason it should be so anomalous. Due to the prevalence of O star binaries and their short lifetimes, there should be many candidate systems for tidally induced pulsations.

System	Period (d)	Eccentricity	No. of observations
14 Cep	3.070508	0.031	0
AO Cas	3.52	0.0	0
δ Cir	3.902463	0.06	0
UW CMa	4.39	0.0	1
δ Ori	5.732436	0.112	3(+1; MOST)
ι Ori	29.17336	0.764	3
HD 199579	48.5216	0.065	0
σ Ori	143.198	0.778	3
τ CMa	154.900	0.312	1

Table 1: BRITE O star binaries

When looking at the literature there are a total of nine O star binaries which have or can be observed by BRITE. While we have mainly discussed heartbeat systems so far as they often show tidally induced oscillations, we are not limited to such systems. Close eclipsing binaries also have the potential of having tidally induced modes (Hambleton et al., 2013). What's more one our candidates, δ Ori, has already shown signs of tidally induced pulsations using MOST data (Pablo et al., 2015). While the number of systems is still small, finding just one system increases the number of known O star pulsators by 10%. What's more these systems represent virtually every luminosity class meaning that each system that we can categorize gives us more precise constraints on evolutionary models. Furthermore, while our focus thus far has been on O stars, extending this number to early B stars increases the number of candidate systems greatly. There is even a second known B star heartbeat in the BRITE observations, ϵ Lupi (Pablo et al. (2016), in prep).

5 Conclusions and future work

In this work we have given a prescription for using heartbeat systems and, more broadly, systems with tidally induced oscillations to enhance and broaden the field of O star astronomy. Due to the stability of these modes we have shown using ι Ori as a test case that it is possible to use multiple observations, regardless of gaps, to increase the number of significant modes. This gives us for the first time, the possibility of doing asteroseismic modeling for O stars with legitimate constraints.

We have also shown, that while ι Ori is the only O star with tidally induced pulsations confirmed currently, there are several candidate systems which have or will be observed by BRITE. There are also two additional systems, not including ι Ori, for which we already have multiple observations. In the future, we will look specifically for tidally induced oscillations in each of these systems, applying asteroseismic modeling in all cases. Once the methods are more developed we can also extend this to early B stars. In this way we hope to place strong constraints on massive star evolution.

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References

Beck, P. G., et al., *Fast core rotation in red-giant stars as revealed by gravity-dominated mixed modes*, Nature **481**, 55 (2012), 1112.2825

Buysschaert, B., et al., *Kepler's first view of O-star variability: K2 data of five O stars in Campaign 0 as a proof of concept for O-star asteroseismology*, MNRAS **453**, 89 (2015), 1507.03091

Christensen-Dalsgaard, J., *On the Asteroseismic HR Diagram*, in T. M. Brown (ed.) GONG 1992. Seismic Investigation of the Sun and Stars, *Astronomical Society of the Pacific Conference Series*, volume 42, 347 (1993)

de Jong, J. A., et al., *Non-radial pulsations in the O stars XI Persei and lambda Cephei*, A&A **345**, 172 (1999)

García Hernández, A., et al., *An in-depth study of HD 174966 with CoRoT photometry and HARPS spectroscopy. Large separation as a new observable for δ Scuti stars*, A&A **559**, A63 (2013), 1307.2739

Guo, Z., Gies, D. R., Fuller, J., *Tidally Induced Pulsations in Kepler Eclipsing Binary KIC 3230227*, ApJ **834**, 59 (2017), 1609.06376

Hambleton, K. M., et al., *KIC 4544587: an eccentric, short-period binary system with δ Sct pulsations and tidally excited modes*, MNRAS **434**, 925 (2013), 1306.1819

Hekker, S., et al., *Characteristics of solar-like oscillations in red giants observed in the CoRoT exoplanet field*, A&A **506**, 465 (2009), 0906.5002

Henrichs, H. F., *Pulsations in O Stars*, in B. Wolf, O. Stahl, A. W. Fullerton (eds.) IAU Colloq. 169: Variable and Non-spherical Stellar Winds in Luminous Hot Stars, *Lecture Notes in Physics, Berlin Springer Verlag*, volume 523, 305 (1999)

Howarth, I. D., et al., *Amplitude variability in satellite photometry of the non-radially pulsating O9.5 V star ζ Oph*, MNRAS **440**, 1674 (2014), 1402.6551

Howell, S. B., et al., *The K2 Mission: Characterization and Early Results*, PASP **126**, 398 (2014), 1402.5163

O'Leary, R. M., Burkart, J., *It takes a village to raise a tide: non-linear multiple-mode coupling and mode identification in KOI-54*, MNRAS **440**, 3036 (2014), 1308.0016

Pablo, H., et al., *A Coordinated X-Ray and Optical Campaign of the Nearest Massive Eclipsing Binary, δ Orionis Aa. III. Analysis of Optical Photometric (MOST) and Spectroscopic (Ground-based) Variations*, ApJ **809**, 134 (2015), 1504.08002

Pablo, H., et al., *The most massive heartbeat: an in-depth analysis of ι Orionis*, MNRAS **467**, 2494 (2017), 1703.02086

Stello, D., et al., *Asteroseismic Classification of Stellar Populations among 13,000 Red Giants Observed by Kepler*, ApJ **765**, L41 (2013), 1302.0858

Thompson, S. E., et al., *A Class of Eccentric Binaries with Dynamic Tidal Distortions Discovered with Kepler*, ApJ **753**, 86 (2012), 1203.6115

Weiss, W. W., et al., *BRITE-Constellation: Nanosatellites for Precision Photometry of Bright Stars*, PASP **126**, 573 (2014), 1406.3778

Willems, B., *Excitation of oscillation modes by tides in close binaries: constraints on stellar and orbital parameters*, MNRAS **346**, 968 (2003), astro-ph/0309031