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Magnetic OB[A] Stars with *TESS*: probing their Evolutionary and Rotational properties (MOBSTER) – I. First-light observations of known magnetic B and A stars

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ABSTRACT

In this paper we introduce the MOBSTER collaboration and lay out its scientific goals. We present first results based on the analysis of 19 previously known magnetic O, B, and A stars observed in 2-min cadence in sectors 1 and 2 of the Transiting Exoplanet Survey Satellite (*TESS*) mission. We derive precise rotational periods from the newly obtained light curves and compare them to previously published values. We also discuss the overall photometric phenomenology of the known magnetic massive and intermediate-mass stars and propose an observational strategy to augment this population by taking advantage of the high-quality observations produced by *TESS*.

Key words: techniques: photometric – stars: early-type – stars: magnetic field – stars: rotation.

1 INTRODUCTION

Unlike their lower mass counterparts (e.g. Böhm-Vitense 2007), massive and intermediate-mass stars are not known to host magnetic fields generated by contemporaneous dynamos at their surfaces. Instead, there exists a distinct population of magnetic O-, B-, and A-type stars whose fields appear to be of fossil origin (Borra, Landstreet & Mestel 1982; Neiner et al. 2015; Alecian et al. 2017).

Magnetic OBA stars host strong surface fields that typically have large-scale, mostly dipolar topologies that are stable over decades (for a broader review, see e.g. Donati & Landstreet 2009). Despite the fact that this spectral type range covers a large variety of stellar parameters (masses, radii, luminosities), the incidence rate of detectable magnetic fields in these stars seems to be uniformly small, ∼10 per cent, and the field properties show no systematic change with, e.g. mass or luminosity (Wade et al. 2014; Morel et al. 2015; Grunhut et al. 2017; Sikora et al. 2019).

These stars exhibit a range of phenomenologies that can be understood in terms of the interaction between their magnetic

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fields and their photospheres or atmospheres. In particular, since the magnetic field is not generally aligned with the rotational axis, many observable quantities across the electromagnetic spectrum are found to be rotationally modulated, in a manner that is understood in the context of the Oblique Rotator Model (Stibbs 1950).

In earlier-type (OB) magnetic massive stars, the interaction between the magnetic field and the strong, supersonic line-driven stellar winds leads to the formation of an observable *magnetosphere* (ud-Doula & Owocki 2002), the global characteristics of which are determined by the stellar rotation rate, wind parameters and magnetic field strength (Townsend & Owocki 2005; ud-Doula, Owocki & Townsend 2009; Petit et al. 2013). More specifically, *dynamical* magnetospheres (DMs) are formed around slow rotators and consist of outflowing ionized material channeled by the closed magnetic field lines creating strong shocks near the magnetic equator. The shocked gas cools radiatively and falls back on to the stellar surface in complex dynamic flows. Fast rotators additionally form a *centrifugal* magnetosphere (CM): centrifugal support of plasma above the co-rotation radius prevents material from falling back on to the star, leading to the formation of dense clouds, which co-rotate with the stellar surface.

The presence of a magnetosphere around these massive stars is inferred from observations at many different wavelengths. In the optical, periodic variations in Hα are detected (e.g. Howarth et al. 2007; Bohlender & Monin 2011; Grunhut et al. 2012; Rivinius et al. 2013), as well as line profile variations in wind-sensitive resonance lines (primarily in the ultraviolet; e.g. Stahl et al. 1996; Marcolino et al. 2012), variable emission in the X-rays (Sanz-Forcada, Franciosini & Pallavicini 2004; Gagné et al. 2005) and in the infrared (Oksala et al. 2015b), and, in some cases, emission in the radio is also observed (e.g. Chandra et al. 2015; Kurapati et al. 2017; Leto et al. 2018). Some of these observations can be understood using magnetohydrodynamic (MHD) simulations (e.g. Marcolino et al. 2013; ud-Doula et al. 2013; Nazé et al. 2014), as well as through simplified analytic prescriptions such as the 'Analytic Dynamical Magnetosphere' model for DMs (ADM; Owocki et al. 2016) and the 'Rigidly Rotating Magnetosphere' model for CMs (RRM; Townsend & Owocki 2005).

In intermediate-mass stars (late B-type and A-type stars), the effect of magnetism is somewhat different, as they do not possess the same fast, dense winds as higher mass stars. Instead, fossil fields are known to affect diffusive processes in their radiative envelope (Michaud 1970; Alecian & Stift 2007), often leading to chemical abundance patches on their surface and, as a result, rotational modulation of spectral lines of various chemical elements in their spectra (e.g. Kochukhov et al. 2015; Yakunin et al. 2015; Silvester et al. 2017). The energy distributions associated with magnetic intermediate-mass stars are also known to exhibit abnormal flux depressions in the ultraviolet (Kodaira 1969; Adelman 1975; Maitzen 1976b). This is understood to be a direct consequence of the presence of strong surface magnetic fields (Kochukhov, Khan & Shulyak 2005).

The Transiting Exoplanet Survey Satellite (*TESS*; Ricker et al. 2015) is the latest high-precision photometric space mission. During its 2-yr nominal mission time, it will observe 85 per cent of the full sky, in overlapping sectors of 96 × 24 deg, for a total of roughly 470 million point sources observed in full-frame images. The targets will be observed with various temporal baselines, from 27.4 d to almost 1 y, depending on their position on the sky. Designed to search for exoplanets transiting in front of their host star, *TESS* was launched on 2018 April 18 and started delivering public data of the first two observed 27.4-d sectors of the sky in 2018 December. Given their high quality, these data can be used for a wide range of astronomical investigations in addition to exoplanet detections, including detailed asteroseismology and, in our case, studies of rotational modulation associated with stellar magnetism in early-type stars.

Of particular relevance to *TESS*, both massive and intermediate-mass stars with surface magnetic fields are known to exhibit periodic photometric variations associated with rotational modulation. In the case of earlier-type stars (earlier than about B1), these variations are due to a changing column density as the viewing angle through the magnetosphere varies with phase. This phenomenon is observed for instance in the light curve of HD 191612 (Wade et al. 2011). For later-type magnetic stars (later than about B5), photometric variations are associated with chemical inhomogeneities on their surface manifesting as brightness spots due to flux redistribution (e.g. Peterson 1970). In fact, two classes of variable stars, as defined by the General Catalog of Variable Stars (GCVS; Samus' et al. 2017), correspond to chemically peculiar B- and A-type stars understood to host strong magnetic fields, the SX Arietis and α^2 Canum Venaticorum (α^2 CVn) variables, respectively. Finally, for stars with an intermediate spectral type (roughly between B1 and B5), their photometric variability can be caused by either one of the two aforementioned effects, although it is often dominated by photospheric inhomogeneities. Indeed, even when magnetospheric eclipses are seen (as is the case with σ Ori E; Townsend 2008; Townsend et al. 2013), there can still be a signature associated with chemical spots (as shown for that same star; Oksala et al. 2015a). Furthermore, pulsations also contribute to photometric variability in a subset of magnetic OBA stars, notably slowly pulsating B stars (SPB; Waelkens & Rufener 1985), β Cephei variables (e.g. Struve 1952), δ Scuti pulsators (e.g. Fath 1937), and rapidly oscillating Ap (roAp) stars (Kurtz 1982).

Therefore, optical time-series photometry can be a powerful means of characterizing known magnetic OBA stars and identifying promising magnetic candidates. Moreover, in some cases additional phenomena that are associated with photometric signatures, such as binarity and pulsations, can be modelled to provide valuable constraints on the physical parameters of these stars. With the rise of high-precision space-based photometric missions over the last decade (e.g. *MOST*, CoRoT, *Kepler*, K2, BRITE-Constellation) and given the comparatively limited availability and time-sampling of high-resolution spectropolarimetry, we can leverage the observations acquired by these missions to further our understanding of phenomena associated with stellar magnetism in the upper Hertzsprung–Russell Diagram (HRD). This approach has been employed to infer the characteristics of putative magnetic fields in extra-Galactic Of?p stars (Nazé et al. 2015; Munoz et al. 2018), a spectral class known to be associated with magnetism in the Milky Way (Grunhut et al. 2017).

1.1 The MOBSTER collaboration

The MOBSTER collaboration (Magnetic OB[A] Stars with *TESS*: probing their Evolutionary and Rotational properties) aims to leverage *TESS* observations to gain further insight and understanding into the nature of magnetic massive and intermediate-mass stars. In particular, this project focuses on three types of targets:

(i) Known magnetic OBA stars with rotational periods shorter than ∼ 27 d: these targets will be observed for at least one full rotational cycle during the *TESS* mission and their photometric variations can be used to test and calibrate models by comparing them to synthetic light curves;

(ii) Known magnetic OBA stars with rotational periods greater than ∼27 d: these targets will likely be observed for only part of their rotational cycle; therefore shorter-term, potentially stochastic processes (e.g. dynamic flows in a DM) as well as other phenomena (such as pulsations) can be investigated; and

(iii) Magnetic OBA candidates: we can identify magnetic candidates directly from their light curves and flag them for spectropolarimetric follow-up; such an observational strategy has proven highly successful for K2 data (Buysschaert et al. 2018a). Such efforts are led in parallel with similar studies classifying variability types in OBA stars observed by *TESS* (e.g. Balona et al. 2019; Pedersen et al. 2019; Sikora et al., submitted; for a complementary study of Ap stars using *TESS* data, see Cunha et al., submitted).

High-quality light curves from *TESS* will allow us to pursue various science goals, such as the asteroseismic characterization of magnetic massive stars (which can teach us about the internal effects of surface magnetic fields; e.g. Briquet et al. 2012; Buysschaert et al. 2018b) and precise determinations of their rotational periods. In this first paper of a series, we focus on the latter objective as we present newly determined rotational periods for 19 known magnetic B and A[1] stars that were observed in *TESS* sectors 1 and 2[2] and compare them to previously published values. By 'known magnetic stars', we mean stars whose surface magnetic fields have been directly diagnosed using the Zeeman effect, in either spectroscopic or spectropolarimetric observations (and sometimes both). The relevant references for each star's magnetic detection can be found in Section 3.2. Seven more B- and A-type stars that were observed in sectors 1 and 2 (HD 10840, HD 19400, HD 58448, HD 65950, HD 221507, HD 203932, and HD 221760) yielded spurious or marginal detections in spectropolarimetric observations, and were not included in this sample.

In Section 2, we present the observations. In Section 3, we report results for known magnetic B and A stars, and discuss each star individually. Finally, we present our conclusions and consider future work in Section 4.

2 *TESS* OBSERVATIONS

The *TESS* data included and analyzed here are the 2-min light curves provided by the *TESS* Science Team and which are publicly available via the Mikulski Archive for Space Telescopes (MAST).[3] A description of the data processing pipeline of these light curves is provided by Jenkins et al. (2016). Full-frame images with 30-min cadence are not considered within the scope of this paper. Sector 1 was observed from 2018 July 25 to August 22, while sector 2 was observed from 2018 August 23 to September 20.

To select our sample, we cross-matched the list of observed stars in sectors 1 and 2 with the SIMBAD database (Wenger et al. 2000) and considered all the stars with known spectral types of A and earlier. The orbital period of *TESS* is 13.7 d and a gap is present in the data with this period (i.e. in the middle of each 27.4-d light curve). The instrumental magnitudes of each target are found in the *TESS* Input Catalog (TIC; Stassun et al. 2018). These values are included in Table 1.

Among the ∼1150 OBA stars (excluding subdwarfs) available in *TESS* sectors 1 and 2, there are no known magnetic O stars, 4 known magnetic B stars, and 15 known magnetic A stars (including HD 213637). Our detrended 2-min light curves of these known magnetic stars are presented in Fig. 1 (B stars) and Fig. 2 (A stars). These 19 objects are discussed below.

[1]We include in this sample a well-known star exhibiting the classic Ap phenomenology, HD 213637, but which is classified as F1. Given the nature of its peculiarities and the typical uncertainty on the spectral type of chemically peculiar stars, we chose to include it in our sample and consider it for all intents and purposes as an A-type star.

[2]While our sample comprises magnetic targets that were observed in sectors 1 and 2, a few of these stars (namely HD 53921, HD 24188, and HD 54118) were also observed in sector 3, so we included these data in our analysis.

[3]https://archive.stsci.edu/missions-and-data/transiting-exoplanet-survey-satellite-tess

3 RESULTS

3.1 Photometric analysis

First, to measure accurate rotational periods using the *TESS* light curves, we improve the detrending of these light curves by manually removing obvious outliers and by fitting rotational modulation (when appropriate) with a periodic model that takes into account both a fundamental rotational frequency and its significant harmonics, following the approach detailed by Bowman et al. (2018). This allows us to both evaluate the rotational periods precisely and model and subtract the residuals (after having evaluated their scatter) using a locally weighted scatterplot smoothing (LoWeSS; Cleveland 1979; Seabold & Perktold 2010) filter, thus improving the long-term detrending.

Rotational periods are reported in Table 1. The uncertainties are propagated using the following equation (from Bloomfield 1976 and Montgomery & O'Donoghue 1999):

$$\sigma_f = \frac{\sqrt{6}\sigma_r}{\pi\sqrt{N}A\Delta t} \quad (1)$$

where σ_f and σ_r represent, respectively, the uncertainty on the measured frequency and the photometric uncertainty, N is the number of points in the light curve, A is the amplitude of the corresponding peak in the periodogram, and Δt corresponds to the temporal baseline of the time series. To evaluate the photometric uncertainty, we use the scatter of the residuals of the pre-whitened light curve after the multiharmonic rotational model has been removed, as described above. In our results, we quote uncertainties in measured rotational periods as three times the formal uncertainty determined using equation (1), to account for the average difference in noise levels in the high- and low-frequency regimes (i.e. 'pink noise') often found in oversampled time-series data (see Schwarzenberg-Czerny 2003; Degroote et al. 2009; Bowman et al. 2018; Holdsworth et al. 2018)

Finally, we perform a Lomb–Scargle analysis (Lomb 1976; Scargle 1982) of these detrended light curves of our 19 targets by using the `LombScargle` class in the `astropy.stats` PYTHON package. The results are presented in Figs 1 and 2. These figures present the detrended light curves, together with their Lomb–Scargle periodogram in which the rotational frequency (and its first harmonic) have been identified, when applicable. Out of our 19 targets, 13 show a clear peak in their periodogram that we ascribe to rotation. For those targets, we show in Figs 1 and 2 a 'window function' that was obtained by computing a Lomb–Scargle periodogram for a pure sinusoidal signal with a frequency corresponding to the frequency peak with the largest amplitude in the observational periodogram and with the same time sampling as the *TESS* light curve. Some of the light curves that are not considered to show convincing rotational modulation have at least one low-frequency peak (e.g. HD 66318), but those peaks are weak (with amplitudes well below 0.5 mmag) and do not convincingly phase the observations.

Table 1. List of known magnetic B- and A-type stars observed by *TESS* in sectors 1 and 2. For each star, we provide the TIC number, a more common identifier (mostly the HD number), the spectral type, the *TESS* instrumental magnitude, as well as three periods that are measured for the star (and that are long enough to potentially be associated with rotation, although in some cases they may be related to other phenomena such as pulsations): published periods based, respectively, on photometry and on other measurements, and our new refined periods derived from the *TESS* data. For these periods, the number appearing between parentheses corresponds to the uncertainty on the final digit of the reported period; the absence of such a number denotes an unreported uncertainty. Finally, we report the largest measured longitudinal magnetic field for each star (and its uncertainty) and the total number of spectropolarimetric observations referenced in the literature (an asterisk denotes a star for which these measurements are considered to be phase resolved, meaning that the sampling in rotational phase is sufficient to trace the variation over the full rotational cycle, while a question mark indicates a lower limit, provided that some sources did not clearly state the total number of observations).

TIC no.	Name	Sp. type	T (mag)	Pub. period (phot.) (d)	Pub. period (other) (d)	*TESS* period (d)	$\|B_{z,\,max}\|$ (G)	N_s
89545031	HD 223640	B9pSiSrCr[a]	5.32	3.72251(97)[c]	3.735239(24)[f]	3.7349(5)	1390 ± 220[f]	40*
279511712	HD 53921	B9III+B8V[b]	5.80	1.6520[d]	1.6518[g]	1.65183(2)	511 ± 83[n]	5
358467049	CPD-60 944B	B9pSi[a]	8.74	3.7367(3)[e]	-	3.759(2)	463 ± 72[n]	2
372913684	HD 65987	B9pSiSr[a]	7.65	1.45610(15)[c]	∼9[h]	1.4561(1)	738 ± 122[n]	2
32035258	HD 24188	A0pSi[a]	6.42	2.23047(4)[c]	-	2.23024(4)	538 ± 44[n]	1
69855370	HD 213637	F1pEuSr[a]	9.18	-	-	-	856 ± 45[n]	30
139191168	HD 217522	A5pSrEuCr[a]	7.17	-	-	-	1123 ± 82[o]	97
159834975	HD 203006	A2pCrEuSr[a]	4.90	2.12230(9)[c]	2.1219[i]	2.122(4)	650 ± 147[p]	14
235007556	HD 221006	A0pSi[a]	5.82	2.31206(36)[c]	2.31483(40)[j]	2.3119(1)	990 ± 180[l]	3
237336864	HD 218495	A2pEuSr[a]	9.23	4.2006(1)[c]	-	4.183(6)	1169 ± 56[n]	5
262956098	HD 3988	A0pCrEuSr[a]	8.10	-	-	-	-	0
277688819	HD 208217	A0pSrEuCr[a]	7.09	8.3200(84)[c]	8.44475(11)[k]	8.317(1)	1843 ± 214[q]	20?∗
278804454	HD 212385	A3pSrEuCr[a]	6.78	2.5062(2)[c]	-	2.5062(2)	639 ± 40[n]	2
279573219	HD 54118	A0pSi[a]	5.30	3.2724(10)[c]	3.27533(20)[l]	3.2759(2)	1680 ± 120[l]	15∗
280051011	HD 18610	A2pCrEuSr[a]	8.06	-	-	-	-	0
281668790	HD 3980	A7pSrEuCr[a]	5.70	3.9517(1)[c]	3.9516(3)[m]	3.951(3)	1688 ± 29[n]	5
348717688	HD 19918	A5pSrEuCr[a]	9.12	-	-	-	777 ± 109[r]	2?
358467700	HD 65712	A0pSiCr[a]	9.30	1.94639(54)[c]	-	1.9460(2)	1296 ± 71[n]	2
410451752	HD 66318	A0pEuCrSr[a]	9.56	0.77688(52)[c]	-	-	6480 ± 91[n]	2

Notes. References for the spectral types, published periods, and maximum longitudinal fields are the following: (*a*) Renson & Manfroid (2009); (*b*) Corbally (1984); (*c*) Cunha et al. (submitted); (*d*) Dubath et al. (2011); (*e*) Bernhard et al. (2015); (*f*) North, Brown & Landstreet (1992); (*g*) Aerts et al. (1999); (*h*) Abt & Levy (1972); (*i*) Maitzen et al. (1974); (*j*) Leone, Catalano & Manfre (1995); (*k*) Manfroid & Mathys (1997); (*l*) Bohlender, Landstreet & Thompson (1993); (*m*) Maitzen, Weiss & Wood (1980); (*n*) Bagnulo et al. (2015); (*o*) Hubrig et al. (2004a); (*p*) Babcock (1958); (*q*) Mathys (2017); and (*r*) Kochukhov & Bagnulo (2006).

Out of the 13 targets exhibiting signs of rotational modulation, 12 show at least one harmonic of that frequency, the lone exception being CPD-60 944B. The frequencies of the first harmonic peaks are labelled in Figs 1 and 2 to confirm their identification. It should be noted that these frequencies are directly measured from the periodograms and are hence much less precise than the period determinations presented in Table 1; hence, they do indeed correspond, within errors, to twice the fundamental frequency.

The amplitudes of the various signals that we detect are well within the typical range associated with α^2 CVn variables, with HD 65712 showing the greatest amplitude (nearly 60 mmag). We further detail our findings for individual stars in the following subsection. The light curves of the stars for which a low-frequency peak potentially associated with rotation is recovered are phase folded using our measured rotational periods and presented in the Appendix (Fig. A1).

3.2 Notes on individual stars

Most of the following stars have multiple period determinations in the literature, therefore we report the most recent one prior to our own study in Table 1. For a number of our targets, an independent period analysis was carried out using the *TESS* data by Cunha et al. (submitted); we report their periods for comparison purposes whenever possible (only in Table 1 for concision, except in the case of HD 218495 since theirs is the only prior rotational period determination available in the literature).

TIC 89545031 (= HD 223640, B9pSiSrCr, V = 5.18)

A photometric period of 3.73 ± 0.03 d was derived for HD 223640 (Morrison & Wolff 1971), a period that was also confirmed spectroscopically (Mégessier 1974, 1975), with infrared photometry (Catalano, Kroll & Leone 1991; Catalano, Leone & Kroll 1998b), and with variations of He I λ5876 (that was however observed to be out of phase with the other reported variability; Catanzaro, Leone & Catalano 1999). The photometric period has been refined a number of times since (Kodaira 1973; North & Burnet 1991), and more recently to 3.735 239 ± 0.000 024 d using photometry and magnetic measurements (North et al. 1992). Changes in the shape of the light curve over time have been proposed to be indicative of precession of the magnetic axis (Adelman & Knox 1994; Adelman 1997, 1999). This star was also observed with *Hipparcos*, and an automated period search yielded a value of 3.7342 d (Dubath et al. 2011). We measure a period of 3.7349 ± 0.0005 d in the *TESS* data, consistent with the previous determination; however, we cannot evaluate the precession hypothesis given the different bandpasses involved.

HD 223640 was first found to be magnetic by Babcock (1958), although its field was not detected in a more recent FORS1 spectropolarimetric observation (Hubrig et al. 2006; Bagnulo et al. 2015). This is not surprising as the observation was taken at the rotational phase corresponding to a magnetic null in the field curve of North et al. (1992).

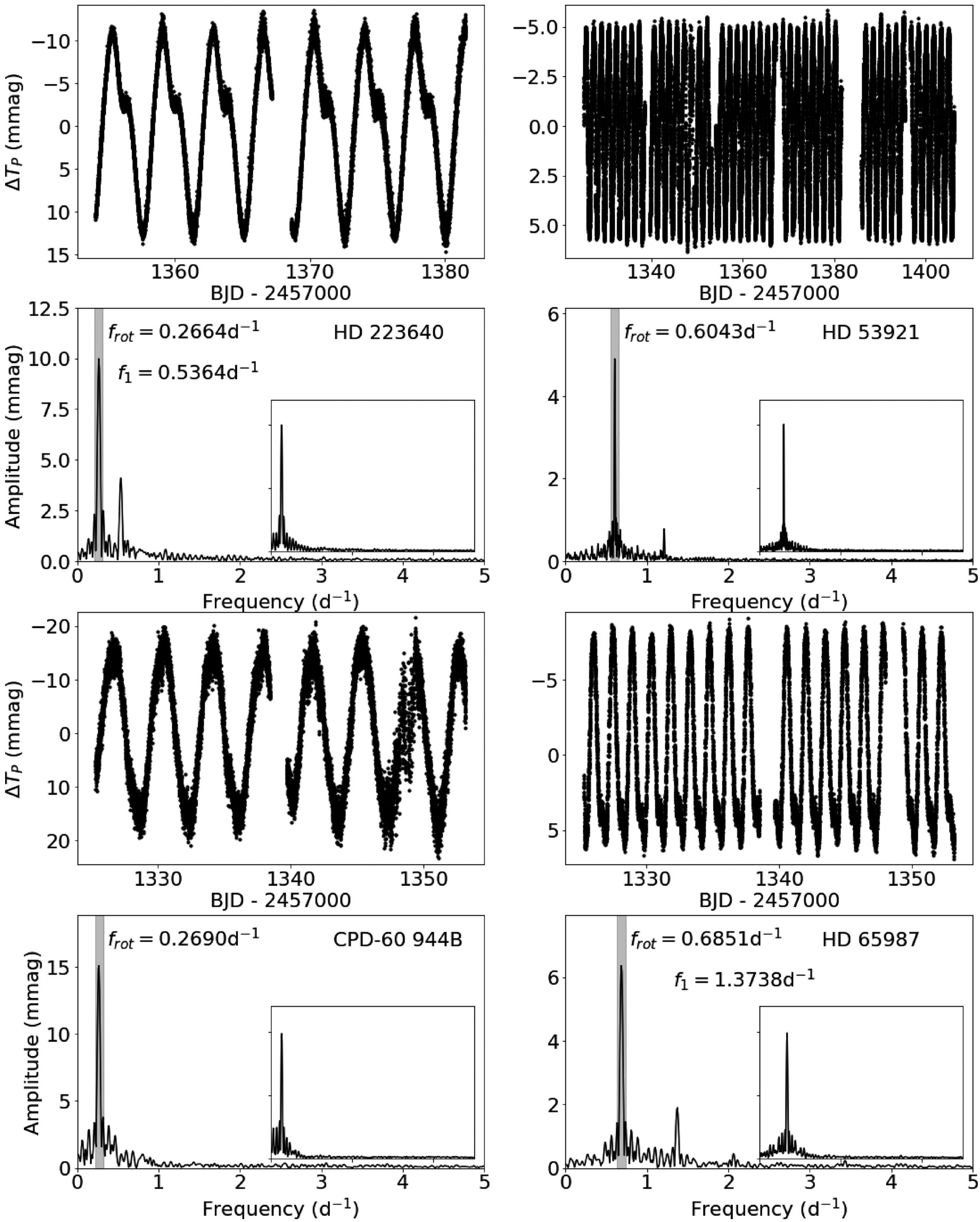

Figure 1. Light curves (top of each panel) and Lomb Scargle periodograms (bottom of each panel) for each of the four known magnetic B stars observed by *TESS* in its sectors 1 and 2. The inferred rotational frequency for each star is highlighted in light grey and labelled, and the first harmonic is also labelled (when applicable). An inset is included to show the window function around the frequency peak with the largest amplitude.

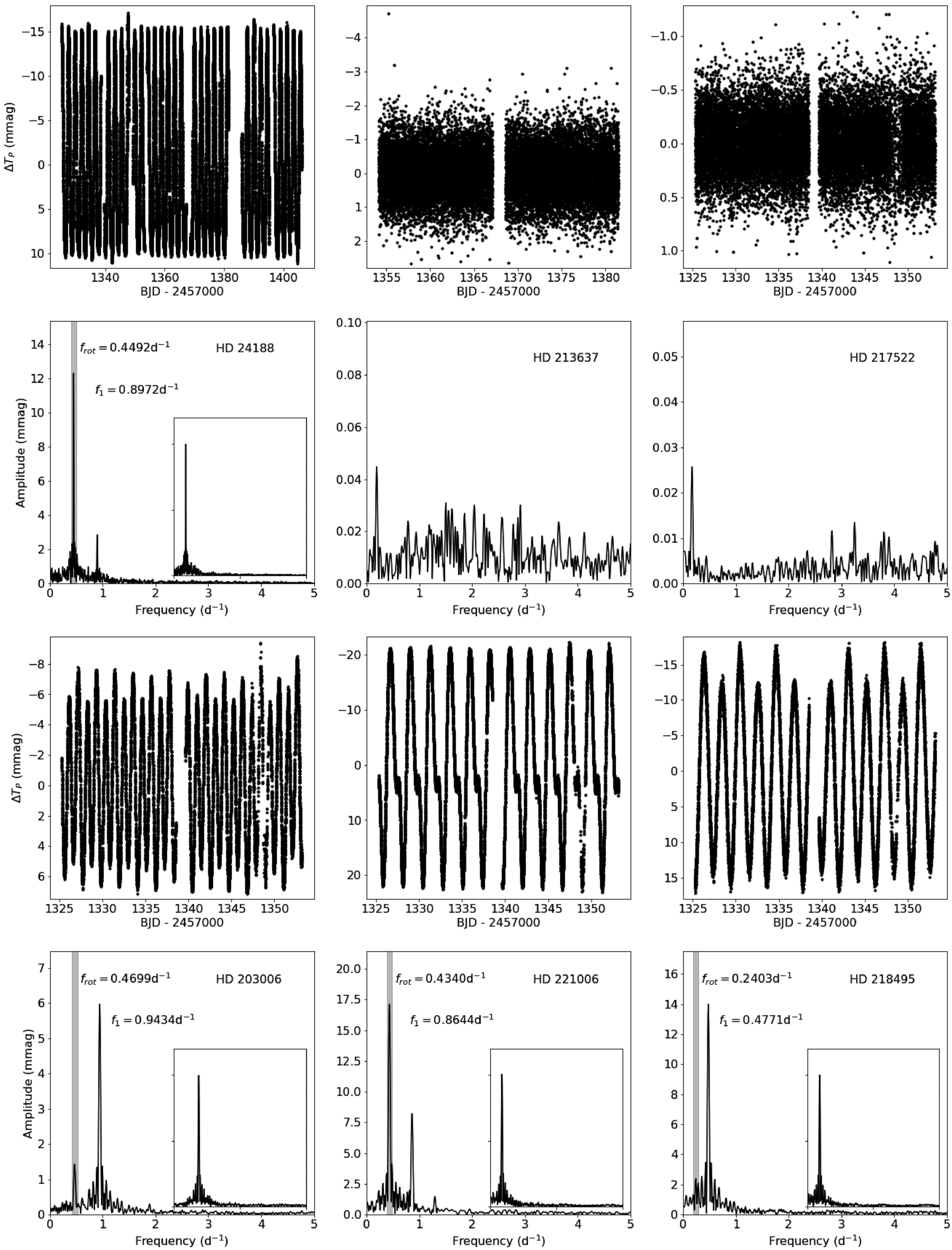

Figure 2. Same as Fig. 1, but for the A stars. For some periodograms, there is no convincing signature of rotational modulation; in those cases, we did not include any window function.

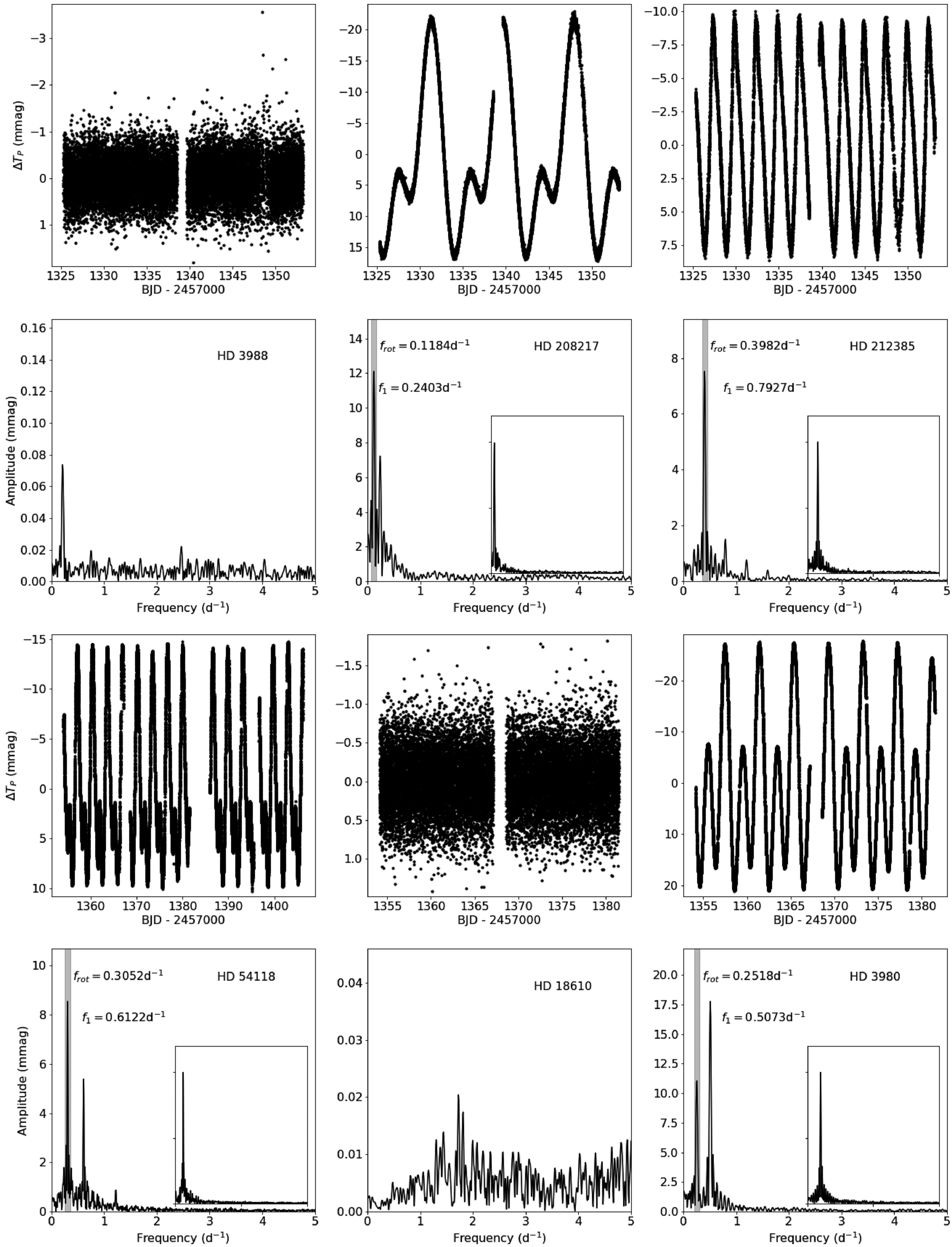

Figure 2 – *continued.*

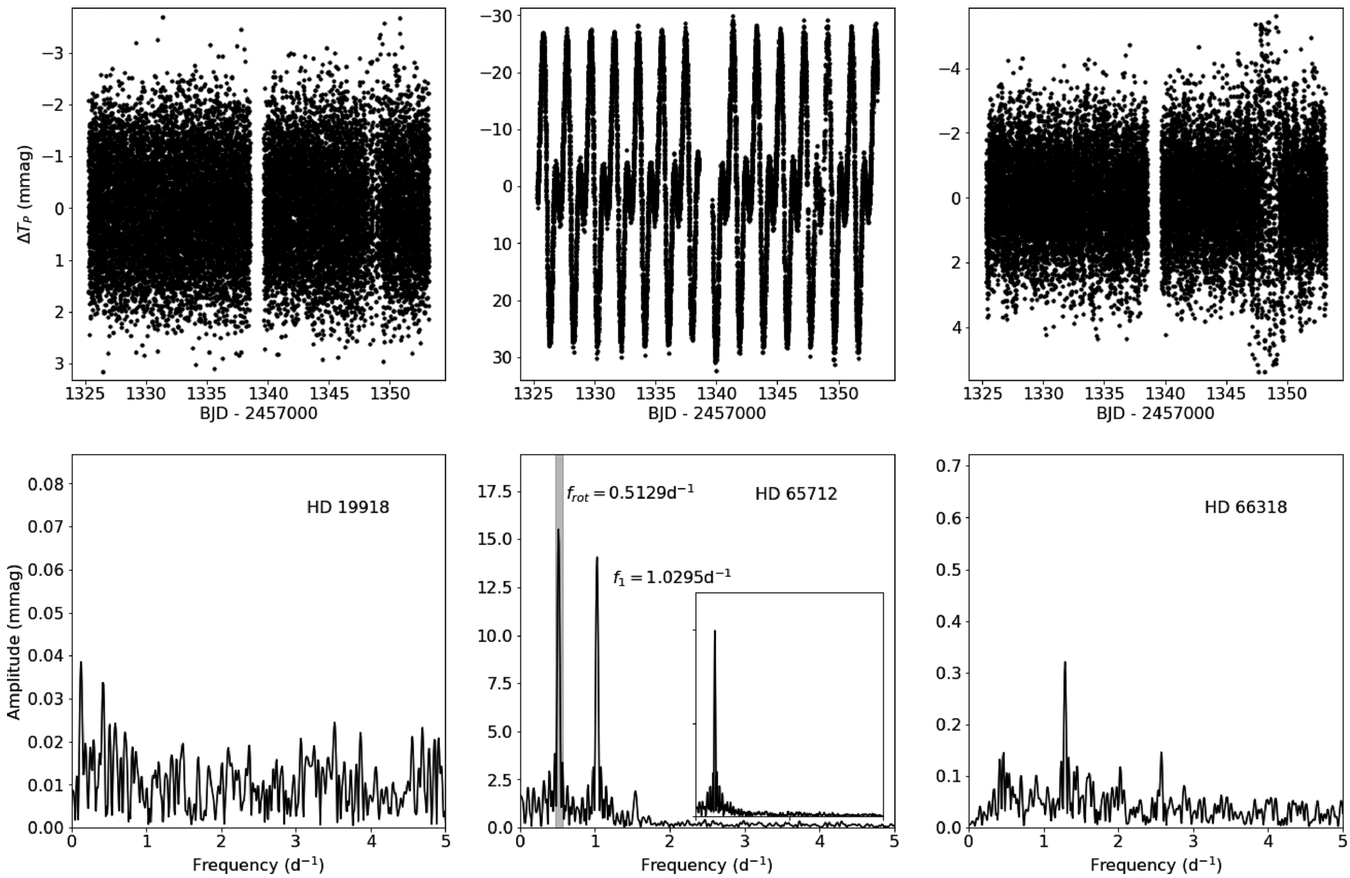

Figure 2 – *continued.*

TIC 279511712 (= HD 53921, B9III + B8V, V = 5.64)

Out of the 19 known magnetic stars discussed in this study, HD 53921 is the only one that is not known to exhibit chemical peculiarities in its spectrum. The *Hipparcos* photometry reveals a 1.65-d period that was attributed to a gravity mode pulsation, implying that HD 53921 is an SPB star (Waelkens et al. 1998). This period determination was refined to 1.6520 d using the same data set, but applying an automatic period search (Dubath et al. 2011). Its radial velocity is also found to vary with the same period (1.6518 d; Aerts et al. 1999). In addition, lower frequencies were detected in the radial velocity measurements, possibly indicating long-period orbital variations (De Cat et al. 2000; consistent with a visual double with separation >1 arcsec, e.g. Horch et al. 2001). This scenario was confirmed by De Cat & Aerts (2002), who found HD 53921 to be an eccentric SB1 with a period of ∼340 d. The components have an ∼1 magnitude difference in the *V* band, with the brightest having a spectral type of B9III, and the fainter one B8V (Corbally 1984). It should be noted that both components lie in the same *TESS* pixel.

The photometric variations are difficult to reconcile with non-radial pulsations (Townsend 2002) and mode identification has proven to be arduous (De Cat et al. 2005). The detected frequency lies within the (large) range of possible rotational frequencies based on its projected rotational velocity and inferred radius (Szewczuk & Daszyńska-Daszkiewicz 2015), and could therefore rather be the rotational period.

Although a first spectropolarimetric observation of HD 53921 yielded only a marginal detection (Hubrig et al. 2006), it was confirmed to be magnetic by Bagnulo et al. (2012). Bagnulo et al. (2015) later identified the B9III primary as the magnetic star. The published frequency is recovered in the *TESS* data (1.651 83 ± 0.000 02 d) with a harmonic pattern typical of rotational modulation. We thus propose that this frequency does not correspond to pulsations, but rather to rotation. Further magnetic characterization would help confirm the nature of this frequency.

TIC 358467049 (= CPD-60 944B, B9pSi, V = 8.76)

CPD-60 944B is a member of an ∼10 arcsec visual pair within the open cluster NGC 2516 (Snowden 1975). Its visual companion, CPD-60 944A, might itself be a binary (González & Lapasset 2000), a hypothesis that has also been supported by González, Veramendi & Cowley (2014), who propose an orbital period of 121.6 d or 182.5 d (they also propose CPD-60 944B to be a HgMn star, a claim that is not supported by other studies). There has historically been some degree of confusion between both of these stars, and the membership of CPD-60 944B in NGC 2516 has been questioned (e.g. Frinchaboy & Majewski 2008).

Bernhard et al. (2015) measured a photometric period of 3.7367 ± 0.0003 d and attributed it to component A, although both visual components were within the aperture of ASAS-3. We report this period in Table 1, since we find a similar period in the *TESS* observations (3.759 ± 0.002 d). However both visual components also fall within the *TESS* aperture. A marginal magnetic field detection was reported by Bagnulo et al. (2006), and later confirmed by Bagnulo et al. (2015).

TIC 372913684 (= HD 65987, B9pSiSr, V = 7.59)

HD 65987 was proposed to be an eclipsing binary system (Snowden 1975), and has often been classified as an eclipsing Algol variable (e.g. Avvakumova, Malkov & Kniazev 2013). Based on radial velocity measurements, Abt & Levy (1972) find a possible periodicity of ∼9 d that could be associated with binarity. Avvakumova & Malkov (2014) evaluate this system to be a detached main-sequence binary, based on its well-established membership in the NGC 2615 cluster (e.g. Landstreet et al. 2007).

Low-level photometric variability was first detected with a putative 1.41-d period (North, Rufener & Bartholdi 1982), which was later refined to 1.44962 ± 0.00018 d by North (1984). If this value is assumed to be related to rotation, the implied small value of $R\sin i$ (Hensberge, van Rensbergen & Blomme 1991) would indicate that the inclination of the rotational axis is likely small. The TESS period (1.4561 ± 0.0001 d) is similar to that of North (1984), and the data are of much better quality than the phased photometry presented by Heck, Mathys & Manfroid (1987). While we ascribe this period to rotation, a binary origin of the light curve variations is not conclusively ruled out. Interestingly, a weak peak appears in the periodogram of the non-detrended light curve at a period of about 9 d, corroborating the idea that that period might be linked to binarity.

HD 65987 was found to be magnetic by Bagnulo et al. (2006), and that detection was later confirmed by Bagnulo et al. (2015). However, new magnetic measurements with improved phase coverage do not seem to vary according to the photometric period (Landstreet et al., in preparation), making this system harder to interpret. More work will be required to confirm the origin of HD 65987's photometric variability.

TIC 32035258 (= HD 24188, A0pSi, V = 6.26)

HD 24188 was found to exhibit non-linear proper motion, making it an astrometric binary candidate (Makarov & Kaplan 2005; Frankowski, Jancart & Jorissen 2007) even though it is not observed to be a spectroscopic binary (Grenier et al. 1999). *Hipparcos* photometry revealed a clear periodicity (2.230 d; Paunzen & Maitzen 1998; Dubath et al. 2011), which was associated with rotation. We confirm and refine this period with the *TESS* light curve (2.23024 ± 0.00004 d).

Based on a single spectropolarimetric observation, HD 24188 was found to be magnetic by Kochukhov & Bagnulo (2006), a conclusion that was since supported through the reanalysis of the same observation (Hubrig et al. 2006; Bagnulo et al. 2015).

TIC 69855370 (= HD 213637, F1pEuSr, V = 9.58)

HD 213637 is a roAp star with an 11-min pulsation period (Martinez, Meintjes & Ratcliff 1997). It has two known frequencies, which vary in amplitude over time (Martinez et al. 1998), possibly due to rotation, although no rotational period has been reported in the literature. It is one of the coolest known roAp stars and is likely evolved, and it exhibits magnetically split lines (Kochukhov 2003). We do not find any convincing signature of rotational variation in the *TESS* light curve.

This star's magnetic field was further diagnosed using FORS1 observations (Hubrig et al. 2004b; Bagnulo et al. 2015). There is no indication of multiplicity (Schöller et al. 2012), and based on magnetic field modulus measurements, the rotational period is likely longer than 115 d (Mathys 2017).

TIC 139191168 (= HD 217522, A5pSrEuCr, V = 7.52)

HD 217522 is a well-studied roAp star (13.72-min pulsational period; Kurtz 1983). It is one of the few roAp stars for which mode switching has been observed (Kreidl et al. 1991). However, no sign of rotational modulation of the pulsational amplitudes has been found by van Heerden, Martinez & Kilkenny (2012), who conclude that either the stellar surface is not very spotted or the rotational axis is nearly aligned with our line of sight, not allowing us to see rotational modulation, a hypothesis further supported by the very low measured value of $v\sin i$ (3 km s^{-1}; Medupe et al. 2015). Additionally, the magnetic axis could be aligned with the rotational axis. While the amplitude modulation occurs on short time-scales (∼1 d), it appears to be stochastic, similar to solar-type oscillations. This also appears to be qualitatively consistent with the fact that we do not find a significant low-frequency series of harmonics in the *TESS* observations of HD 217522, and in particular, no sign of rotation. Analysis of the high-frequency variability using *TESS* observations was performed by Cunha et al. (submitted).

A marginal detection of a magnetic field was reported by Mathys & Hubrig (1997), and has since then been confirmed (Hubrig et al. 2004b; Bagnulo et al. 2015). The field strength is not found to vary on the pulsational time-scale (Hubrig et al. 2004a; they acquired 91 short observations within <0.25 d, a time span insufficient to detect rotational modulation).

TIC 159834975 (= HD 203006, A2pCrEuSr, V = 4.82)

HD 203006 is a visual double with a close faint companion (2 mag fainter in the *Hipparcos* bandpass, separation of 0.1 arcsec; Lindegren et al. 1997). A number of rotational periods have been published for HD 203006. Morrison & Wolff (1971) first reported probable photometric periods of 0.941 d and 1.062 d, then the latter was refined to 1.0609 d by Maitzen (1973). The rotation period was found to be in fact about twice as long as previously thought (2.1219 d, based on photometric and spectroscopic data; Maitzen et al. 1974), which was then refined to 2.1215 ± 0.0001 d (Deul & van Genderen 1983), although an automated period search using *Hipparcos* data yielded a period half as long (1.0610 d; Dubath et al. 2011). We find a similar longer period in the *TESS* data (2.122 ± 0.004 d); it should be noted that it is not the strongest peak in the periodogram, as the first harmonic dominates the spectrum, hence the earlier confusion. HD 203006 has also been observed to vary in the ultraviolet, although there were not enough observations to establish a period (van Dijk et al. 1978). Low-level variability was also observed in the near-infrared with a period of 2.1224 d (Catalano, Leone & Kroll 1998a). It was first observed to be magnetic by Babcock (1958). Later undetected by Borra & Landstreet (1980), its field was eventually confirmed by Bohlender & Landstreet (1990).

TIC 235007556 (= HD 221006, A0pSi, V = 5.68)

HD 221006 was shown to vary photometrically with a period of 2.32 ± 0.03 d (Renson 1978), which was later refined to 2.3148 ± 0.0004 d (Manfroid & Mathys 1985). Spectroscopic variations also phase coherently with this period, as well as photometric variability in many filters, including in the infrared (Leone et al. 1995). This star was also observed with *Hipparcos*, and an automated period search yielded a period of 2.3147 d. The *TESS* photometry of HD 221006 shows a similar period of

2.3119 ± 0.0001 d. This star was detected to be magnetic by Bohlender et al. (1993).

TIC 237336864 (= HD 218495, A2pEuSr, V = 9.38)

HD 218495 was found to host high-frequency pulsations (P = 7.44 min; Martinez & Kurtz 1990; Martinez, Kurtz & Kauffmann 1991). No other variability period is reported in the literature for this roAp star prior to the *TESS* observations.

Although the periodogram is clearly dominated by the first harmonic (see Fig. 2, the amplitude of the signal is clearly modulated on a period that is twice as long as the one that we would derive from the dominant peak), we determine a rotational period of 4.183 ± 0.006 d. This is similar to the value given by Cunha et al. (submitted), which offer the first determination of this star's rotational period (4.2006 ± 0.0001 d).

A first attempt to observe HD 218495's magnetic field did not yield a significant detection (Mathys & Hubrig 1997), but it has since been found to be magnetic (Hubrig et al. 2004b), a detection that was confirmed by Bagnulo et al. (2015).

TIC 262956098 (= HD 3988, A0pCrEuSr, V = 8.35)

A double-lined spectroscopic binary with magnetically split lines ($B_d \sim 2.7$ kG; Elkin, Kurtz & Nitschelm 2012), HD 3988 does not show evidence of a companion in speckle interferometry (White et al. 1991). It also does not vary with any known rotational or pulsational period (Martinez & Kurtz 1994b); similarly, no evidence of rotational modulation is found in the *TESS* light curve.

TIC 277688819 (= HD 208217, A0pSrEuCr, V = 7.19)

HD 208217 is an astrometric binary candidate based on proper motion measurements (Frankowski et al. 2007). HD 208217 was found to vary photometrically with a period of 8.35 ± 0.10 d (Manfroid & Renson 1983). Its period was refined to 8.444 75 ± 0.000 11 d (Manfroid & Mathys 1997) using both photometry and magnetic field modulus measurements derived from resolved line splitting (for the latter, see also Mathys et al. 1997; they mention this is a spectroscopic binary with a potentially long period, on the order of 2 yr). We recover a slightly shorter period based on its *TESS* light curve (8.317 ± 0.001 d). HD 208217's magnetic field was detected and measured to provide a phase-resolved longitudinal field curve by Landstreet & Mathys (2000), with additional measurements published by Mathys (2017).

TIC 278804454 (= HD 212385, A3pSrEuCr, V = 6.84)

HD 212385 exhibits non-linear proper motion that makes it an astrometric binary candidate (Makarov & Kaplan 2005; Frankowski et al. 2007). A period of 2.48 ± 0.04 d was found in photometry (Renson 1978), and then refined to 2.5265 ± 0.0015 d (Manfroid & Mathys 1985). We find a slightly shorter period in the *TESS* data (2.5062 ± 0.0002 d). HD 212385 was discovered to be magnetic by Hubrig et al. (2006), a detection confirmed by Kochukhov & Bagnulo (2006) and Bagnulo et al. (2015).

TIC 279573219 (= HD 54118, A0pSi, V = 5.17)

Identified as an astrometric binary candidate due to non-linear proper motion (Makarov & Kaplan 2005; Frankowski et al. 2007), HD 54118 was later found to be a spectroscopic binary by Ammler-von Eiff & Reiners (2012), though its companion is not well characterized. Its optical light curve was found to vary on a period of 3.275 ± 0.015 d (Manfroid & Renson 1981), a period that was refined a few times using ground-based photometry (Manfroid & Mathys 1985; Catalano & Leone 1993), most recently to 3.275 35 ± 0.000 10 d (Manfroid & Renson 1994). This star was also observed with *Hipparcos*, and an automated period search yielded a rotational period of 3.2749 d (Dubath et al. 2011).

Found to be magnetic with $P_{\rm rot} = 3.2 \pm 0.1$ d (Borra & Landstreet 1975), its field detection was confirmed by Bohlender et al. (1993) using phase resolved observations; they also refined the period to 3.275 33 ± 0.000 20 d, which is consistent with the photometric period. There was also a further follow-up spectroscopic observation by Donati et al. (1997). The *TESS* light curve reveals a period of 3.2759 ± 0.0002 d, consistent with the previous results.

TIC 280051011 (= HD 18610, A2pCrEuSr, V = 8.14)

Zeeman splitting in the spectra of HD 18610 led to discovery of a magnetic field with a modulus of about 5.7 kG (Stütz, Ryabchikova & Weiss 2003). This star has no rotational or pulsational periods reported in the literature (Martinez & Kurtz 1994b), and no signature of rotation is detected in the *TESS* data.

TIC 281668790 (= HD 3980, A7pSrEuCr, V = 5.70)

HD 3980 is a known visual double (Kopal 1955; De Rosa et al. 2014; its companion is 2.89 mag fainter in the K band and separated by ∼13 arcsec). The first photometric period determined for HD 3980 was 0.4 d (Maitzen 1976a). Since then, different photometric periods have been reported: 2.13 d or 0.68 d (Renson 1979), and later 3.9516 ± 0.0003 d (Maitzen et al. 1980). The latter study also took into account magnetic measurements based on Zeeman line broadening/splitting. Photometric variability in the infrared (J, H, and K bands) is also found to phase coherently with the longer optical period (Catalano et al. 1991, 1998a). *Hipparcos* data reveal, as a result of an automated search, a potential 1.1628 d period (Dubath et al. 2011), but this value does not agree with any other study.

We find a period in the *TESS* light curve that is similar to the values obtained from earlier ground-based observations (3.951 ± 0.003 d); it should be noted that it is not the strongest peak in the periodogram, as the first harmonic dominates the spectrum. The detection of a magnetic field at the surface of HD 3980 has been reported by Hubrig et al. (2006) and Bagnulo et al. (2015), supporting the earlier Zeeman line broadening measurements.

TIC 348717688 (= HD 19918, A5pSrEuCr, V = 9.35)

HD 19918 is a well-known roAp star discovered in the Cape survey (Martinez & Kurtz 1991, 1994a; Martinez et al. 1995; see also Cunha et al. submitted) with no visual companion (Schöller et al. 2012). A marginal field detection (Mathys & Hubrig 1997) was later confirmed by Kochukhov & Bagnulo (2006) (see also Hubrig et al. 2006; Bagnulo et al. 2015), and investigated through line broadening as well (Ryabchikova et al. 2007). The *TESS* light curve does not yield any frequency peak compatible with rotational modulation.

TIC 358467700 (= HD 65712, A0pSiCr, V = 9.35)

HD 65712 is a member of NGC 2516 (Snowden 1975), despite being identified as a possible high-velocity star by Jaschek et al. (1983). Its membership in the cluster was confirmed by Landstreet et al. (2007).

HD 65712 was found to have a 1.943 ± 0.001-d photometric rotation period by Warhurst (2004), although a shorter period of 1.88 d was found by Paunzen et al. (2011). We find a period in the *TESS* photometry of this star (1.9460 ± 0.0002 d) that appears to be more consistent with the earlier determination of Warhurst (2004); hence, we choose to report that value in Table 1. A magnetic field was detected by Bagnulo et al. (2006) (and confirmed by Bagnulo et al. 2015).

TIC 410451752 (= HD 66318, A0pEuCrSr, V = 9.56)

HD 66318 is a probable member of NGC 2516 (Cox 1955; Frinchaboy & Majewski 2008). No previous study of this star has discovered photometric variability (North et al. 1982; North 1987; Dachs & Kabus 1989). A strong magnetic field was detected by Bagnulo et al. (2003) and later confirmed by Bagnulo et al. (2006) and Bagnulo et al. (2015), with a significant discrepancy observed between the field strengths measured from hydrogen and metal lines (Landstreet, Bagnulo & Fossati 2014). These authors do not find spectral variability, suggesting a very long rotation period (potentially on the order of years). This is also consistent with their finding that the projected rotational velocity is very low as determined from high-resolution UVES spectra, contradicting previous findings that $v\sin i = 30\,\mathrm{km\,s^{-1}}$ (Dachs 1972; Wolff 1981); this indicates that the viewing angle might simply not allow us to detect significant rotational modulation.

Similarly, we do not detect a convincing rotational period in the *TESS* photometry; as such, we reiterate the conclusion of Mathys (2017) that more observations are required to characterize the long-term variability of this star. However, there appears to be a weak potential rotational peak at 1.3 $\mathrm{d^{-1}}$ (and its first harmonic); given that the pixels from which this star's signal is measured are highly contaminated (contamination ratio of 0.815 according to the TIC), it is plausible that the flux of nearby stars is within the light curves of HD 66318. A similar conclusion is reached by Cunha et al. (submitted), who report a period of 0.776 88 ± 0.000 52 d.

4 DISCUSSION AND CONCLUSIONS

This paper introduces the MOBSTER collaboration, a group consisting of both observers and theorists with the aim of using *TESS* data to further the study and characterization of magnetic OBA stars and to discover new magnetic stars out of a photometrically pre-selected sample of targets. Upcoming studies will include the characterization of specific magnetic objects of interest via spectropolarimetry and will confront analytic models with observations.

12 out of the 19 known magnetic B and A stars observed in the first two sectors of *TESS* show periodograms displaying a main frequency peak and at least one harmonic – this is a characteristic signature of rotational modulation (e.g. Bowman et al. 2018), understood to be due to the presence of an oblique dipolar magnetic field – with an additional star exhibiting only a fundamental peak, but whose light curve still appears to be rotationally modulated. Other targets showing this behaviour in the periodogram of their *TESS* light-curves should be considered as promising magnetic candidates. Such candidates have been identified for OB stars in sectors 1 and 2 by Pedersen et al. (2019) and for A stars in sectors 1 to 4 by Sikora et al. (submitted). They are prime targets for future spectropolarimetric observations. This identification is a crucial first step to increase the sample size of magnetic OBA stars (especially for the earliest spectral types) since spectropolarimetry is an expensive observational technique. Large spectropolarimetric surveys have uncovered a number of such stars, but the efficiency limit of these (essentially magnitude limited) surveys has been reached. Therefore, photometrically pre-selecting strong candidates among a fainter sample of stars with a high expected detection rate (e.g. Buysschaert et al. 2018a) constitutes our best possible strategy moving forward, and this is uniquely enabled by the high-quality light curves obtained with *TESS*.

We have refined the period determinations for 13 targets, and in some cases, compared to published values based both on photometric studies and other types of observations. We also present phase folded light curves for these 13 stars in the Appendix (Fig. A1); these show a wide variety of morphologies and nicely illustrate the exquisite quality of the *TESS* observations. We find our results to be consistent with the literature values overall, and in particular, unsurprisingly, with the values derived by Cunha et al. (submitted) using the same data set. In a few cases (especially in the case of HD 223640), there is an apparently significant departure between our values and the latter; this is likely due to the different methodologies employed to calculate the rotational periods. These results also illustrate the immense potential of *TESS*, compared to other large space-based surveys, as we detect rotational modulation and derive the rotational period in three stars (HD 65987, HD 208217, and HD 212385) that were observed by *Hipparcos*, but for which no period was recovered.

As for the six stars that did not show significant low-frequency peaks in their periodograms (HD 213637, HD 217522, HD 3988, HD 18610, HD 19918, and HD 66318), we are not able to conclude anything about their rotational periods. Half of them (HD 213637, HD 217522, and HD 19918) are known to exhibit rapid oscillations, identifying them as roAp stars, while the last one is likely too heavily contaminated for its rotational modulation to be significantly detected (although a weak signal with a period of about 0.8 d might be present). The most useful constraint to evaluate these stars' rotational periods would be to obtain phase-resolved magnetic measurements, although it is possible that the lack of apparent rotational modulation is due to an unfavourable alignment of the rotational and magnetic axes with respect to the line of sight.

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APPENDIX: PHASED LIGHT CURVES

In this section, we present phase folded light curves for each star showing rotational modulation (with overlaid binned light curves using 20 phase bins over the full rotational cycle).

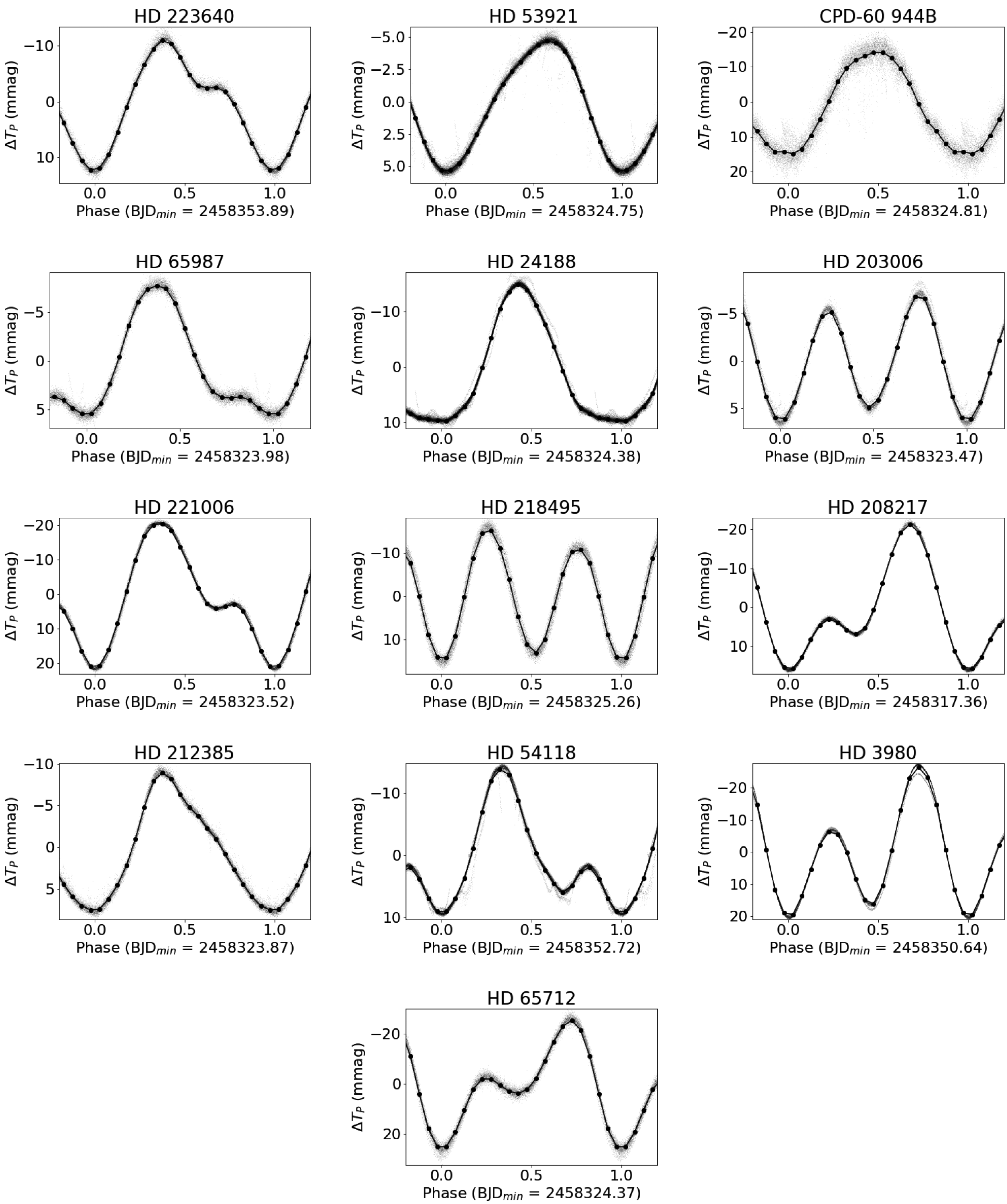

Figure A1. Phase folded light curves (with phase 0 corresponding approximately to minimum light; the time of minimum light used to phase the light curve is indicated on the *x*-axis of each plot for reference) for the 13 stars showing potential rotational modulation. The light grey points correspond to individual measurements, and the larger black points connected by a line correspond to binned data (with bins of 0.05 in phase). For some stars, we see streaks of outliers; these are due to artefacts that could not be completely detrended. We find that the light curves have diverse morphologies, with at least 9 out of the 13 showing signs of double-wave variations, and all of them having an asymmetric profile.

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