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Photometric Monitoring of ROSAT-Selected Weak Line T Tauri Stars *

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Abstract We monitored the light curves of 22 weak-line T Tauri stars (WTTSs) discovered among the X-ray sources in the field of the Taurus-Auriga cloud. For 12 of the 22 WTTSs photometric periodic variability is confirmed and their rotational periods are determined using Phase Dispersion Minimization (PDM) and Fourier analysis. Most of them are found to have periods shorter than one day. This gives further evidence for the spin up of solar-type stars predicted by the models of angular momentum evolution of pre-main sequence stars.

Key words: stars: late-type– stars: pre-main sequence– stars: rotation

1 INTRODUCTION

T Tauri stars (TTSs) are young ($\leq 10^8$yr), low-mass ($M \leq 2M_\odot$), late spectral type (typically G0 or later) pre-main sequence (PMS) stars. It is well-known that TTSs are photometric variables (Joy 1945). These stars were originally classified as irregular variables (Herbig 1962). Their light variation periods range from minutes to decades and amplitudes from a few magnitudes down to a few hundredths (Herbst 1994). Irregular variations of up to several magnitudes are interpreted as results of accretion and, perhaps, occultation events within the dusty and gaseous disks surrounding classical T Tauri stars (CTTSs). One also sees periodic variations of typically a few tenths of a magnitude or less in weak-line T Tauri stars (WTTSs) that may be largely or entirely attributed to cool (magnetic) spots on the stellar surface (Herbst 1994). Spots on the photosphere modulate the light curve at the rotational period and so allow the rotational period to be obtained.

As of date, photometric surveys in star formation regions and young open clusters have resulted in several hundreds of periodically varying WTTSs and youngest dwarfs (Bouvier et al. 1993, 1995; Grankin et al. 1995; Prosser et al. 1995; Shevchenko et al. 1998; Herbst et al. 2000; Lawson et al. 2001), but the number of short-period (<1d) objects is still very small. It is hard to understand that there seems to be a gap in periods between one day and a few hours, or in other words, a gap between the oldest TTSs and the youngest variable dwarfs. According to the theory of stellar structure evolution, when a low-mass star evolves from a PMS star to a normal main-sequence star, its interior will change rapidly from completely convective to mostly radiative, and this usually causes the most rapid and drastic surface variations such as spot activity and chromospheric emissions. Therefore, searching for short-period WTTSs could be of special interest. For that, X-ray sources in star formation regions should be the most suitable objects, since the optical counterparts of X-ray sources might have selected stars with very high coronal emission, typical of faster rotators.

The Taurus-Auriga cloud is a famous star formation region. In this field, the ROSAT all-sky survey has identified a large number of X-ray sources. Photometric observations on these X-ray sources have revealed

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a total of 22 WTTSs or WTTS candidates (O'Neal et al. 1990; Gregorio-Hetem & Hetem 1992; Wichmann et al. 1996; Li & Hu 1998). The rotational periods of three definite WTTSs were determined by Zakinov et al. (1993), Grankin (1994) and Bouvier et al. (1997), respectively. One of them was found to be a short-period variable. For the other 19 candidates, their light variations and periods are still uncertain, and we estimate that there could be some more short-period WTTS samples among them (most of the stars are found located outside of the dense dark cloud; it is usually in such clouds that optical-selected classical T Tauri stars appear in clusters).

In the observational seasons of 2004 and 2005, we carried out a long-term CCD photometric monitoring on all these 22 stars. Our main goal is to derive the rotational periods of these WTTS, and hope to fill the above-mentioned gap in period. In this paper we present the results of our observations, and a discussion on the angular momentum evolution of PMS stars, based on the results.

2 OBSERVATIONS AND DATA REDUCTION

Table 1 lists the basic data of our program stars. Thirteen of these are collected from Li & Hu (1998), seven, from Wichmann (1996), and the remaining two, from O'Neal et al. (1990) and Gregorio-Hetem & Hetem (1992).

Table 1 Photometric BVR Amplitudes and Rotational Periods of 12 WTTSs

Stars	ΔB (mag)	ΔV (mag)	ΔR (mag)	Periods (day)	$(B-V)$
[LH98]37	0.155	0.140	0.125	1.130	0.85
[LH98]53	0.175	0.161	0.146	0.728	0.69
HD 285372	0.268	0.205	0.153	0.287	1.07
HD 283323	0.105	0.086	0.082	1.93	0.82
HD 284503	0.191	0.150	0.148	0.741	0.65
HD 285840	0.160	0.150	0.128	1.558	0.84
HD 283716	0.079	0.077	0.065	1.48	0.94
HD 282346	0.122	0.110	0.109	0.730	0.77
GSC 01292–00639	0.080	0.080	0.080	0.919	0.93
TAP 57NW	0.162	0.132	0.096	9.12	1.12
HD 287927	0.162	0.138	0.126	0.772	0.80
HD 245358	0.126	0.093	0.085	0.736	0.76

Observations were carried out from October 2004 to February 2005 on the 60-cm reflector telescope at Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Science (NAOC), equipped with a PI 1300×1340 photometric CCD. The plate-scale of the camera is $0''.46$/pixel, and the size of the field of view is $9'.93 \times 10'.24$. The standard Johnson B, V and R filters were used. In total we obtained more than 200 CCD frames in each band for each of the stars.

Data reduction is carried out with the Image Reductions and Analysis Facility (IRAF) software. All images were corrected for electronic bias and pixel-to-pixel gain variations (with sky flats). To obtain relative magnitudes of the objects, the routines in the DAOPHOT package are used for crowded fields, and those in the APPHOT package, for uncrowded fields. We adopt the standard method to perform the differential photometry. In each field we analyzed the light-curves of several stars and selected those that did not vary over the ten nights as our reference stars. We discarded those stars that have very different instrumental magnitudes and colors from the targets. The remaining reference stars were examined for stability, and we have computed their averaged instrumental magnitudes as the magnitude of "artificial comparison". Transformation of the instrumental magnitudes to a standard system was not done, since the main task of this paper is to check the light variations. The precision of the differential photometry for all the stars is better than 0.023 mag.

3 RESULTS AND DISCUSSION

Our photometric observations confirm the variability of 12 of the 22 targets. The BVR light curves of these definite WTTSs are displayed in Figure 1. For the other ten stars, we failed to detect light variations at the present photometric accuracy. It is suggested that they might be WTTSs with long-period, low-amplitude variations.

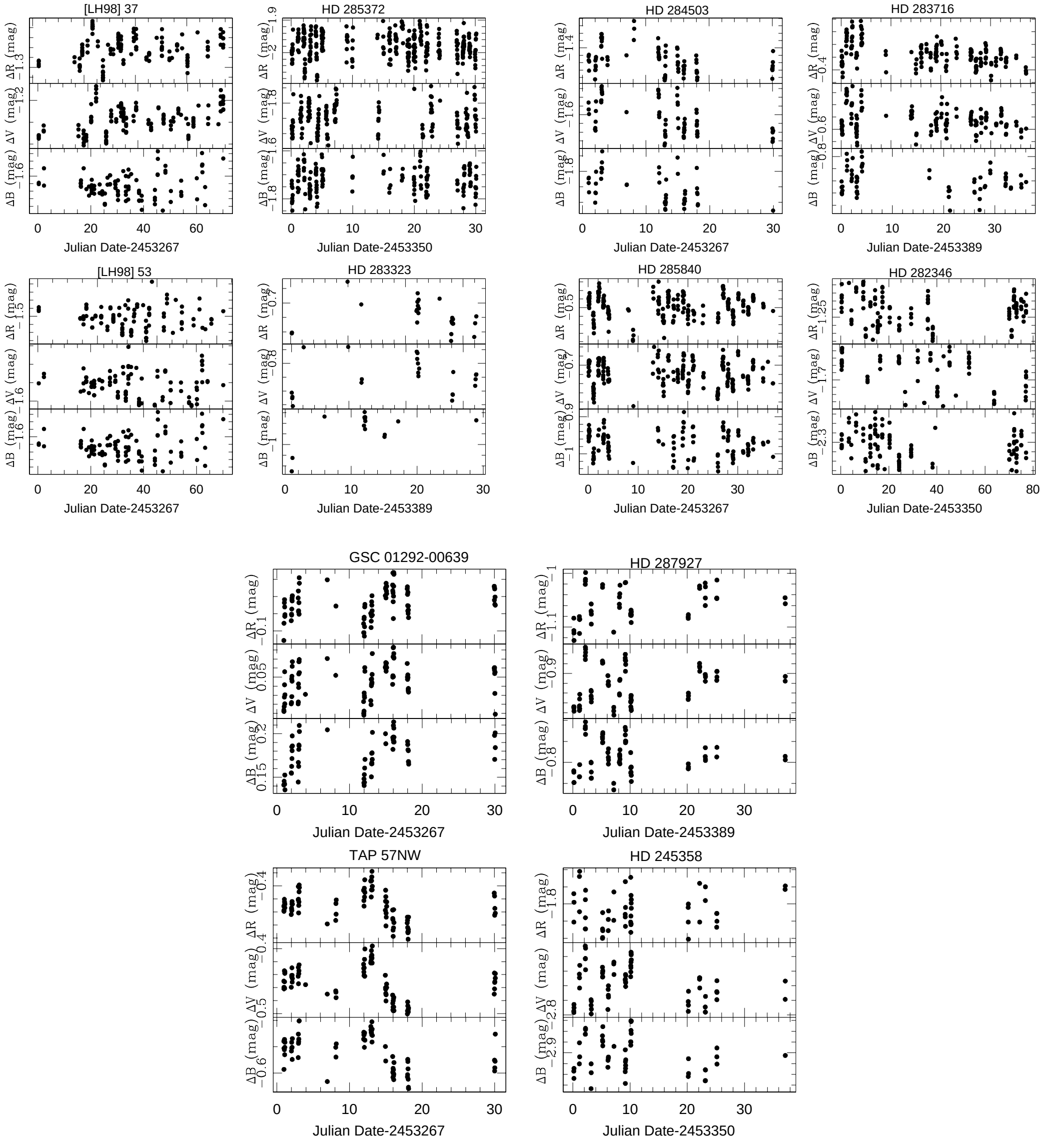

Fig. 1 BVR light curves of the observed WTTSs.

With the newly derived photometric measurements, the rotational periods of the 12 variables were determined. The periods were computed by using the Phase Dispersion Minimization (PDM) method (Lafler & Kinman 1965; Stellingwerf 1978), and were checked by Fourier analysis with the code PERIOD04 (Lenz & Breger 2004). In Table 2 we present the main results for the 12 WTTSs. The phased V-band light curves formed with the derived periods are shown in Figure 2.

The periods of HD 285840 and TAP 57NW determined by us are in good agreement with those given by Bouvier et al. (1997, period of HD 285840 is 1.55 days) and by Grankin (1994, period of TAP 57NW is 9.34 days). For HD 285372, its period was refined to 0.287 days, which is precisely one-half the value of 0.573 days, previously reported by Bouvier et al. (1997).

Among the 12 definite variables, we find that most (seven) of them are short-period WTTSs (with $P < 1$ days, very close to the periods of the stars in the Pleiades cluster). This confirms our prediction

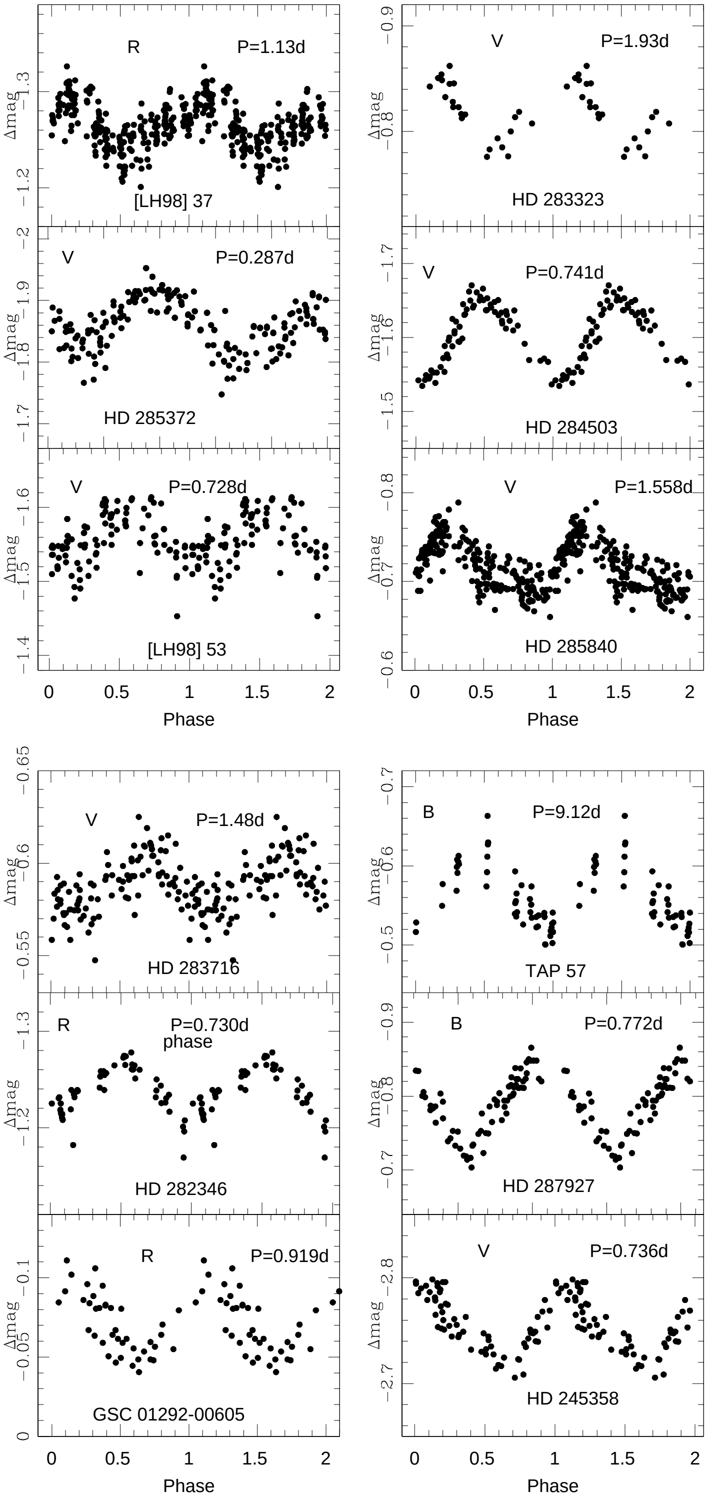

Fig. 2 Phase–folded light curves of the 12 WTTSs.

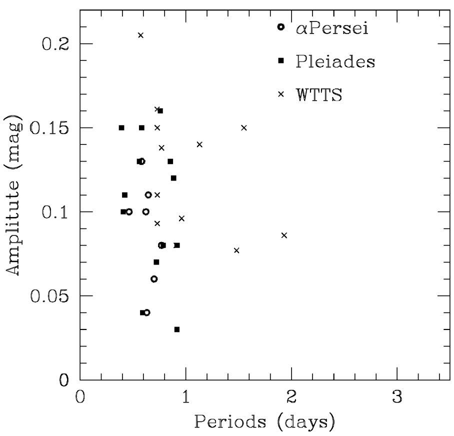

Fig. 3 Rotational periods vs. V light-curve amplitude.

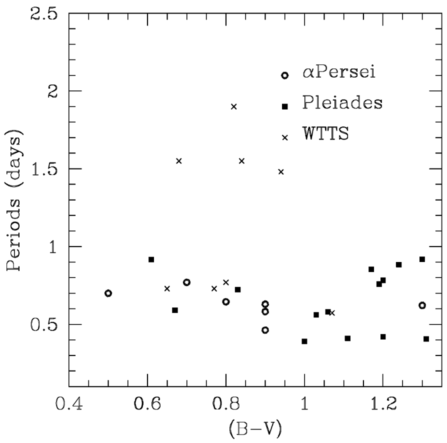

Fig. 4 Rotational periods vs. $(B-V)$ color indices for stars of the young open cluster α Persei (empty circles), Pleiades (filled squares) and our sample of WTTSs (crosses).

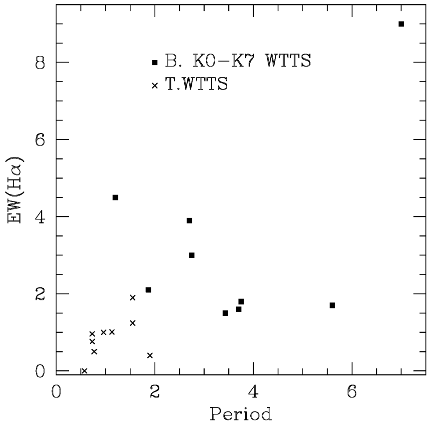

Fig. 5 Rotational periods vs. EW(H_α) for the WTTSs of Bouvier et al. (1993) (filled squares) and of our sample (crosses).

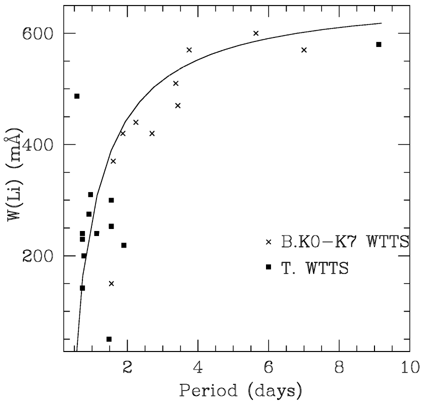

Fig. 6 Rotational periods vs. EW(Li) for the WTTSs of Bouvier et al. (1993) (filled squares) and of our sample (crosses).

above. Our result improves substantially the WTTS data and provides important clues on the study of the angular momentum evolution of PMS stars.

The amplitude of the photometric variability might depend on the periods. In order to study this we have compiled from the literature data on Post-TTSs (Bouvier et al. 1997) and Zero-Age Main Sequence (ZAMS) in Pleiades and α Persei clusters (Messina 2001). In Figure 3 we plot the photometric amplitude (ΔV) vs. rotational period for the Post-TTSs and ZAMS stars. There is indeed an obvious indication that for stars with cool spots, the amplitude does not depend on the period within the range of periods considered.

Figure 4, plotting the rotational periods against the $(B-V)$ color indices, does not show any particular trend in the spectral range from G0 to K7. This confirms what was already found for young open clusters (e.g. Marilli et al. 1997).

Figure 5 plots the rotational periods against the H_α equivalent widths. The figure shows there is no correlation between EW(H_α) and $P_{\rm rot}$ for the WTTSs and Post-TTSs.

Table 2 Stars of Our Observational Sample

Objects (1)	RA (α2000) (2)	DEC (δ2000) (3)	SpT (4)	B (mag) (5)	V (mag) (6)	EW(Li) (mÅ) (7)	EW(Hα) (Å) (8)	Class. (9)	Ref. (10)
[LH98]37	03:03:57	37:39:05	K0IV		11.7	–240	1.01	WTTS	L
[LH98]53	03:16:43	19:23:04	G0	11.33	11.07	–230	0.76	WTTS	L
[LH98]56	03:19:07	39:34:10	K0V		11.6	–300	0.68	WTTS	L
[FS2003]0127	03:25:48	36:51:47	K0IV		13.1	–270	0.94	WTTS	L
[LH98]87	03:44:12	24:01:54	K0V	12.26	10.86	–210	1.44	WTTS	L
[LH98]98	03:46:29	24:26:05	K0V		11.4	–190	0.71	WTTS	L
HD 285281	04:00:31	19:35:20	K0	11.17	10.4	–258		WTTS	W
HD 285372	04:03:24	17:24:26	K3	12.77	11.73	–487		PTTS	W
HD 283323	04:05:12	26:32:44	K2	12.29	11.47	–210		WTTS	W
HD 26182	04:10:04	36:39:12	G0	9.99	9.47	–140	1.00	WTTS	L
HD 284503	04:30:49	21:14:10	G8	11.20	10.30	–141		WTTS	W
HD 285840	04:32:42	18:55:09	K1	10.78	10.8v	–253		WTTS	W
HD 283716	04:34:39	25:01:01	K0IV	11.10	10.33	–50		WTTS	O
HD 282346	04:39:31	34:07:46	K2	10.42	9.65	–240	0.96	WTTS	L
GSC 01292–00639	04:50:00	22:29:57	K1		11.08	–275		WTTS	W
TAP 57NW	04:56:02	30:21:03	K5	12.88	11.60	–580		WTTS	W
[LH98]179	05:15:49	18:44:20	G7IV	11.4	10.7			WTTS	L
HD 287927	05:30:48	02:59:34	G5	11.30	10.6	–200	0.5	WTTS	G
HD 244354	05:31:04	23:12:34	G0	9.78	9.18	–350	1.78	WTTS	L
[LH98]212	05:36:50	13:37:56	K0V	11.4	10.7	–360	1.63	WTTS	L
HD 245358	05:36:51	23:26:15	G0	9.48	8.8	–300	1.24	WTTS	L
HD 245567	05:37:18	13:34:52	G5	10.26	9.53	–250	0.80	WTTS	L

References to Table 1: L: Li & Hu (1998), W: Wichmann (1996), O: O'Neal et al. (1990) and G: Gregorio-Heterm et al. (1992)

To investigate possible effect of rotation on Lithium depletion, we plot in Figure 6 the Li I λ 6707 Å equivalent widths (EW(Li)) versus the rotational periods, $P_{\rm rot}$, for stars of our sample and the WTTSs of the Bouvier sample (1993). Only stars with spectral types between G0 and K7 are considered. There is a hint of a correlation between EW(Li) and $P_{\rm rot}$ in the sense that, on average, slow rotating WTTSs have larger lithium equivalent widths than fast rotating WTTSs (Bouvier et al. 1993). Furthermore, as the rotational period decreases to about three days and below, the Li depletion hastens: indicating that rapid rotation will lead to a faster lithium depletion in the WTTS phase. More observations on the rotational periods and equivalent widths of WTTSs would be useful for confirming this trend.

4 CONCLUSIONS

In summary, we have presented photometric monitoring of 22 X-ray emission WTTSs in the Taurus-Auriga star forming region. Periodic variation is confirmed in 12 of these WTTSs, and their rotational periods are determined to range from 0.287 to 9.12 days. Several models have been proposed in the last years for the evolution of the surface rotation rate for solar-type stars from their youngest T Tauri stage up to the age of ZAMS (e.g. Bouvier 1994; Keppens et al. 1995; Bouvier 1997 and Collier Cameron et al. 1995), and our result provides further evidence for the enhanced angular velocity of PMS stars as they approach the ZAMS predicted by models of evolution of the angular momentum of pre-main sequence stars.

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