Photometric Variability Properties of 21 T Tauri and Related Stars From AAVSO Visual Observations

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Abstract T Tauri variables are sun-like stars in various stages of their birth. We have analyzed long-term AAVSO visual observations of 21 T Tauri and related stars, using Fourier and self-correlation techniques. This follows our previous study of eleven such stars in *JAAVSO* **35**, 290 (2006). Only a few of the variables showed periodic behavior, but self-correlation analysis makes it possible to construct a "variability profile"—amount of variability versus time scale—for *all* the stars, not just the periodic ones. For some of the periodic variables, we have studied the long-term behavior of the periods and amplitudes: T Cha and HT Lup appear to be rotating variables with stable periods less than 10 days; RU Lup, UX Ori, and TU Phe appear to show transient cycles of typically 50–500 days, probably arising in the accretion disc. R CrA has a stable 66-day period, which would be unusually long for a rotation period; its cause is not clear. We also discuss interesting but spurious low-amplitude one-year and one-month periodicities which occur in a few of the stars. Finally: we comment on the star AQ Dra, an RR Lyrae star, originally classified as a T Tauri star with a 5.5-day period.

1. Introduction

T Tauri stars are sun-like stars in various stages of birth, with or without an accretion disc still present. Although they are all photometrically variable, they are defined *spectroscopically*, on the basis of various emission lines and lithium lines being present in the spectrum. The types and causes of photometric variability include: (i) strict periodicity (periods 0.5 to several days) due to rotation of a spotted star; (ii) rapid flickering connected with accretion onto the star; (iii) slow variations due to variations in the rate of accretion; (iv) quasiperiodic variations (periods 10s to 1000s of days), possibly due to effects of a companion, or inhomogeneities or other processes in the accretion disc. Herbst *et al.* (1994) have classified T Tauri stars into CTTS: classical T Tauri stars, with spectroscopically-visible accretion discs; WTTS: weak-lined T Tauri stars, without visible accretion discs; GTTS: G-type T Tauri stars; HAEBE: Herbig Ae/Be stars, more massive counterparts of T Tauri stars; and FUORs: FU Orionis stars, with long-lasting photometric outbursts.

There is an extensive literature on long-term CCD photometry of T Tauri stars, especially by Herbst (Wesleyan University) and his students and other collaborators (e.g. Herbst *et al.* (1994); Grankin *et al.* (2007); Grankin *et al.* (2008); Artemenko *et al.* (2010)). AAVSO visual observers have also measured T Tauri stars systematically for over three decades but, as explained by Percy and Palaniappan (2006), the data were only recently validated. Percy and Palaniappan (2006) analyzed the first few stars that were validated, as a pilot project, and showed that the visual data have definite scientific value. In the present paper, we report on the analysis of twenty-two more stars. We have also made a study of the long-term behavior of the period and amplitude of some of the periodic variables, especially those with unusually long periods.

2. Data and analysis

Visual measurements of the stars listed in Table 1 were made by AAVSO observers, validated by AAVSO staff, and made available in the AAVSO International Database. The stars in our sample are those which AAVSO staff considered to be promising. A preliminary pilot project analyzed a few stars which were classified as T Tauri in the AAVSO Validation File, and for which there were data available on the AAVSO website. Following Percy and Palaniappan (2006), the stars were analyzed by two time-series techniques: self-correlation analysis (Percy and Mohammed 2004, and references therein) and Fourier analysis as implemented in PERIOD04 (Lenz and Breger 2005). The Fourier analysis function in PERIOD04 is based on a discrete Fourier transform algorithm. It can plot the Fourier spectrum as power or amplitude; we chose to use the latter. There are many other useful functions built into this package.

The datasets were typically three decades long, and contained several hundred or more observations. Light curves of the stars in Table 1 can be inspected by using the light curve generator function on the AAVSO website: http://www.aavso.org/lcg

Self-correlation analysis was originally developed to analyze variable stars which were somewhat irregular and/or which had seasonal gaps which were of the same order of length as the period. Even if the variability is not periodic, the method can still provide a “profile” of the variability—the average variability as a function of time scale.

3. Results

The results are summarized in Table 1, which lists the star, the Herbst type (if known), the average observational error as determined from the intercept on the vertical axis of the self-correlation diagram, the half-range of variability as determined from the value of Δmag at large Δt in the self-correlation diagram, the period if any, the dominant time scales of variability (the time scales at which Δmag is increasing in the self-correlation diagram), and whether or not there is any evidence for periodicity on a time scale of one year (Y) or one month (M). Note that the Δmag, at any Δt, is approximately equal to half the peak-to-peak range; the exact relationship will depend on the exact form of the variation.

4. Spurious periods of one year and one month

In a recent analysis of visual observations of irregular pulsating red giants (Percy *et al.* 2009), we had noticed the presence of low-amplitude variability, with a period of one year, in some stars. This period is spurious, and is due to a physiological process—the Ceraski effect—which is due to the changing orientation of the star field, relative to the observer's eyes, at different times of year. In the present study, we have noticed several stars which have low-amplitude periods close to *one sidereal month*, a frequency of 0.0366 cycle/day. These are noted in Table 1. Figure 1 shows one example. Since observers do not usually observe a variable star when the moon is nearby in the sky, we hypothesize that the monthly periods are also spurious, and due to the changing orientation of the star field, observed at different times of the night at different times of the month.

5. True periods and profiles

For a few stars in Table 1, periods are given. Some are less than 10 days, and some are considerably more. See Paper I for examples of self-correlation diagrams and Fourier spectra of periodic variables. For the stars which do not have periods, and they are the majority, it is still possible to use the self-correlation diagram to show the "profile" of the variability—the amount of variability as a function of time. Figure 2 shows an example, T Cha. The diagram rises smoothly from the intercept, which is a measure of the average observational error plus any very rapid variability. It then reaches a plateau at Δt about 30 days, indicating that most of the variability takes place on time scales of 0 to 30 days.

6. Amplitude variations in periodic stars

Most periodic T Tauri stars have periods of 0.5 to 5 days. These are the stars' rotation periods, and the stars vary in brightness because they have cool starspots. The amplitude of variability depends on the size, contrast, and distribution of the starspots. Stelzer *et al.* (2003) carried out an intensive photometric study of V410 Tau (period 1.87 days), and showed that the amplitude rose and fell on a time scale of 3,000 days. Percy *et al.* (2010) analyzed CCD observations of several other short-period T Tauri stars, and found that the amplitudes also varied on time scales of 1,500 to 3,500 days.

In the course of our analysis of long-term visual and CCD observations of T Tauri stars, we have encountered several stars with periods *greater* than 10 days, or even greater than 100 days. While these could be unusually-slow rotators, it is possible that the periodic variability has some other cause. We were therefore curious to know whether and how the amplitudes of these stars varied with time.

6.1. R CrA

R CrA has a period of 66 days (Percy and Palaniappan 2006), which is significantly longer than for T Tauri stars that are rotational variables. We grouped the observations into sets of about a thousand days, because the lengths of individual seasons were not much longer than the period. We used Fourier and self-correlation techniques to determine the period and amplitude. The amplitude results are shown in Figure 3. The period was constant from season to season, within its error. The result was confirmed through wavelet analysis, using the WWZ package on the AAVSO website. Detailed information about WWZ can be found there. The amplitude behavior, in both Figure 3 and the wavelet analysis, was less clear, mostly because of the effect of the seasonal gaps. There are variations in amplitude which are marginally convincing, including a larger amplitude around JD 2450000–2455000. The change in amplitude appears significant in all three forms of analysis.

6.2. RU Lup

RU Lup has an average period of 230 days but, when we analyzed the data on a season-to-season basis, we found that its behavior was much more complicated. Because of the length of the period, we divided the data into bins of approximately a thousand days, and used Fourier and self-correlation analysis to determine the period and amplitude. We found that, in some intervals, there was no significant period but, in others, there was a significant period ranging from 90 to 350 days, with an amplitude of up to 0.5 magnitude! Self-correlation diagrams for four intervals are shown in Figure 4. This result was confirmed through wavelet analysis; there was no frequency at which there was a *sustained* signal.

The AAVSO visual light curve of RU Lup shows a discontinuity of about 0.5 magnitude at JD 2444200. AAVSO Headquarters staff are not aware of any possible spurious reason for this discontinuity, such as changes to the charts or comparison stars, so we must assume that the discontinuity is real (Templeton 2010).

6.3. TU Phe

The best period for this star, based on the entire dataset, was about 200 days, but it appears that the analysis was dominated by an interval—JD 2451000–

2452000—when there was a large-amplitude signal of about this length. From JD 2450000 to 2451000, there was a weak signal at about 100 days, and from JD 2452000 to 2454000 there was a weak signal at about 500 days. Wavelet analysis confirmed the presence of random transient signals at periods between 60 and 500 days.

6.4. UX Ori

The situation was very similar to that with TU Phe: the 200-day period in the entire dataset was dominated by the interval JD 2452000–2453000, when there was a very strong (amplitude 0.5 magnitude) signal with a period of 210 days. In the intervals before and after this, there was no strong signal at this or any other period. These results are confirmed by the wavelet analysis.

7. Discussion and conclusions

7.1. Periods and variability profiles

Three stars in Table 1 have periods of less than 10 days, and are almost certainly rotational variables; the period is the rotation period.

Three stars in Table 1 have periods of about 200 days, as derived from the whole dataset. When the datasets are subdivided into different intervals, however, it turns out that the periods are unstable and transient. They may arise from some transient phenomenon in the accretion disc, at a place where the orbital period takes these period values.

R CrA (Percy and Palaniappan 2006) is an interesting case. When the data are analyzed on a season-to-season basis, the 66-day period is stable. Perhaps the star is a rotational variable with an unusually long rotation period and starspots that do not change significantly over many years. Or perhaps the 66-day period is caused by some dynamical effect such as the presence of a companion star or planet. In fact, Kraus *et al.* (2009) present evidence for a puffed-up inner rim of the accretion disc, at about 0.4 AU from the star, where the orbital period would be close to 66 days.

For all of the stars, the self-correlation diagram provides a “profile” of the variability, including the range of time scales over which variability takes place. These are given in column 6 of Table 1. They are generally 0–100 days, although some stars vary on longer time scales also, and some only on shorter time scales.

7.2. Spurious periods

The spurious one-year period appears to be due to a known effect—the Ceraski effect; see Percy *et al.* 2009 for a discussion. The spurious one-month period may arise from the same effect if the stars are observed systematically at different times of night at different times of the sidereal month.

7.3. Amplitude variations

The long period stars UX Ori, TU Phe, and especially RU Lup seem to be dominated by the effect of intervals when there is a large-amplitude cyclic variation. In other intervals, there are either other cycle lengths present, or no obvious cyclic variability at all. This suggests that the variability arises from transient phenomena in the disc, with a time scale determined by the orbital period at a specific place in the disc.

RU Lup is a particularly interesting star. Herczeg *et al.* (2005) have reviewed its properties. Much of its light comes from accretion energy, so some photometric variability may be due to variability in the accretion rate. The underlying star is slightly cooler, less massive, and less luminous than the sun, but is slightly larger; it is still contracting to the main sequence. The distance is about 140 pc, and the age is 2–3 Myr. Claims of a 3.7- (or 5.6-) day photometric period have not been confirmed. The accretion disc is probably seen nearly (but not exactly) edge-on. Takami *et al.* (2001) have used spectro-astrometric observations to study gas motions near the star. They see evidence of a bipolar outflow, magnetically driven, and also a wind emanating from the disc. The infrared spectral energy distribution is consistent with the presence of a gap in the disc, with an outer radius of 3–4 AU. This gap could be induced by an unseen companion such as a young planet.

7.4. The interesting case of AQ Dra

AQ Dra, an apparent T Tauri star, showed a stable 5.5-day period, and amplitude variations that were typical of those of other short-period T Tauri stars, for which the periodic variability is assumed to be due to rotation of a spotted star. The amplitude varied on a time scale of thousands of days, indicating that the inhomogeneities (spots) on the star varied on that time scale.

The referee, however, pointed out an interesting problem with this star. In the AAVSO Validation File, this star was listed as a type IS variable (rapid irregular variable) with a period of 5.5 days and an F2 spectral type. In the *General Catalogue of Variable Stars* (via SIMBAD), it is listed as ISB (rapid irregular variable of mid to late type), but claimed to be an RR Lyrae star! RR Lyrae stars have periods less than a day. Both Fourier and self-correlation analysis *seemed* to show that the period of AQ Dra is was 5.474 days, with variable amplitude. George Herbig (1960), a pioneering expert on T Tauri and related stars, had assigned this star to the RW Aur type, which is another name for IS type variables. In classifying its spectrum as F2, he notes that "absorption Hβ is absent, as if filled in by emission." This would also be evidence for its IS or T Tauri nature.

AAVSO Science Director Dr. Matthew Templeton, however, pointed out to us that this star was *definitely* an RR Lyrae star! NSVS (Northern Sky Variability Survey) data clearly showed this to be the case, and the star is listed as such in the most recent catalogues of RR Lyrae stars, having a period of 0.55025 day. It is instructive, therefore, to see how we mis-analyzed the AAVSO data.

T Tauri stars may have periods as short as a few hours but, since the AAVSO visual observations were mostly made once a night, we did not look for periods shorter than about 2 days, since it would be inappropriate to do so. However, if a star with a period of 0.55025 day is sampled once a night, at approximately the same time, it will *appear* to have a period of about 5.5 days. This is a classic example of an "alias period" (e.g. Fullerton 1986, Figure 2). When we re-examined the AAVSO data with both Fourier and self-correlation analysis, looking for periods less than a day, we indeed found the 0.55025-day period, though the data were not well-suited to this purpose. In future, we will analyze the AAVSO visual data on AQ Dra in a way that is appropriate for an RR Lyrae star. The variable amplitude may be due to a Blazhko effect.

7.5. The value of visual observations of T Tauri stars

Visual observations are capable of revealing periodic variability, both real and spurious, even though the precision of individual observations is low; that is the power of time-series analysis, especially when applied to datasets that are large and long. Even for the stars that are not periodic, the observations provide a "profile" of the variability which may, with sufficient analysis and interpretation, provide further information about the stars. The long datasets provide information on the *long-term* changes in period and amplitude which could not be determined from shorter datasets. AAVSO visual data *definitely* have value!

8. Acknowledgements

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Table 1. Time–Series analysis of T Tauri stars and related objects.

Star	*Type*	*Error*	*Half-Range*	*P (d)*	*Timescales (d)*	*Comments*
SU Aur	GTTS	0.16	0.25	—	1–800	—
YZ Cep	—	0.23	0.26	—	1–100	Y
DI Cep	GTTS	0.21	0.28	—	1–50	—
T Cha	HAEBE	0.25	1.5!	3.3	1–20	M, no Y
T CrA	HAEBE	0.22	0.5:	—	1–1000	M?, Y?
AQ Dra	see text	0.2:	0.5	0.55	—	no M or Y
RU Lup	CTTS	0.24	0.4	230	1–100	Y, M
GQ Lup	—	0.33	0.55	—	1–100	Y
HT Lup	WTTS	0.08	0.23	6.25	1–100	Y
T Ori	HAEBE	0.34	0.6	—	1–40	—
RY Ori	—	0.35	0.7	—	1–1000	—
UX Ori	HAEBE	0.30	0.0	200	1–100	no M or Y
BF Ori	HAEBE	0.28	0.7	6:	1–30	Y
BN Ori	HAEBE	0.18	0.30	—	1–150	—
V350 Ori	—	0.21	0.5	—	1–10, 10–100	Y, no M
TU Phe	—	0.10:	0.25	200	—	—
RZ Psc	—	0.15	0.20	—	1–2000	no M
NX Pup	—	0.15	0.38:	—	1–70	Y?
AK Sco	HAEBE	0.16	0.24	—	1–100	Y
V856 Sco	—	0.15:	0.5	—	1–100	no M or Y
RR Tau	HAEBE	0.27	0.7	—	1–20	Y, no M
RY Tau	GTTS	0.22	0.5:	—	1–150	Y

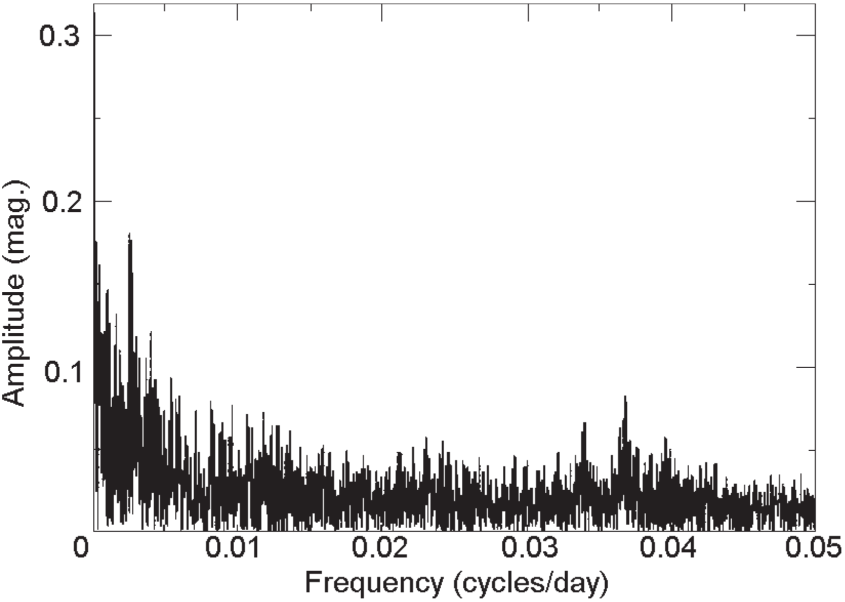

Figure 1. Fourier spectrum (PERIOD04) for RY Tau, showing spurious peaks at frequencies of 0.036 (one month) and 0.00274 (one year) cycle per day. See text for a discussion of possible origins of these features.

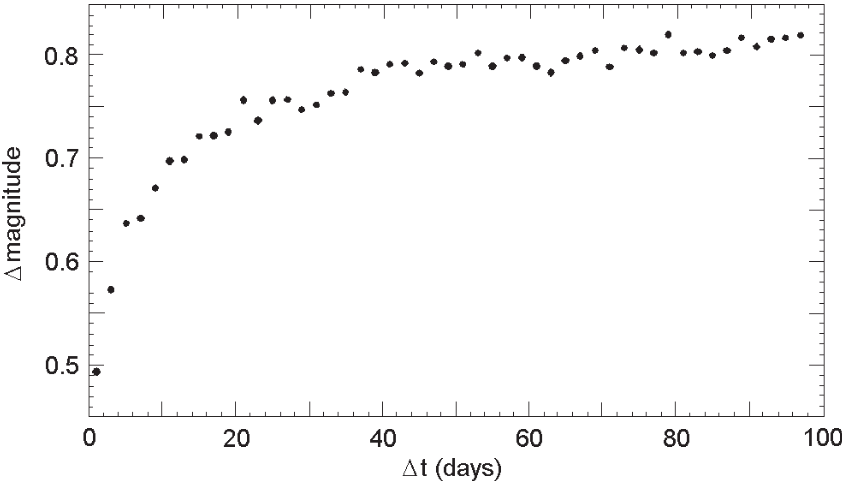

Figure 2. Self-correlation diagram for T Cha. The diagram rises smoothly from the intercept on the vertical axis to a plateau. There are no repeating minima which would indicate that a period was present, though a low-amplitude 3.3-day period is clearly visible in the Fourier spectrum. However, the diagram does provide a "profile" of the variability, indicating that most of the variability occurs on time scales of 0 to 30 days.

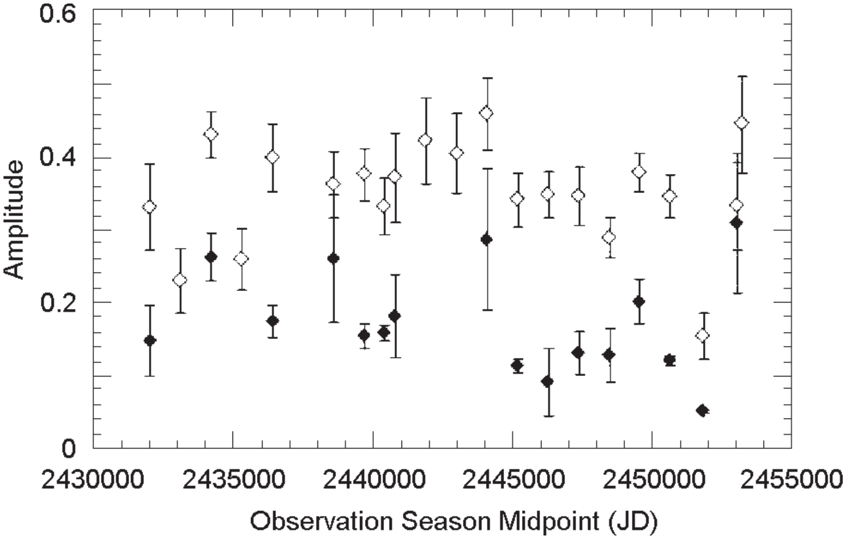

Figure 3. The amplitude variation of R CrA over several seasons; open diamonds are from PERIOD04, filled diamonds are from self-correlation. The former are higher than the latter because they include a contribution from noise. See section 6.1.

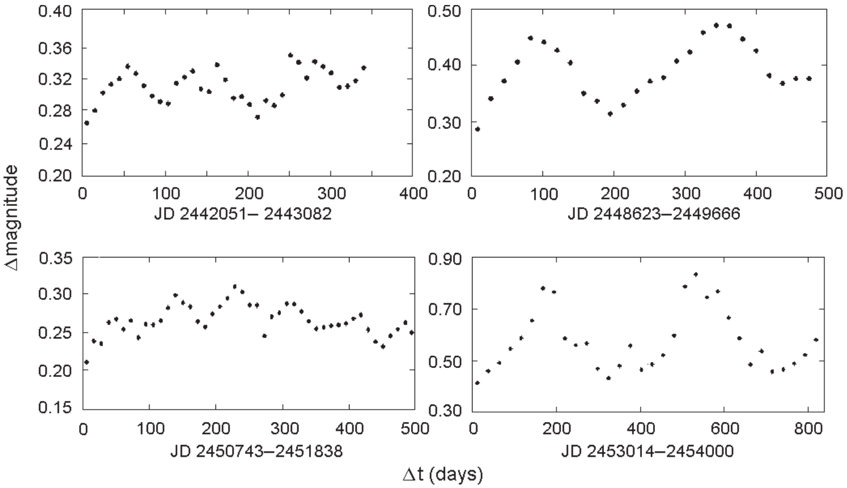

Figure 4. The self-correlation diagrams for RU Lupi over several intervals of time. The period is variable: about 105 days (upper left), 225 days (upper right), 90 days (lower left), and 360 days (lower right).