Observational Constraints, Stellar Models, and Kepler Data for θ Cyg, the Brightest Star Observable by Kepler

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Abstract. The $V = 4.48$ F4 main-sequence star θ Cyg is the brightest star observable in the Kepler spacecraft field of view. Short-cadence (58.8 s) photometric data were obtained by Kepler during 2010 June–September. Preliminary analysis shows solar-like oscillations in the frequency range $1200 – 2500\mu$Hz. To interpret these data and to motivate further observations, we use observational constraints from the literature to construct stellar evolution and pulsation models for this star. We compare the observed large frequency separation of the solar-like oscillations with the model predictions, and discuss the prospects for γ Doradus-like g-mode pulsations, given the observational constraints. We discuss the value of angular diameter measurements from optical interferometry for constraining stellar properties and the implications for asteroseismology.
1. Introduction

The main mission of the NASA Kepler spacecraft, launched 2009 March 7, is to search for Earth-sized planets around Sun-like stars using high precision CCD photometry to detect planetary transits (Borucki et al. 2010). As a secondary mission objective, Kepler is surveying and monitoring over 10 000 stars for asteroseismology, i.e., using the intrinsic brightness variations caused by pulsations to infer the star’s mass, age, and interior structure (Gilliland et al. 2010).

The V = 4.48 F4V star θ Cyg (13 Cyg, HR 7469, HD 185395, KIC 11918630, where KIC = Kepler Input Catalogue) is the brightest star that falls on active pixels in the Kepler field of view. Because θ Cyg is nearby and bright, excellent ground-based data can be combined with extremely high signal-to-noise long time series Kepler photometry to provide constraints for asteroseismology. The position of θ Cyg in the HR Diagram is among known γ Dor pulsators, suggesting the possibility that it may exhibit high-order gravity mode pulsations, which would probe the stellar interior just outside its convective core. θ Cyg is also cool enough to exhibit solar-like p-mode acoustic oscillations, which would probe both the interior and envelope. θ Cyg’s projected rotational velocity \( v \sin i \) is 7 km s\(^{-1}\) (Erspamer & North 2003). If the inclination angle of the rotation axis is not too large, θ Cyg’s slow rotation should simplify mode identification and pulsation modeling, as spherical approximations and low-order perturbation theory for the rotational splitting should be adequate.

θ Cyg has been the object of recent adaptive optics observations (Desort et al. 2009). It has a resolved binary M-dwarf companion of \( \sim 0.35 \, M_\odot \) with separation 46 AU. Following the orbit for nearly an orbital period (unfortunately, 100 – 200 y) will eventually give an accurate dynamical mass for θ Cyg. Also, the system shows a 150-d quasiperiod in radial velocity, suggesting that possibly one or more planets could accompany the stars.

The revised Hipparcos parallax of 54.54 ± 0.15 milliarcseconds (van Leeuwen 2007) gives a distance of 18.33 ± 0.05 pc, which, combined with an estimate of its apparent bolometric luminosity (van Belle et al. 2008), gives \( \log L = 0.63 \pm 0.03 \, L_\odot \). Other parameters derived from multi-color photometry and high-resolution spectroscopy are \( T_{\text{eff}} = 6745 \pm 150 \, K, \log g = 4.2 \pm 0.2 \) (cgs), and \( [\text{M/H}] = -0.04 \) (Erspamer & North 2003; Gray et al. 2003). Nordström et al. (2004) give a mass 1.38 ± 0.05 M\(_\odot\), and age 1.5 ±0.6/−0.7 Gyr using Strömgren photometry plus the Padova stellar model grid.

θ Cyg has also been the object of optical interferometry observations. van Belle et al. (2008) used the Palomar Testbed Interferometer to identify 350 stars, including θ Cyg, that are suitably pointlike to be used for as calibrators for optical long-baseline interferometric observations. They then used spectral energy distribution (SED) fitting (not the interferometry measurements) based on 91 photometric observations of θ Cyg to estimate its angular diameter to be 0.760 ± 0.021 milliarcseconds. Combining this estimate with the revised Hipparcos parallax, the interferometric radius is 1.50 ± 0.04 R\(_\odot\). If one uses only the literature \( L \) and \( T_{\text{eff}} \) and their associated error estimates, the derived radius is 1.53 ± 0.13 R\(_\odot\).

Optical interferometry has the potential to constrain the radius of θ Cyg better than spectroscopy and photometry alone. At this conference we learned of unpublished interferometric measurements by T. Boyajian using the CHARA array. Boyajian mea-

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\(^1\)See [http://kepler.nasa.gov](http://kepler.nasa.gov) for more information about the Kepler mission.
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Table 1. θ Cyg Models and Observational Constraints

| Property    | Observation | Model 1 | Model 2 |
|-------------|-------------|---------|---------|
| Mass (M_☉)  | 1.38 ± 0.05 | 1.38    | 1.29    |
| [M/H]       | –0.04       |         |         |
| Z^a         | 0.017       | 0.013   |         |
| T_eff (K)   | 6745 ± 150  | 6744    | 6834    |
| log L (L_☉) | 0.63 ± 0.03 | 0.666   | 0.603   |
| Radius (R_☉)| 1.50 ± 0.04 | 1.58    | 1.43    |
| log g       | 4.2 ± 0.2   | 4.18    | 4.24    |
| Core X^b    | 0.351       | 0.386   |         |
| Age (Gyr)   | 1.61        | 1.63    |         |
| T_CZ^c base (K) | 494 800 | 456 600 |         |

^a Z is mass fraction of elements heavier than H and He

^b X is hydrogen mass fraction

^c CZ = convection zone

2. Kepler θ Cyg Observations

θ Cyg was observed 2010 June–September (Kepler Quarter 6). It is the brightest star on active silicon in the Kepler field of view, and is 7 magnitudes brighter than the saturation limit. Kepler stars are observed using one of a set of masks that define the pixels to be stored for that star. For V < 8, these masks grow prohibitively large. Special apertures can be defined to better conform to the distribution of charge for extremely saturated bright stars. For θ Cyg the number of recorded pixels was reduced from >10 000 to ~1 300 by using a special aperture. Both short-cadence (58.8 s) and long-cadence (29.4 min) data were obtained. Fig. 1 shows the 90-d unprocessed light curve^2 θ Cyg was not well-captured by the dedicated mask for ~50% of the quarter (a problem that is now resolved), so 42 d of the best-quality data were used in the pulsation analysis (Fig. 2). These data were processed to remove outliers and a small remaining trend before Fourier analysis. The frequency power spectrum (Fig. 3) shows a rich spectrum of overtones of solar-like oscillations, with detectable modes in the range from approximately 1200 to 2500 µHz. The appearance of the oscillation spectrum is very similar to that of two other well-studied F stars: Procyon A (Bedding et al.

^2 The data are available at [http://keplergo.arc.nasa.gov/ArchivePublicDataThetaCygni.shtml](http://keplergo.arc.nasa.gov/ArchivePublicDataThetaCygni.shtml) (see also Haas et al. 2011).
Figure 1. *Kepler* θCyg light curve for Quarter 6. The custom aperture captured the target completely only during 42 days (approximately days 39 to 81) used in this analysis.

It is clear from the *Kepler* data that θCyg is a solar-like oscillator. However, the granulation noise and background are too high at low frequencies with the short data set to tell whether there are also modes with low frequencies around 11 µHz (or 1 d⁻¹) characteristic of γ Dor g-mode pulsators (see Grigahcène et al. 2010 and references therein). It is hoped that further observations of θCyg will reduce the noise level to reveal longer-period γ Dor pulsations, as it would be advantageous to find a star that shows both γ Dor and solar-like oscillations to help constrain the properties of the stellar interior and test the physics of stellar evolution and pulsation models.

### 3. θCyg models

To determine whether γDor-like g modes could be present in a star such as θCyg, we calculated stellar models that match the $L$ and $T_{\text{eff}}$ inferred from the ground-based observations. We calculated the evolutionary tracks of two models, one with mass $1.38 M_\odot$ and $Z = 0.017$, close to the present photospheric $Z$ of the Sun (that has de-
Figure 2. Processed 42-d portion of θ Cyg light curve used for pulsation analysis

Figure 3. Fourier analysis of data showing power excess above background between 1200 and 2500 µHz (bottom) and many solar-like oscillation peaks (top)
increased from its initial value due to diffusive settling during the Sun’s lifetime\textsuperscript{3} using the Grevesse & Noels (1993) solar mixture, and a model with mass $1.29 \, M_\odot$ and $Z = 0.013$, close to the Asplund et al. (2005) solar abundance determination. We used the OPAL (Iglesias & Rogers 1996) opacities, initial helium mass fraction $Y = 0.28$, and mixing length/pressure scale height ratio 1.9. We did not include diffusive settling or convective overshoot. Fig. 4 shows an HR diagram of the evolution tracks and a box bounding the $L - T_{\text{eff}}$ observational constraints from the literature. Table 1 summarizes the observational constraints and the properties of two models marked along the evolution tracks that lie at the top and bottom of the luminosity bounds, which we chose to analyse for pulsations. The radius of the $1.38 \, M_\odot$ model at the top of the box is a little too high, and the radius of the $1.29 \, M_\odot$ model at the bottom of the box is a little too low, but we chose these models to bracket the extremes in convection zone depth, which is an important property for $\gamma$ Dor pulsation driving (see discussion below), given the luminosity constraint.

The $1.38 \, M_\odot$ higher-metallicity model has a deeper convective envelope, with temperature at the base of the envelope convection zone near 500 000 K, whereas the $1.29 \, M_\odot$ model with lower metallicity has a convective envelope base temperature of $\sim$450 000 K. For $\gamma$ Dor stars, the convective envelope base temperature that optimizes the growth rates and number of unstable g modes is predicted to be about 300 000 K (see Guzik et al. 2000 and Warner et al. 2003). Therefore, the majority of $\gamma$ Dor g-mode

\textsuperscript{3}Z is the mass fraction of elements heavier than hydrogen and helium
pulsators are expected to have somewhat larger mass ($\sim 1.6 \, M_\odot$) for solar metallicity and therefore shallower convective envelopes than $\theta$ Cyg. For models with convective envelopes that are too deep, the radiative damping below the convective envelope quenches the pulsation driving; for models with convective envelopes that are too shallow, the convective time scale becomes shorter than the g-mode pulsation periods, and convection can adapt during the pulsation cycle to transport radiation, making the convective blocking mechanism ineffective for driving the pulsations.

### 3.1. Expectations for $\gamma$ Dor g-mode Oscillations

We analysed the models for pulsations using the Pesnell (1990) non-adiabatic pulsation code, which also was used by Guzik et al. (2000) and Warner et al. (2003) to explain the pulsation driving mechanism for $\gamma$ Dor pulsations and to predict the instability strip location. The results are summarized in Table 2. For the 1.38-$M_\odot$ model with the deeper convective envelope, only one $l = 1$ high-order g mode is predicted to be pulsationally unstable. For the 1.29-$M_\odot$ model with a shallower convective envelope, several $l = 1$ and $l = 2$ modes with periods in the range 0.33 $-$ 1 d are predicted to be unstable. Therefore, if lower metallicities, appropriate for the Asplund et al. (2005) solar abundances, are adopted, $\theta$ Cyg has potential to show $\gamma$ Dor g-mode pulsations, as well as the already-observed solar-like oscillations. This star would then become the first known hybrid $\gamma$ Dor/solar-like oscillator. Longer time series observations will be required to improve the signal-to-noise ratio and separate the g modes from the granulation signal at low frequency to detect the potential g modes. On the other hand, if this star does not show g modes, such observations would support the higher metallicity more appropriate for the older solar abundances, also favored by helioseismology (see, e.g., Basu & Antia 2008; Guzik & Mussack 2010), and/or help to constrain the location of the red edge of the $\gamma$ Dor instability strip. Therefore, continued observations of $\theta$ Cyg could shed light both on $\gamma$ Dor g-mode instability, and on the solar abundance problem.

| Table 2. g-mode Predictions for $\theta$ Cyg Models |
|---------------------------------------------------|
| g-mode Properties | 1.38-$M_\odot$ Model 1 | 1.29-$M_\odot$ Model 2 |
| $l=1$ period spacings (d) | $\sim 0.040$ | $\sim 0.038$ |
| radial orders $n$ | 22 | 18 to 25 |
| growth rates/period$^a$ | 4.5e-09 | $<1.0e-07$ |
| periods (d) | 0.77 | 0.58 to 0.95 |
| $l=2$ period spacings (d) | $\sim 0.027$ | $\sim 0.025$ |
| radial orders $n$ | no unstable modes | 20 to 28 |
| growth rates/period$^a$ | $<1.0e-7$ | |
| periods (d) | 0.37 to 0.55 | |

$^a$Calculated $\gamma$ Dor growth rates can be as high as $1.0e-05$/period
3.2. Large Separations of Solar-like Oscillations

Solar-like oscillations with high radial order exhibit characteristic large frequency separations, $\Delta \nu$, between $l = 1$ and $l = 0$ modes of the same radial order, and small separations, $\delta \nu$, between $l = 2$ and $l = 0$ and between $l = 1$ and $l = 3$ modes of consecutive radial order (e.g., Aerts et al. 2010). An autocorrelation analysis of the frequency separations in the $\theta$ Cyg solar-like oscillations shows a peak at multiples of 42 $\mu$Hz, interpreted to be half the large separation, $\frac{1}{2} \Delta \nu$ (Fig. 5). By comparison, half of the large frequency separation for the Sun is 67.5 $\mu$Hz. Fig. 6 shows a histogram of the number of frequency spacings per one-$\mu$Hz bin for all of the calculated p-mode frequencies between 1200 and 2500 $\mu$Hz for our 1.38- and 1.29-$M_\odot$ models. The 1.38-$M_\odot$ model has a mean $\frac{1}{2} \Delta \nu = 38.9 \pm 1.4 \mu$Hz, while the 1.29-$M_\odot$ model has mean $\frac{1}{2} \Delta \nu = 43.2 \pm 1.2 \mu$Hz; the results for the two models bracket the observed large separation.

4. Follow-up and Advantages of Optical Interferometry

Follow-up Kepler photometry of $\theta$ Cyg, as well as optical interferometry and spectroscopic abundance analyses, will be worthwhile. The first data show solar-like p modes but no evidence (yet) of $\gamma$ Dor gravity modes. Our stellar models show that $\theta$ Cyg is likely on, or very near, the red edge of the $\gamma$ Dor instability strip. An interferometric angular diameter combined with the Hipparcos parallax can narrow the constraints for $\theta$ Cyg to better accuracy than spectroscopic/photometric analyses alone. Improved constraints are essential for g-mode predictions, since a lower radius from interferometry would drive model solutions to lower metallicity for a given luminosity, so that the convective envelope may be shallow enough to allow some unstable g-mode pulsations. Resolving and tracking the 0.35 $M_\odot$ M-dwarf companion for most of its very long orbital period, or finding one or more planets in closer orbits around $\theta$ Cyg would help further to constrain its mass. $\theta$ Cyg Kepler data for p modes and, if found, for g modes...
Figure 6. Separations between calculated p-mode oscillations for 1.38- and 1.29-
$M_\odot$ models, binned into 1-$\mu$Hz intervals. Half the large separation is $\sim 39$-$\mu$Hz for the 
1.38-$M_\odot$ model, and $\sim 44$-$\mu$Hz for the 1.29-$M_\odot$ model, bracketing the observations at 
about 42 $\mu$Hz.

modes, combined with detailed abundance analyses, has high potential to shed light on 
the ongoing solar abundance problem.

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