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ROTATIONAL VARIABILITY IN PRE-MAIN-SEQUENCE STARS: TWA 6 IN 2008

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TWA 6 (= 2MASS J10182870–3150029) is a K7 spectral-type member of the TW Hydrae association (TWA), one of the nearest pre-main sequence (PMS) stellar populations to Earth (Webb et al., 1999; Reid, 2003; Zuckerman & Song, 2004). Located at a distance of ≈ 50 pc (Mamajek, 2005), TWA 6 has a mass of $\approx 0.7\ M_\odot$ and a luminosity of $\approx 0.25\ L_\odot$ (Skelly et al., 2008). The association has an estimated age of ≈ 10 Myr, and this is consistent with the age inferred for TWA 6 (~ 12 Myr) following Hertzsprung-Russell diagram placement of the star and comparison with PMS evolutionary tracks (Skelly et al., 2009). TWA 6 is an example of a weak-lined T Tauri (WTT) star, with weak Balmer emission lines (the Hα equivalent width is ≈ 5 Å), and no near-infrared excess that would indicate the presence of an inner circumstellar disk.

The most-remarkable feature of TWA 6 is its large photometric amplitude that is a consequence of the rotational modulation of cool starspots that cover a few tens of percent of the photosphere. Lawson & Crause (2005) found the star to have a V-band amplitude of 0.49 mag modulated on a rotation period of 0.54 d, in BVI_C CCD differential photometry of the star obtained with the 1-m telescope at the South African Astronomical Observatory (SAAO) in 2001. (In this paper, the light curve amplitude is given as the peak-to-peak amplitude.) A trial series of previously-unpublished V-band observations of TWA 6 obtained at SAAO in 2000 returned the same period, although the star had a slightly-lower V_ampl of 0.40 mag. In Table 1, we present these data for the first time. Compared to other WTT stars, the photometric amplitude of TWA 6 is large; most WTT stars have rotational amplitudes of ~ 0.1 mag, and few have rotational amplitudes > 0.2 mag (Lawson et al., 2001; Lawson & Crause, 2005). Lawson et al. (2001) summarise the observing procedure at SAAO, and the production of the differential light curves.

The combination of a short rotation period for the star's spectral type, with a $v \sin i = 72$ km s^{-1} placing TWA 6 firmly in the 'fast rotator' regime ($v \sin i > 50$ km s^{-1}) for T Tauri stars, and a large photometric amplitude makes TWA 6 an ideal target for Doppler mapping studies, where spectral line profile variations allow for reconstruction of stellar surface features such as starspots, and other structures such as solar-type 'plages' and prominences. Skelly et al. (2008) observed TWA 6 using the UCLES echelle spectrograph at the 3.9-m Anglo-Australian Telescope in 2006, with the resulting Doppler map showing a large polar spot, and other starspot groups extending to the equator. The outcome was a starspot distribution similar to that seen in other young, fast-rotating stars. However, the inferred luminosity variation resulting from the Doppler study was only 0.1 mag, a factor of 4 − 5 lower than that observed at SAAO in 2000 and 2001. While Doppler-reconstructed light curves are suspected of under-estimating the level of photometric variability, it is unlikely that the light amplitude is under-estimated by more than a factor of 2. Skelly et al. (2009) discussed this aspect for the Doppler studies of TWA 6 and TWA 17 and concluded that, in 2006, TWA 6 probably did have lower photometric variability than was observed during the 2000 and 2001 observing seasons.

With this background of variability information in mind, we observed TWA 6 again at SAAO in 2008, obtaining 15 epochs of data over 7 nights, or a time baseline of nearly 12 rotational periods. Our differential $BVR_{\rm C}I_{\rm C}$ observations are presented in Table 2, where the phase of each observation is calculated assuming $\mathrm{JD}_0 = 2454499.1050$, and where we adopt the Skelly et al. (2008) spectroscopic period of 0.5409 d. We have not merged the 2008 photometry with our earlier datasets in an attempt to further improve the rotation period, as the interval between the datasets is long, and there is very little information available on the timescale at which spot patterns evolve in WTT stars, i.e. the appearance or disappearance of major starspot groups could have the effect of introducing a significant phase shift in the light curve.

Table 1. 2000 SAAO V-band differential photometry of TWA 6.

JD–2450000	Phase	ΔV	JD–2450000	Phase	ΔV
1584.3945	0.0000	0.156	1619.2773	0.4903	–0.268
1585.0000	0.0438	0.160	1619.3906	0.6997	–0.141
1586.3945	0.6975	–0.106	1622.2656	0.0150	0.124
1587.3867	0.5319	–0.256	1622.3828	0.2316	0.009
1588.3047	0.2290	0.010	1623.3359	0.9937	0.126
1590.3086	0.9337	0.117	1623.4688	0.2393	0.126
1590.4922	0.2732	–0.050	1624.2852	0.7486	–0.108
1591.5664	0.2592	–0.030	1624.4453	0.0447	0.144
1596.2852	0.9830	0.137	1624.5625	0.2614	–0.017
1596.4414	0.2719	–0.028			

Table 2. 2008 SAAO $BVR_{\rm C}I_{\rm C}$ differential photometry of TWA 6.

JD–2450000	Phase	ΔB	ΔV	$\Delta R_{\rm C}$	$\Delta I_{\rm C}$
4522.2950	0.1250	0.084	0.068	0.056	0.026
4522.3172	0.0838	0.113	0.090	0.070	0.052
4522.4952	0.7546	–0.017	–0.022	–0.018	–0.011
4522.5040	0.7385	–0.037	–0.031	–0.027	–0.022
4523.3652	0.1468	0.074	0.061	0.054	0.042
4523.3701	0.1376	0.082	0.066	0.045	0.031
4524.3934	0.2455	–0.002	0.004	–0.006	–0.004
4525.3110	0.5491	–0.099	–0.085	–0.082	–0.049
4525.5570	0.0943	0.108	0.093	0.089	0.079
4526.3160	0.6910	–0.044	–0.042	–0.032	–0.026
4526.4752	0.3966	–0.094	–0.082	–0.083	–0.053
4527.4125	0.6637	–0.048	–0.046	—	—
4527.6224	0.2757	–0.039	–0.026	–0.016	–0.025
4528.3740	0.8866	0.042	0.039	0.032	0.026
4528.6040	0.4616	–0.123	–0.086	–0.084	–0.067

Phase-folded $BVR_{\rm C}I_{\rm C}$ light and colour curves of TWA 6 in 2008 are shown in Fig. 1. The overall trend of the light curve amplitudes follows that seen in the $BVI_{\rm C}$ observations obtained in 2001 by Lawson & Crause (2005), where there is a general decrease in amplitude towards longer wavelengths, but in 2008 the light amplitude was distinctly lower than in 2000 and 2001, with $V_{\rm ampl} = 0.19$ mag. We note that if the 2006 Doppler-inferred amplitude was under-estimated by a factor of ~ 2, then the 2006 and 2008 light amplitudes are similar.

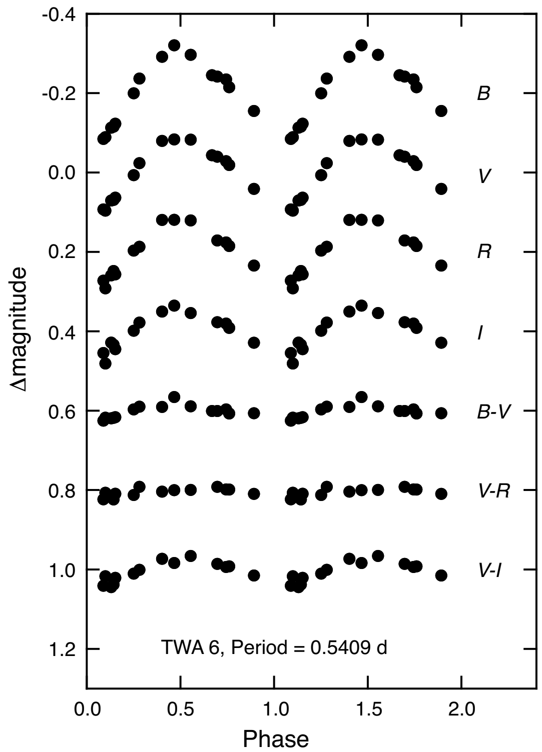

Figure 1. Phase-folded $BVR_{\rm C}I_{\rm C}$ differential photometry of TWA 6, obtained at SAAO during 2008.

Table 3 summarises light curve amplitudes for TWA 6 measured in 2000, 2001, and 2008, along with the mean V-band magnitude. Clearly a more-complete dataset of amplitudes would be interesting to obtain, to allow investigation of temporal changes in the light curve amplitude, as would the production of Doppler maps at different epochs to investigate the evolution of the starspot distribution. We keep in mind that photometry measures the contrast of spot coverage during a rotation cycle, i.e. the photometric amplitude is determined from the brightness difference between the most-spotted, and least-spotted, hemispheres of the star. If the large polar spot indicated in the Doppler maps of Skelly et al. (2008) is always present and is roughly constant in extent, then it might contribute little to the luminosity variations, given that the inclination angle of the star is $\approx 50^\circ$ and the polar cap is always exposed. This suggests that the presence of lower latitude spots may be principally responsible for driving the light curve amplitude.

Table 3. Summary of SAAO CCD photometric light amplitudes for TWA 6.

Year	$V_{\rm mean}$	$B_{\rm ampl}$	$V_{\rm ampl}$	$R_{\rm C,ampl}$	$I_{\rm C,ampl}$
2000	11.68	—	0.40	—	—
2001	11.74	0.54	0.49	—	0.27
2008	11.43	0.25	0.19	0.18	0.14

Since we obtained multi-color observations in 2001 and 2008, we can estimate the starspot temperature and compare that to the spot temperature of 3300 K derived in the Doppler imaging study of Skelly et al. (2008). Assuming a $T_{\rm eff}$ for TWA 6 of 4000 ± 200 K (Skelly et al., 2008), we obtain a spot temperature of ≈ 3400 K with a spot filling factor of ≈ 50 % in 2001, and a spot temperature of ≈ 3700 K and a filling factor of ≈ 40 % in 2008. The mean V-band magnitude of the star changes from $2000-2001$ to 2008 both as a consequence of the reduced photometric amplitude, but also from an increase in the maximum V-band magnitude from 11.5 in $2000-2001$ to 11.3 in 2008. TWA 6 may have a younger, higher mass analogue in the few Myr-old, early K-type star V410 Tau which also displays significant variations in its long-term light curve behaviour. After a recent Zeeman-Doppler imaging study to reconstruct the surface spot pattern, the photometric variations of V410 Tau have been interpreted as being due to long-term changes in the spot distribution (Skelly et al., 2010, and references therein).

In summary, TWA 6 is a T Tauri star worthy of on-going monitoring for photometric variability. Its brightness ($V_{\rm max} \approx 11.5$), combined with its short period (0.54 d) and stable (on timescales of at least a few weeks), large amplitude ($0.2-0.5$ mag) visual light curve makes TWA 6 an accessible target for observation even for small telescopes equipped with a CCD camera or photoelectric photometer.

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