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Asteroseismic inference on rotation, gyrochronology and planetary system dynamics of 16 Cygni

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ABSTRACT

The solar analogs 16 Cyg A and 16 Cyg B are excellent asteroseismic targets in the *Kepler* field of view and together with a red dwarf and a Jovian planet form an interesting system. The dynamics of this system have been studied previously but currently there is no reliable information on the rotation of the stellar components. Here, we use the technique of asteroseimology to determine the period of rotation and the angle of inclination for 16 Cyg A and B. We use the results on rotational period to demonstrate that asteroseismic analyses can provide constraints on mass-period-age relations. We perform a Bayesian model comparison between two gyrochronology relations that produces a decisive Bayes factor. Furthermore, with the excellent constraints available on mass, age, and rotational period we suggest that 16 Cyg A could be used in addition to the Sun as an anchor when calibrating gyrochronology relations. In addition, the results for the angle of inclination in 16 Cyg B do not contradict a low obliquity between the star and its eccentric planet. Given that the time scale to reach a low obliquity due to tidal interactions is much greater than the age of the system, we discuss the star-planet eccentricity and low obliquity which is consistent with Kozai cycling.

Key words: stars: oscillations, stars: rotation, planet-star interactions

1 INTRODUCTION

16 Cyg is a hierarchical triple star system composed of two Sun-like stars in a wide orbit (16 Cyg A and B) together with a red dwarf orbiting component A (16 Cyg C) and a Jovian planet orbiting component B (16 Cyg Bb). 16 Cyg is a well studied system with an extensive literature (Cochran et al. 1997; Holman, Touma & Tremaine 1997; Hauser & Marcy 1999). Recently, the *Kepler* space telescope has observed 16 Cyg A and B and Metcalfe et al. (2012) have determined accurate fundamental stellar properties using the technique of asteroseismology.

Despite extensive observation the stellar rotation of 16 Cyg A and B is not well constrained. The projected rotation rate ($v \sin i$) cannot be accurately determined from spectroscopic observation. In addition, 16 Cyg A and B are evolved main-sequence stars, with low surface magnetism and a corresponding lack of star spots, complicating measurements of surface rotation. Estimates of rotational periods have been derived from Ca II H&K measurements (Soderblom, Duncan & Johnson 1991) but these values rely on scaling from other stellar parameters and cannot be considered definitive. A set of well determined rotational parameters for 16 Cyg A and B, in combination with existing measurements, would allow us to test gyrochronology (Barnes 2007; Mamajek & Hillenbrand 2008; Meibom, Mathieu & Stassun 2009; Schlaufman 2010) in a region of the HR diagram not normally accessible to classical methods. In addition, such a measurement constrains the star-planet obliquity in the 16 Cyg Bb system.

To study the stellar rotation of 16 Cyg A and B we have examined the *Kepler* asteroseismic data sets for the signatures of stellar rotation. The very high asteroseismic signal-to-noise ratios in both 16 Cyg A and B make this system an excellent candidate to study. Based on the observed rotational splitting, we estimate the rate of stellar rotation and the angle of inclination of the rotation relative to the line of sight. We use this new information on the period of rotation to test two gyrochronology relations. In addition, we use the estimated angle of inclination of 16 Cyg B to determine the projected obliquity and hence discuss possible Kozai cycling of the planet-star system.

2 ADOPTED PROPERTIES OF THE SYSTEM

Table 1 shows the properties of the stellar and planetary components adopted for this work. The asteroseismic results are taken from Metcalfe et al. (2012), their results being a collaborative effort using a number of different stellar evolution codes and detailed asteroseismic modelling approaches. Perrin & Spite (1981a) give $B-V$ values for the A and B components. In the absence of a quoted precision we adopt uncertanties on $B-V$ as ± 0.01 which more than encompasses the spread in results from other observations (Johnson 1953; Argue 1966; Moffett & Barnes 1979). Accuracy or precision greater than this level is not required in this study. The planet 16 Cyg Bb is in an eccentric orbit around the star 16 Cyg B and the inclination of the orbit ($i = 45/135 \pm 1\,^{\circ}$) has been estimated as part of a three-body problem (Plávalová & Solovaya 2013). It is not clear whether 16 Cyg A induces the observed eccentricity in the planetary orbit (Holman, Touma & Tremaine 1997) or not (Hauser & Marcy 1999). And as only a single planet has been detected, if planet-planet scattering is responsible for the orbit of 16 Cyg Bb, then the other planets in the system must have been ejected through scattering events (Nagasawa, Ida & Bessho 2008; Beaugé & Nesvorný 2012).

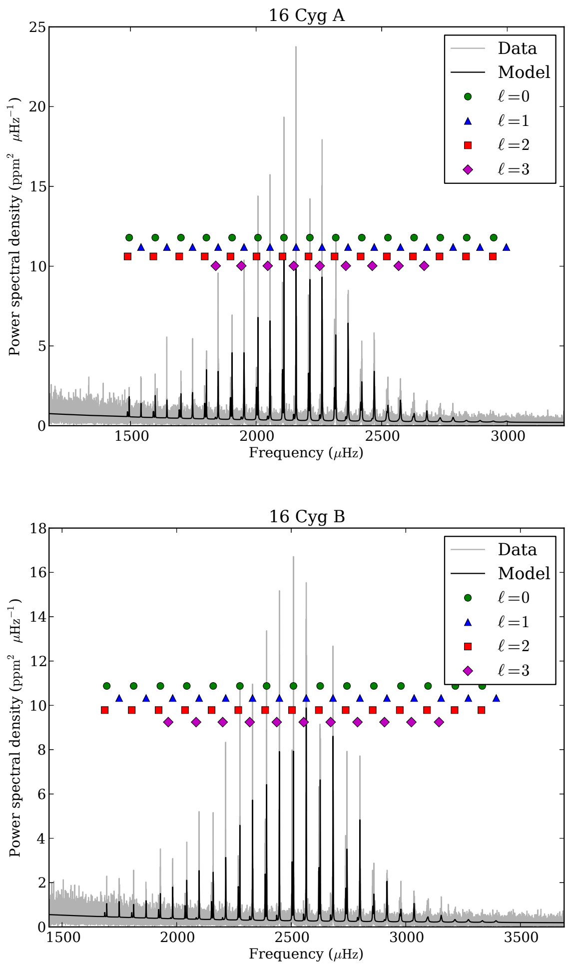

Figure 1. Power spectra in the region of modes of oscillation. Top: 16 Cyg A; Bottom: 16 Cyg B. The data are presented along with a fitted model of the power spectrum and labels for each mode of oscillation considered.

3 DATA PREPARATION

Both 16 Cyg A and B are brighter (V $\sim$ 6) than the saturation limit for which *Kepler* observations were designed. However, it was possible to capture the full stellar flux by using custom photometric aperture masks. Thus, 928 days of short-cadence observations (Gilliland et al. 2010) - from Quarter 7 to 16 - were generated using simple aperture photometry (Jenkins et al. 2010) and then corrected for instrumental perturbations following the methods described by García et al. (2011). The final light curves used for asteroseismic analyses were high-pass filtered using a triangular smooth of 4 days width and have a duty cycle of 90.5 %. The power density spectra were computed using a Lomb-Scargle algorithm.

4 ASTEROSEISMIC DETERMINATION OF ROTATION

Asteroseismic estimation of stellar rotation rests on our ability to detect the signature of rotation in the non-radial modes of the frequency-power spectrum. Excellent constraints can be found for the rotational splitting multiplied by the sine of the angle of inclination, i.e. the projected rotational splitting (Ballot, García & Lambert 2006), and good constraints can be found for the angle of inclination. Here we followed the procedure set out in Chaplin et al. (2013) to estimate the asteroseismic rotation.

The desired rotation estimates are outputs of 'peak bagging' (Appourchaux 2003), which is modelling of the observed power spectrum. We modelled a background with the sum of two Harvey-like components (Harvey 1985). Modes of oscillation are modelled as a sum of Lorentzian profiles that characterise the power limit spectrum of stochastically excited and intrinsically damped modes. Peak bagging was performed using Markov Chain Monte Carlo (MCMC) methods (see Benomar, Appourchaux & Baudin (2009) and Handberg & Campante (2011)).

Figure 1 shows the *Kepler* power spectra for 16 Cyg A and B together with models of the modes of oscillation and background.

Table 1. Adopted properties of the system.

	16 Cyg A	16 Cyg B	16 Cyg Bb
Age (Gyr)	6.8 ± 0.4^{a}	6.8 ± 0.4^{a}	6.8 ± 0.4
Mass	1.11 ± 0.02^{a} M$_{\odot}$	1.07 ± 0.02^{a} M$_{\odot}$	2.38 ± 0.04^{c} M$_{\rm Jup}$
Radius	1.243 ± 0.008^{a} R$_{\odot}$	1.127 ± 0.007^{a} R$_{\odot}$	-
$B-V$	$0.64^{b} \pm 0.01$	$0.66^{b} \pm 0.01$	n/a
Orbital Period	$> 13000^{c}$ yr	$> 13000^{c}$ yr	798.5 ± 1.0^{c} days
Eccentricity	0.54 to 1^{d}	0.54 to 1^{d}	0.689 ± 0.011^{c}
Orbital Inclination (°)	100 to 160^{d}	100 to 160^{d}	$45/135^{c}$

[a] Metcalfe et al. (2012) ; [b] Perrin & Spite (1981b) ; [c] Plávalová & Solovaya (2013) ; [d] Hauser & Marcy (1999).

Table 2. Summary statistics for stellar rotation.

	16 Cyg A	16 Cyg B
Projected splitting (μHz)	0.411 ± 0.013	0.274 ± 0.017
Angle of inclination (°)	56^{+6}_{-5}	36^{+17}_{-7}
Rotational Period (days)	$23.8^{+1.5}_{-1.8}$	$23.2^{+11.5}_{-3.2}$
Asteroseismic $v \sin i$ (km s^{-1})	2.23 ± 0.07	1.35 ± 0.08

5 RESULTS

The results from our analysis of the internal rotation of both stars are given in Figure 2 as the marginalised posterior probability distributions (PPD). We present both the 2D PPD of projected splitting versus angle of inclination and the corresponding 1D PPD's and the rotational period 1D PPD.

The projected splitting is well described by a normal distribution but the angle of inclination is more complicated. For the projected splitting we report the median value together with the standard deviation which defines the 68% credible region. For the angle of inclination we report the mode of the distribution together with the 68% highest posterior density intervals. In tests on simulated data we find the mode to be a better estimate of the simulated inclination than other summary statistics (e.g. mean or median).

Figure 2 also shows the PPD's for rotational period equivalent to the measured rotation. Again, the PPD's are best described by the modes of the distributions together with the 68% highest posterior density credible regions. Table 2 contains the statistical descriptions of the PPD's.

We estimate the asteroseismic $v \sin i$ from the projected splitting and the adopted radius, i.e. $v \sin i = 2\pi R \langle \delta\nu_s \rangle \sin i$. Of course, the rotation we estimate asteroseismically is not surface rotation. However, the sensitivity of $\langle \delta\nu_s \rangle$ in the radial direction, determined from the rotational kernels of an optimal model, places 90% of the weight in the upper 6% (by radius) of the star.

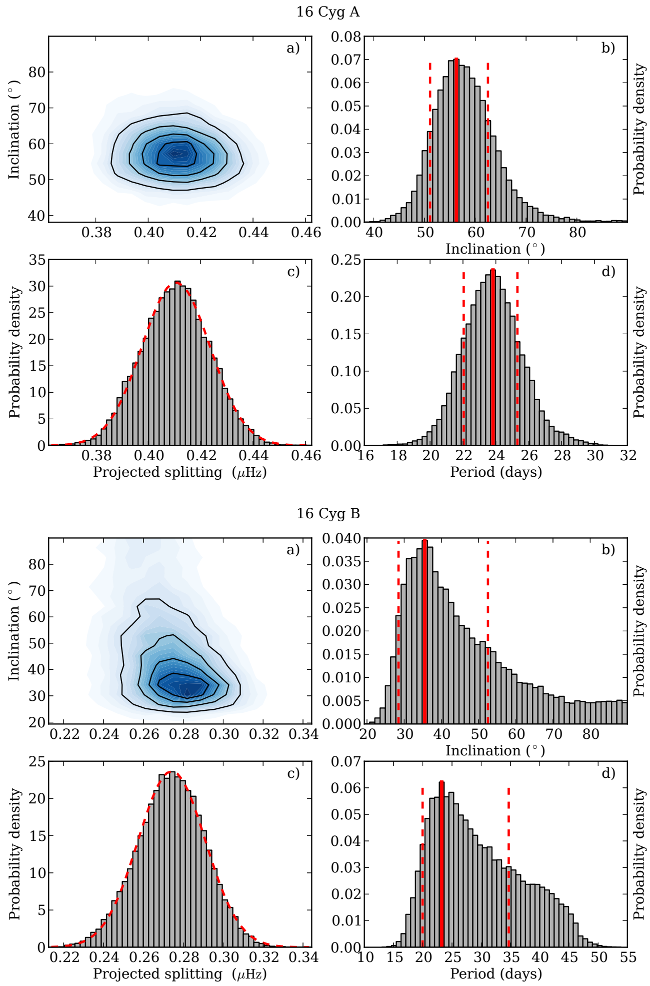

Figure 2. Posterior probability distributions for stellar rotation. Top: 16 Cyg A; Bottom: 16 Cyg B. Each quad plot is composed of: a) inclination vs projected splitting PPD; b) projected inclination PPD; c) projected splitting PPD; and d) period of rotation PPD.

5.1 Surface activity

In order to identify signals present due to surface rotation we have analysed both stars in the same manner as Mathur et al. (2014) and Garcia et al. (2013). There are signals across the periodogram and particularly in the region of 20 to 30 days but we cannot determine if they are genuine stellar signals or if they are due to a "pollution" related to the *Kepler* months. Therefore, we conclude we cannot detect surface rotation of these stars from the current *Kepler* light curves.

We have analysed data on the Ca II H&K line from both stars taken at the Lowell observatory from 5 December 1993 to 9 August 2012 (J. Hall, private communication). Once again, analysis of this data does not produce unambiguous detection of a surface rotation signal. Tantalisingly, the 16 Cyg A H&K data show a prominent but not conclusive peak at a period of 26 days but only when considering data collected after 2008, the date of a marked improvement in the

quality of the H&K data.
Marsden et al. (2013) give chromospheric activity S indices of 0.1556 ± 0.0011 and 0.1537 ± 0.0005 for A and B respectively, representing low-levels of activity. The lack of an unambiguous surface activity signature is consistent with the expected low surface magnetic activity of a late main-sequence star.

6 DISCUSSION

6.1 Asteroseismic Gyrochronology

With the determination of the rotational periods presented here, asteroseismology has provided all three properties required to test mass-age-period relations for 16 Cyg A and B. Here we show that the asteroseismic results give sufficient constraints so as to provide diagnostic potential. We leave the determination of a new gyrochronology relation to future work.
The asteroseismically determined period of rotation is a measure of internal rotation while the classical periods of rotation used to calibrate gyrochronology are a measure of surface rotation. In the case of solid-body rotation these measures are near identical but with the introduction of differential rotation small differences may appear. Both measures average over latitudinal differential rotation with asteroseismic values weighted away from the poles, the same being true for spot modulation and spectroscopic $v \sin i$. Surface methods are obviously insensitive to radial differential rotation while the asteroseismic method for both 16 Cyg stars is most sensitive to the outer 6% by radius. Hence, if radial differential rotation is not strong over this region the measure is comparable to the surface measures. In the region of interest in the Sun we observe modest rates of differential rotation, and for three other solar-like stars Gizon et al. (2013) and Chaplin et al. (2013) find excellent agreement between asteroseismic and surface measures. We conclude that for 16 Cyg A and B it is sensible to equate the two types of rotation for the purpose of gyrochronology.
We selected two gyrochronology models, Barnes (2007) and Schlaufman (2010), that show deviation in the region of parameter space occupied by 16 Cyg A and B. Figure 3 shows the models and asteroseismic data for 16 Cyg A and B and the Sun. These gyrochronology models predict a specific relationship from mass or color, age, and period. We determined which model is preferable based on a comparison of observables to the relation specified by the model, Barnes or Schlaufman, by calculating the Bayes factor. We then assessed the evidence for both models and created the factor as the Schlaufman evidence divided by the Barnes evidence. The resulting Bayes factors (Jeffreys 1961) are: 16 Cyg A ($\gg 1000$) "decisive" in favour of Schlaufman; 16 Cyg B (≈ 2.3) in favour of Schlaufman but "barely worth mentioning".
The asteroseismic value for 16 Cyg A has a clear diagnostic potential and allows for an unambiguous model selection. Given the recent work determining mass and age (Chaplin et al. 2014) and period (McQuillan, Mazeh & Aigrain 2014), in future work 16 Cyg A could provide an additional anchor when calibrating mass-age-period relations. The ambiguity in the 16 Cyg B measurements are a result of the uncertainty in the measurement of the angle of inclination and this propagates through to the uncertainty in the rotational period.

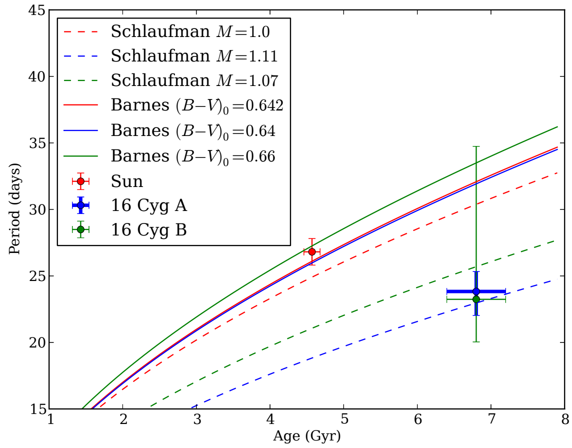

Figure 3. Asteroseismic rotation data points for 16 Cyg and the Sun on a period vs. age plot. Predictions using two common mass-age-period relations (Barnes 2007; Schlaufman 2010) are displayed.

Given the Schlaufmann gyrochronology relation we can define a prior probability distribution for the period of 16 Cyg B in order to better constrain the angle of inclination. We define a uniform prior between the 3 sigma limits of the Schlaufmann relation, that is a uniform prior between 21 and 30 days. Repeating the analysis above with the addition of this prior gives a consistent but much better constrained result. We now have the angle of inclination for 16 Cyg B of 36^{+5}_{-4} degrees.

6.2 Inclinations and orbital properties

Systems such as 16 Cyg constitute a promising laboratory to probe star-planet interactions such as tides. Because of the large separation between 16 Cyg A and 16 Cyg B, i.e. around 750 AU (Plávalová & Solovaya 2013), and the strength of tidal interactions falling with distance cubed, we can consider the tidal effects in the star-planet system 16 Cyg B-Bb as if it is isolated from 16 Cyg A. This reduces the problem to the standard case of a binary system in tidal interaction. We can then apply the method described in detail in Hut (1981) and Mardling (2011) to predict the circularisation time for the orbit and the alignment and synchronisation timescales for 16 Cyg B and Bb.
First, we adopt the asteroseismic mass and radius for 16 Cyg B (Metcalfe et al. 2012, Table 1). Next, following Plávalová & Solovaya (2013), we assume that $M_{\rm p} = 2.38\, M_{\rm J}$, where $M_{\rm p}$ and $M_{\rm J}$ are respectively the mass of 16 Cyg Bb and of Jupiter. This leads us to its approximate radius, that $R_{\rm p} \approx R_{\rm J}$ using the mass-radius relation for giant planets (Chabrier, Leconte & Baraffe 2011). Next, assuming the usual values for tidal dissipation in low-mass stars and giant planets (Barker & Ogilvie 2009), we are able to predict the time scales of circularisation for the orbit, the alignment, and synchronisation times for 16 Cyg B, and 16 Cyg Bb given in Table 3.
These results suggest that the rotation of the planet 16 Cyg

Table 3. Tidal dynamical time scales of the 16 Cyg B-Bb system

	16 Cyg B	16 Cyg Bb
Circularisation time scale (Gyr)	$3.455\,10^7$	$3.455\,10^7$
Alignment time scale (Gyr)	$2.913\,10^5$	7.131
Synchronisation time scale (Gyr)	$1.458\,10^5$	3.566

Bb is synchronised with its orbital motion (tidally locked) while its spin is still evolving to become aligned with the total angular momentum of the system, assuming it had an initial non zero obliquity.

The timescale of star-planet orbit circularisation due to tidal effects is much greater than the age of the system, over 6 orders of magnitude greater, which is consistent with the observed high level of eccentricity.

For the purpose of the tidal effects we considered the B-Bb system as isolated but it is still possible that other dynamical effects can impact the state of the system. It is unclear whether the eccentricity of the star-planet orbit is due to ongoing interactions with 16 Cyg A (Hauser & Marcy 1999; Holman, Touma & Tremaine 1997; Mazeh, Krymolowski & Rosenfeld 1997) or primordial (Albrecht et al. 2012). Our own dynamical orbital calculations suggest that about 5 to 10% of the orbital phase space consistent with the constraints in Table 1 result in dynamical interactions between 16 Cyg B-Bb and 16 Cyg A (Kozai cycling) that produce significant ($e > 0.5$) eccentricity on a timescale of a Gyr.

The stellar orbit of B around A is given as inclined at 100 to 160 degrees (Hauser & Marcy 1999), which is consistent, but does not discriminate, with the other angles measured here. In addition, the angle of inclination for B of 36^{+5}_{-4} degrees and the Bb orbit angle of inclination of 45 ± 1 degrees gives a low projected obliquity when assuming co-rotation. This low projected obliquity corresponds to a true obliquity mode of 16 degrees, with a 68% upper limit of 39 degrees. This obliquity may be simply primordial or may be a result of the orbit's phase in a Kozai cycle due to the gravitational interaction with 16 Cyg A, with other phases having higher obliquity; in either case, the tidal alignment timescale is much larger than the age of the system.

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