

A young massive planet in a star-disk system

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Supplementary Tables

Supplementary Table 1:
Stellar parameters of TW Hya.

Parameter	Value	Unit	Reference
Spectral type	K7Ve		31
Distance	56 ± 7	pc	32
Mass	0.7 ± 0.1	M_{Sun}	33
Radius	0.9 ± 0.1	R_{Sun}	34
Effective temperature	4000 ± 150	K	34
Luminosity	0.20 ± 0.05	L_{Sun}	19
Age	8 – 10	Myr	34
Projected rotational velocity ($v \sin i$)	6.9 ± 1.0	km s^{-1}	this work
Disk inclination	7 ± 1	deg	12

TW Hya is one of the best-studied young stars in the solar neighbourhood. It is the nearest known classical T-Tauri star. With an age of only 8–10 Myr and a large and massive circumstellar disk, TW Hya is a very important target to study planet formation.

The projected rotational velocity $v \sin i$ was determined by using a cross-correlation technique³⁵ which has been adapted for FEROS³⁶ (see also Supplementary Methods).

Supplementary Table 2.
Radial velocity measurements of TW Hya

The time is given in Julian Date (JD) minus 2,450,000. Several details about the RV computations are given in Supplementary Methods.

Data set 1: February – March 2007

Time	RV (m s^{-1})	uncertainty (m s^{-1})
4158.87483	12631.981	35.91
4159.60602	12300.144	48.46
4160.72350	12203.973	42.05
4160.89623	12242.839	27.63
4161.54624	12544.027	43.39
4161.64004	12573.295	36.15
4161.94028	12607.145	40.96
4162.56455	12519.773	35.47
4162.78902	12455.979	30.24
4162.89244	12405.776	44.10
4163.60348	12282.121	36.62
4163.80129	12251.532	34.28
4163.85063	12169.278	42.16
4164.60323	12383.956	41.92
4164.78188	12437.942	39.40
4164.82594	12404.094	47.11

4165.61156	12511.398	24.97
4165.76160	12566.662	30.79
4165.83776	12589.607	29.65
4167.53473	12195.195	48.26
4167.65984	12279.790	32.04
4167.78416	12321.428	34.14
4167.85679	12354.363	31.03
4168.53015	12476.821	35.79
4168.65793	12550.961	27.65
4168.78395	12654.375	25.01
4169.53763	12543.738	39.68
4169.65967	12590.403	31.20
4169.79057	12487.067	42.40
4170.74475	12231.969	39.33
4171.76412	12365.224	39.40
4171.87613	12484.874	45.20
4172.58888	12599.744	28.19

Data set 2: April – May 2007

Time	RV (m s^{-1})	uncertainty (m s^{-1})
4215.66141	12689.625	59.46
4215.71105	12646.549	44.51
4216.48965	12252.076	44.74
4216.54997	12315.095	42.14
4216.67976	12314.656	27.71
4217.48949	12172.139	33.37
4217.63023	12197.675	34.52
4217.72173	12304.251	60.64
4219.68871	12425.431	63.86
4220.47028	12152.066	44.26
4220.72009	12169.643	77.35
4221.47858	12292.914	50.25
4221.72683	12424.398	81.77
4222.46130	12545.975	38.99
4222.59657	12624.963	32.15
4222.69044	12584.255	26.13
4223.47254	12464.632	70.71
4223.58873	12338.258	42.38
4223.69694	12413.202	38.29
4224.47494	12370.189	38.17
4224.57008	12393.263	39.01
4224.66443	12230.458	57.38
4225.48801	12428.662	29.76
4225.58674	12595.261	37.41
4225.68763	12616.106	30.65
4227.74662	12273.699	52.37
4228.48806	12379.933	42.94
4228.60377	12350.142	40.56
4228.68582	12407.201	21.79
4230.46058	12663.709	32.14
4231.46572	12158.115	34.68
4232.45578	12420.629	26.59
4233.45815	12722.004	52.23

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Supplementary Table 3:
Rotation period of TW Hya.

Data set	Published period (days)	Our analysis (days)	False Alarm Probabilities
(24)	1.28	1.28	$2.5 \cdot 10^{-2}$
(24) with data from (31)	1.83	1.74 ... 1.98	$5.2 \cdot 10^{-5}$
(24) with data from (37)	1.66	1.98 ... 2.38	$3.2 \cdot 10^{-5}$
(25)	2.16	2.33 ... 2.65	$1.1 \cdot 10^{-2}$
		1.60 ... 1.74	$1.3 \cdot 10^{-2}$
		1.80 ... 2.20	$4.5 \cdot 10^{-3}$

Several authors have tried to derive the stellar rotation period of TW Hya by using photometric observations and interpreting the observed variability as rotational modulation due activity-related surface features like, e.g., star spots. Photometric variations of TW Hya have been observed for several years^{24,31,37} and were summarized in a catalogue³⁸. (Ref 24) derived a rotation period of 1.28 days. By reanalyzing the data from (Ref 31) and (Ref 37) they found periods of $P=1.83$ days and $P=1.66$ days.

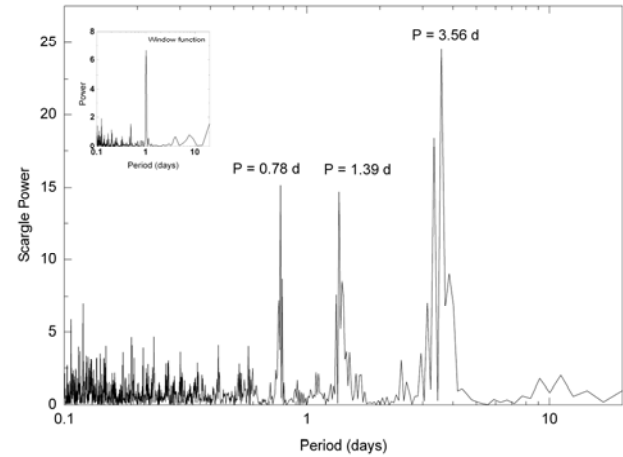
We have also reanalyzed all data sets from this catalogue³⁸. By using the boot-strap randomization method and the Lomb-Scargle periodogram, we find that the signals in the interval 1.74...2.38 days have the lowest FAPs. Contrary to (Ref 24), we found that the signal at $P=1.28$ days is not significant. Another long-term photometric survey²⁵ reported a period of 2.16 days. When reanalyzed these data, we also found significant signals within 1.80...2.20 days. The periodogram signals with the lowest FAP, which are candidates for stellar rotation period, are marked with bold face in Supplementary Table 3.

Our analysis shows that, when the widths of the periodogram signals are taken into account, there is no discrepancy between the two long-term photometric monitoring surveys of TW Hya. All photometric data point towards a stellar rotation period of $P = 2.1 \pm 0.5$ days. Within the uncertainty interval this result is in good agreement with our spectroscopic analysis (Supplementary Figure 3).

We also note that there are concerns about differential rotation effect in the case of TW Hya. However, observations³⁹ and theoretical^{40,41} studies have shown that this effect is negligible in T-Tauri stars. A possible explanation for this fact is that T-Tauri stars seem to undergo α^2 dynamo instead of $\alpha\Omega$ -dynamo like the Sun^{40,41}. So far, there is only one T-Tauri star that has been detected to show a differential rotation effect⁴². This phenomenon was found among a sample of about 1000 T-Tauri stars. Based on the results of observations and theoretical work mentioned above, we concluded that differential rotation is unlikely to be the reason for the large period uncertainties in TW Hya. The large uncertainties are more likely due to the fact that unstable, short-lived activity features lead to irregular phase shifts in the rotational modulation and thus partially mask the stellar rotation

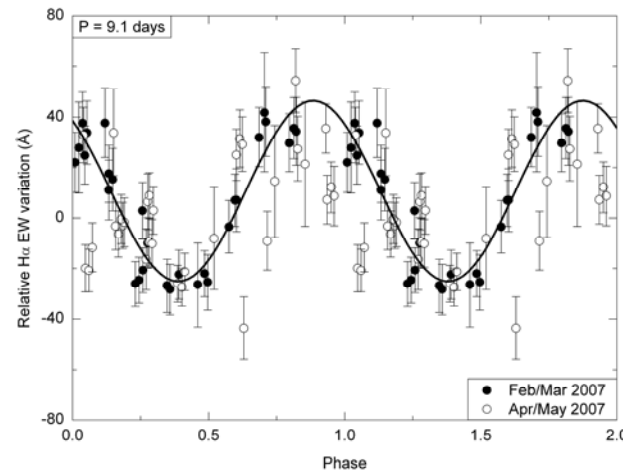
Supplementary Figures

Supplementary Figure 1.
Lomb-Scargle Periodogram of RV variation.

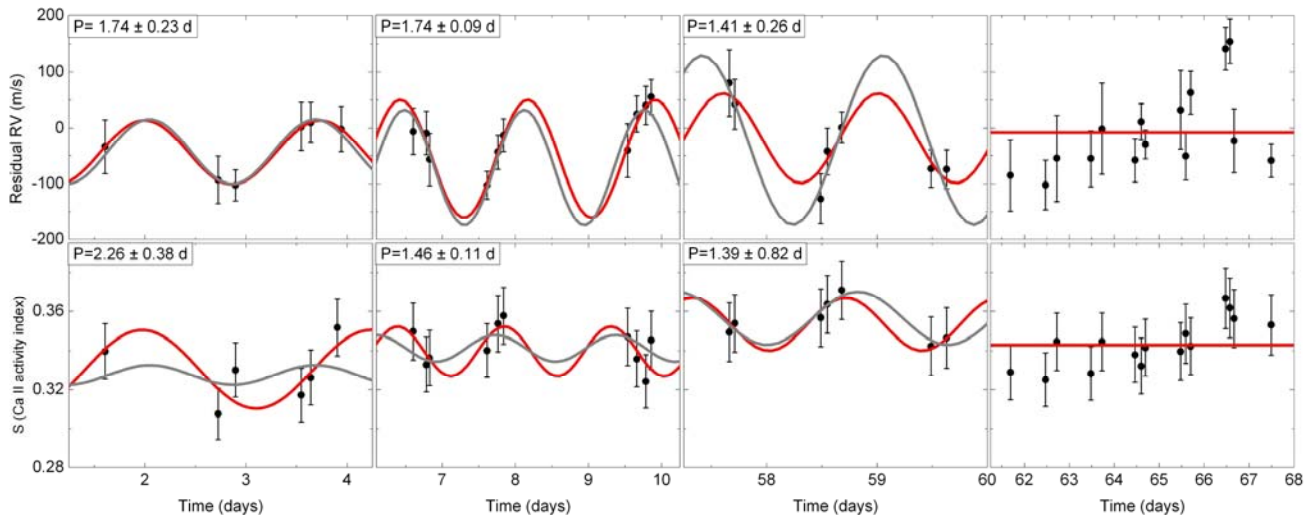


Similar to the sine-fitting periodogram given in Figure 3, the LS-periodogram⁴³ of the RV variation shows three distinct signals. The signal at $P=3.56$ days has the highest significance (the lowest FAP), whereas the other two signals turn out to be aliases of the 3.56-day signal. These signals disappear in the residual RVs when the 3.56-day signal is subtracted.

Supplementary Figure 2.
Variation of H α emission line equivalent width.



The figure shows the phase-folded (with $P=9.05$ d) variation of the H-alpha equivalent width in the spectra of TW Hya, obtained from all data sets. The source of this periodic variability remains unclear, but we assume that it is related to a phenomenon in the disk. The corresponding Keplerian radius of ≈ 0.07 AU is close to the inner edge of the disk.



Supplementary Figure 3. Signatures of stellar activity in four time windows.

The figure shows variations of two stellar activity indicators in four time intervals. The upper panel shows the residual RV variation after subtracting the regular 3.56-day period. The lower panel shows, for the same nights, the variation of the Ca II ($\lambda 8662$) activity index. While the first three windows show periodic variations with changing amplitude, there is no significant periodic variability observed in the last time window. The reason might simply be that activity-related surface features were not strong enough during these nights to cause a significant rotational modulation.

The red curves show χ^2 -optimized sinusoidal fits to the data points. The individual fitted periods are noted in the plots. All individual periods agree within the error margins and no period longer than 2.3 days was found. Therefore we attribute the weighted mean value to the stellar rotation period, i.e. $P_{\text{rot}} = 1.6 \pm 0.3$ days. The grey curves show the fitted curves with the period fixed to the (weighted) mean period of all sub-sets with periodic signals ($P = 1.6$ day).

From the projected rotational velocity of $v \sin i = 6.9 \pm 1.0 \text{ km s}^{-1}$ and the stellar radius of $0.9 \pm 0.1 R_{\text{Sun}}$ (Supplementary Table 1) we derived an inclination angle of the stellar rotation axis of $i = 14^\circ \pm 4^\circ$. If the rotation period of the star would be 3.56 days, one would either need a stellar radius of $2.0 R_{\text{Sun}}$ for $i = 14^\circ$, or $i = 32^\circ$ for $R = 0.9 R_{\text{Sun}}$. Both combinations would contradict earlier observational results.

Supplementary Discussion

Disk inclination and planetary mass

The determination of the true mass of the planet TW Hya b depends strongly on the adopted inclination of the orbit. We assume that the planet orbits the star in the plane of the disk. The inclination of the disk has been derived from kinematic modelling of interferometric sub-mm CO line emission channel maps ($7^\circ \pm 1^\circ$)¹². This method does not depend on geometrical assumptions, but uses the kinematic signatures of the disk gas, which are described by Kepler's third law (deviations due to pressure gradients are negligible). The projected radial velocity field of the gas depends strongly on the inclination angle, in particular at low inclinations. The uncertainty of the fit result mainly depends on the angular resolution and signal to noise of the data. Therefore, the systematic uncertainties are small and the method is robust and often used. It has been applied by several other authors to measure the disk inclinations of many well known T-Tauri stars, e.g., DM Tau⁴⁴, AB Aurigae⁴⁵ and others (see, e.g., Table 4 column 5 in Ref 44). Uncertainties of $\pm 1^\circ \dots 2^\circ$ are not unusual and have been achieved for various other T Tauri star disks.

There is only one other quantitative estimate of TW Hya's disk inclination, based on HST NIR observations of asymmetries in the scattered light images from the disk ($i = 15^\circ \pm 7^\circ$)⁴⁶. However, recent studies have shown that deriving disk inclinations from scattered light images depends on too many and too idealistic model assumptions (e.g., a perfectly circular disk geometry) and is not reliable at all. Therefore we do not consider this value an equivalent representation of the true disk inclination. Using a weighted mean of the two inclination measurements would neither reflect these systematic uncertainties, nor would it change the result.

Therefore, we concluded that the value $7^\circ \pm 1^\circ$ is currently the only reliable measurement of the disk inclination in TW Hya, and we use it as it stands.

With a mass of $9.8 M_{\text{Jup}}$ the planet TW Hya b is another example of a massive close-in planet, as detected recently with the transit method^{47,48}. These detections show that TW Hya is not unique, and super massive planets on close-in orbits do exist. Perhaps several other close-in giant planets with currently unknown $\sin i$ values belong to this class.

Supplementary Note

Radial velocity planet searches in T-Tauri stars

T-Tauri stars are known to have high levels of stellar activity and to be challenging targets for planet searches with the RV technique. The applicability of this method is therefore limited to massive giant planets. Massive planets still can be detected because their signature in the RV variation is usually higher than that of the stellar activity.

Due to this difficulty, T-Tauri stars were not included in most of the large RV surveys. These surveys are usually biased by the goal to detect many and the smallest planets and perhaps “earth-like” ones, mostly around quiet solar-like stars. Such planets, of course, cause tiny RV variations of, e.g. less than 1 m s^{-1} . Such a small RV variation will be buried in the stellar activity noise of T-Tauri stars. It is therefore usually impossible to detect low-mass planets around T-Tauri stars with the RV technique.

Recent results of RV planet searches around other types of stars, especially active stars, showed that, if the planetary companions are massive and produce large and regular RV variations, the stellar activity can be distinguished from the signature of planetary companions. E.g., starspots either disappear or change their characteristics after a few rotation cycles. This irregularity will be also observed in the corresponding RV and line profile variation. Also non-radial pulsations (NRP) will leave an imprint on the line profile variation. With the exception of M-giants, NRP have different timescales, which are mostly much shorter (minutes to hours) than those of RV variations due to planetary companions.

Recently, some authors^{49,50} also showed that the RV method can be successfully be applied to search for planets around T-Tauri stars, if the stellar activity can be discerned from the signature of the companion. Based on the results of RV monitoring of young stars during 4 years (2003-2007) of observations we are also able to characterize the stellar activity of the majority of the targets in our sample. With these extensions the RV method will still provide important new contributions for planet detections, in particular for young stars.

Supplementary Methods

Supplementary method 1: RV computations

To measure the stellar radial velocity, the spectrum of TW Hya is cross-correlated with a numerical template (mask) of a K-type star. A description of this technique for RV planet searches was given in (Ref 51). When we started in 1999 to use FEROS for planet searches around another type of active stars, i.e., G and K giants, we have developed data reduction procedures and RV computation tool for FEROS spectra including building the calibration template, and checked the instrumental drift effects. The procedures were described in (Ref 21,52).

In the RV computations the uncertainties are given by the standard errors of the mean RV (obtained from individual RVs of the available 22 echelle orders). Here we do not use quadratic summation of photon error and instrument long-term stability as done by authors in RV surveys of quiet solar-like stars. The typical photon errors of FEROS are only $2\text{--}3 \text{ m s}^{-1}$ and the instrumental long-term accuracy is better than 10 m s^{-1} . Using these values as RV uncertainties will underestimate the RV errors due to stellar activity and could lead to wrong interpretations.

All of the procedures have been applied successfully to active stars⁵³, both to search planets and characterize stellar activity⁵⁴. Since 2003 this technique has been applied to young stars⁵⁵.

Supplementary method 2: Computations of projected rotational velocities $v \sin i$

The determination of $v \sin i$ has been done by using a cross-correlation method³⁵. This technique has been applied for many stars, in particular those in the planet search RV surveys. It was mentioned in (Ref 35) that the cross-correlation method can achieve an accuracy of 1 km s^{-1} in the $v \sin i$ determination for spectrographs with moderate resolution. The technique has been adopted for FEROS by measuring the instrumental calibration parameters³⁶. The results are in good agreement with those of other methods⁵⁶.

Our $v \sin i$ for TW Hya is given in Supplementary Table 1. The uncertainty of 1 km s^{-1} for FEROS ($R=48000$) is not an underestimation. Other spectrographs with similar resolutions achieved a similar accuracy in $v \sin i$ with this cross-correlation method⁵⁷. The formal description of the error analysis in $v \sin i$ for FEROS spectra is given in (Ref 36). From the equations given in this paper, we calculated a formal error of 0.53 km s^{-1} for the $v \sin i$ of TW Hya. By considering other unknown error sources, we give 1 km s^{-1} as the uncertainty of the projected rotational velocity.

Supplementary method 3: Line-depth ratio as a stellar activity indicator

In addition to the well known stellar activity indicators (Ca II, H α), the variation of the effective temperature can be used to trace the stellar activity (e.g., starspots). By using the line-depth ratio⁵⁸ the starspot temperature and effective temperature variation can be measured. This technique works well for young solar-like stars⁵⁹. Thus, it can be used as a cross-check with other stellar activity indicators.

We have already used the line-depth ratio analysis to check the effective temperature variation as an additional tool, complementary to the standard activity indicators and bisector analysis¹⁰. In case of TW Hya, we found a periodicity in the effective temperature variation of $P \sim 1.8$ days in several short time intervals. This result is in good agreement with the period of $P = 1.6 \pm 0.3$ days, presented Supplementary Figure 3.

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