PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **118**: 1390–1395, 2006 October

Self-Correlation Analysis of the Photometric Variability of T Tauri Stars

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Received 2006 June 23; accepted 2006 August 21; published 2006 October 12

ABSTRACT. T Tauri stars are variable stars that are in an early phase of evolution, in which accretion and contraction to the main sequence are still taking place. Their photometric variability is complex; it takes place on a variety of timescales, due to a variety of physical processes. Periodic variability occurs due to rotation and the presence of cool or hot spots on the star. It may also occur due to periodic obscuration of the star by inhomogeneities in the still present accretion disk. But the periodicity may be masked by other forms of variability, or by time variation in the cool or hot spots, or the obscuring inhomogeneities. For other types of variable stars, self-correlation has proven to be a useful adjunct to Fourier analysis for studying semiregular variability; it determines the cycle-to-cycle behavior of the star, averaged over all the data. We have therefore used it to investigate the photometric variability of about 30 T Tauri stars using existing data. It has provided useful information about periods and their coherence, about the amplitude of the periodic variation, or its upper limit, and about the "profile" of the amplitude-timescale behavior. In most cases, it has confirmed periods previously determined by Fourier analysis, but in some cases it has suggested that the previously determined period is spurious.

1. INTRODUCTION

T Tauri stars, first studied by A. Joy (1945), are Sun-like stars in the final stages of birth, in which accretion and contraction to the main sequence are still taking place. The prototype, T Tauri, is an irregular variable star within a dark cloud in the constellation Taurus. However, classical T Tauri stars are defined spectroscopically, on the basis of (1) (usually) cool spectrum, (2) excess continuum emission, (3) strong emission in selected lines, and (4) strong lithium lines. The current model of a classical T Tauri star is of a newly formed, rapidly rotating Sun-like star with a significant magnetic field that is still surrounded by an accretion disk. The rotation produces the magnetic field, which together with the accretion produces various forms of stellar activity, including hot and cool starspots. The magnetic field is also linked to the accretion disk; this may channel accreting matter onto hot spots on the photosphere that corotate with the star. The rotation of the star initially increases due to conservation of angular momentum as the star contracts, but it may also be braked by the accretion disk. After the accretion disk disappears, the rotation is slowly braked as a result of the stellar wind, which flows outward along the corotating magnetic field lines.

There are separate subtypes of T Tauri stars and their relatives: (1) classical T Tauri stars (CTTSs) have evidence of an accretion disk, (2) weak-lined, or "naked," T Tauri stars (WTTSs) have little or no spectroscopically visible accretion disk, although there may be a cool outer "debris disk" still present, (3) Herbig Ae/Be (HAeBe) stars are higher mass analogs of T Tauri stars, and (4) FU Orionis (FUOR) stars are T Tauri stars that exhibit brightenings of several magnitudes, followed by slow declines. Herbst et al. (1994) also include early-type T Tauri stars (ETTSs), which partly overlap with HAeBe stars, and G-type T Tauri stars (GTTSs), whose variability is somewhat different from that of CTTSs. The *General Catalogue of Variable Stars* (Kholopov et al. 1985) has a system of classification of T Tauri stars that seems to have little or no physical significance.

T Tauri stars vary in brightness on timescales of minutes to years, with ranges of up to several magnitudes (e.g., Herbst 2001). An important criterion for the classification of variability is the presence of "periodicity." Periodicity was suspected in T Cha in the 1950s, but it was three decades before periods were confirmed in large samples of T Tauri stars (e.g., Bouvier et al. 1993). Periodicity is difficult to establish in T Tauri stars because of their complexity (Herbst & Wittenmyer 1996); to quote W. H. in connection with his photometric monitoring and analysis program: "it soon became clear that most of the bright CTTS and HAEBE stars were not going to yield periodicities easily, if at all. Unlike the WTTS, where dogged monitoring is usually rewarded with a period … the CTTS and HAEBE stars only rarely show significant periods…. Claims to the contrary … were based on a too-optimistic interpretation of noise peaks in periodograms" (Herbst 2001).[1]

An additional problem is that the periods may be less than a day, in which case nightly observations may be insufficient. A. Scholz and colleagues (e.g., Scholz & Eislöffel 2004a, 2004b) have determined photometric rotation periods for very low mass stars in the Pleiades and in the σ Ori cluster. They find many periods that are less than a day. They also point out that many stars with masses between 0.6 and 0.8 $M_{\odot}$ also have periods of a day or less. Nevertheless, periods are now routinely and reliably determined; Lamm et al. (2004) have studied stars in NGC 2264 and identified 543 periodic variables and 484 irregular variables.

Herbst et al. (1994) classified T Tauri stars on the basis of their photometric variability:

1. *Type I*.—Cyclic variations with periods of 0.5 to 18 days or more, seen mostly in WTTSs, and with amplitudes of a few tenths of a magnitude in *V*, due to rotational modulation by cool spots.
2. *Type II*.—Generally irregular variations on timescales of hours or more, seen almost entirely in CTTSs, and with amplitudes of typically a magnitude (occasionally larger), due to variations in mass accretion rate (and therefore in veiling continuum), producing hot spots and some rotational variability.
3. *Type IIp*.—Like Type II, but quasi-periodic.
4. *Type III*.—"UXORs," generally irregular variations on timescales of days to weeks, seen in ETTSs, and with amplitudes of typically a magnitude (occasionally larger), which may be due to variable circumstellar obscuration (Herbst & Shevchenko 1999).

2. PURPOSE OF THIS PROJECT

The periodicity of the photometric variability of T Tauri stars is due to rotational modulation by cool or hot spots, or in some cases, possibly by periodic obscuration by orbiting inhomogeneities in the disk, or by eclipses by a companion or its disk. Previous studies of T Tauri star periodicity have used Fourier analysis, but this approach might be hampered by (1) variations in the *amplitude* of the periodicity, (2) phase shifts in the periodicity due to cool or hot spots that form and decay at changing longitudes, (3) large nonperiodic variability superimposed on the periodic component, such as by variability in the accretion rate onto hot spots, and (4) possible aliasing due to the regularity of the observations, which are often made only once a night at the same hour angle.

Self-correlation provides an independent, adjunct approach that can help to determine new periods or confirm old periods (or not). It is especially useful in stars whose periodicity is not entirely regular. This is a pilot project to investigate the application of self-correlation to a sample of T Tauri stars, some whose periodicity is well known, some whose periodicity needs confirmation, and some that are complex and challenging. We have analyzed about 30 stars in total, and this analysis has provided considerable information about the usefulness of the method and about the stars themselves. The stars are mostly in the range $V = 9$–13, but AB Aur has $V = 7.1$. The original photometric data by W. H. and collaborators are available online,[2] as is the freely available self-correlation software.[3]

3. SELF-CORRELATION

Self-correlation (SC) is a simple method of time-series analysis that measures the cycle-to-cycle behavior of the star, averaged over all the data (Percy & Sen 1991; Percy et al. 1993). It is a useful adjunct to Fourier analysis (e.g., Percy et al. 2001 [red giants], 2003 [RV Tauri stars], 2004 [Be stars]), especially for stars that are not strictly periodic. It does not have the equivalent of the "aliasing" problem found in Fourier analysis. We developed it partly because it was useful in distinguishing between true and alias periods in pulsating red giants (Percy et al. 1993).

For all pairs of measurements, the difference in magnitude (Δmag) and the difference in time (Δt) are calculated. Then Δmag is plotted against Δt from zero up to some appropriate upper limit that, if possible, is a few times the expected period or timescale but is less than the total time span of the data. In this project, for instance, we expected periods of days or tens of days. The Δmag are binned in Δt so that, if possible, there are at least 10 values in each bin. The values for Δmag in each bin are averaged and then plotted against Δt. The following features of the self-correlation diagram are useful for estimating the properties of the variability:

1. There are minima at multiples (N) of the period or timescale. Each of these minima can be used to estimate its value by dividing the time difference Δt of the Nth minimum by N. The N values, so derived, can then be averaged to determine the value of the period. When the periodicity is coherent, the period can be derived to 0.1% accuracy, and it agrees with the period derived from Fourier analysis.
2. The level of the zeroth minimum (at $N = 0$) reflects the size of the measurement error, plus any very rapid variability due to flickering. In the limiting case in which the time interval between the observations approaches zero, the difference will be due to measurement error only. The measurement error in CCD photometry is generally about 0.02, so if the level of the zeroth minimum is much greater than this, rapid variability is probably present.
3. Minima will gradually disappear with increasing N if the variability is semiregular, multiperiodic, or irregular or is otherwise noncoherent. The persistence of the minima is thus an indication of the strictness of the periodicity.

[1] "HAEBE" is the term used in the original work by Herbst.

[2] See ftp://ftp.astro.wesleyan.edu/ttauri.

[3] See http://www.astro.utoronto.ca/~percy/analysis.html.

TABLE 1
PROPERTIES OF AND RESULTS FOR PROGRAM STARS

Star	Type	*A*	*E*	*P*	Comments
AB Aur	…	0.02	0.01	1.0:	…
GM Aur	CTTS	0.04	≤0.02	6.1	…
RW Aur	CTTS	0.20	≤0.05	5 or 10	…
SU Aur	GTTS	0.00	0.02	…	Type III
BF Ori	HAeBe	0.00	≤0.03	>10	…
CO Ori	GTTS	0.1:	0.1	100?	Type III
UX Ori	HAeBe	0.1:	≤0.05	17	Type III
T Tau	GTTS	0.02	≤0.005	…	…
AA Tau	CTTS	0.12	≤0.1	8.20	…
BP Tau	CTTS	0.02	≤0.05	8.19	B: 7.6 days
DE Tau	CTTS	0.1:	0.01	1.2?	Sparse; B: 7.6 days
DG Tau	CTTS	??	≤0.03	3.8?	B: 6.3 days
DH Tau	CTTS	0.20	≤0.05	7.0	B: 7.2 days
DK Tau	CTTS	0.40	0.4!	8.33	B: 8.4 days
DL Tau	CTTS	0.00	0.2!	…	…
DN Tau	CTTS	0.04	0.01	6.43	B: 6.0 days
GG Tau	CTTS	<0.01	0.05	…	B: 10.3 days
GI Tau	CTTS	0.10	≤0.1	7.24	B: 7.2 days
GK Tau	CTTS	0.10	≤0.1	4.63	B: 4.65 days
IP Tau	CTTS	…	…	…	Sparse; B: 3.5 days
IW Tau	WTTS	0.10	≤0.02	6	B: 5.6 days
RY Tau	GTTS	0.05	≤0.05	11	Type III
V410 Tau	WTTS	0.17	≤0.05	2.2	B: 1.87 days
AS 310	…	…	…	1.5:	…
AS 441	…	≤0.01	≤0.01	None	…
AS 442	…	≤0.01	…	None	…
BD +651637	…	≤0.01	0.015	None	…
LkCa 19	WTTS	0.07	0.01	2.2:	B: 2.24 days
Tap 9	WTTS	0.03	0.01	3.1	B: 1.6 days
Tap 40	WTTS	0.06	≤0.02	3.1	B: 3.38 days
Tap 41	WTTS	0.04	0.01	1.4:	B: 1.21 days
Tap 57	WTTS	…	…	…	B: 4.7 days

4. The difference between the levels of the maxima and minima (especially for low *N*) is about 0.9 times the average semiamplitude of the variability; the factor of 0.9 was determined by analysis of synthetic data (Percy et al. 2003).

The SC diagram is useful for studying periodicity in variable stars, but even if periods are not present, it provides a "profile" of the typical or average amount of variability Δmag as a function of Δtime.

However, self-correlation does have disadvantages. The statistical properties of Fourier analysis are well known, but those of self-correlation are not. For instance, the statistical significance of peaks in the Fourier spectrum can be determined (Horne & Baliunas 1986). Fourier analysis is well-suited to multiperiodic variables; the Period04 package that we use was developed especially for this purpose (Lenz & Breger 2005).

4. RESULTS

We calculated SC diagrams for the stars listed in Table 1, using the data available from W. H.'s Web site. We also referred to the (Fourier) periodograms of these data, which are also available on the same Web site. The results of the analysis are summarized in the table, where *A* is the semiamplitude, in magnitudes, of the SC diagram (it is 0.45 times the peak-to-peak amplitude of the light curve), *E* is the value of Δmag as Δ*t* approaches zero (it is a measure of the observational error and/or the size of the variability on very short timescales), *P* is the period, in days, determined from self-correlation, and B refers to the period obtained by Bouvier et al. (1993) from Fourier analysis. The following comments apply to individual stars:

AB Aur.—The SC diagram has an interesting structure (Fig. 1), which may be due to a period near 1 day. The overall level of variability is low.

RW Aur.—There is very weak evidence for a timescale of 10 days in the SC diagram and in the power spectrum. The overall level of variability on timescales greater than 5 days is 0.3 mag.

SU Aur.—This is a Type III T Tauri star, according to W. H.'s classification. Any persistent minima at multiples of a few days have an amplitude much less than 0.01 mag (Fig. 1). There are minima in the SC diagram at multiples of 16 days, but the amplitude is only 0.02 mag or less. This period is too long to be a rotation period of a young star, but it could be an

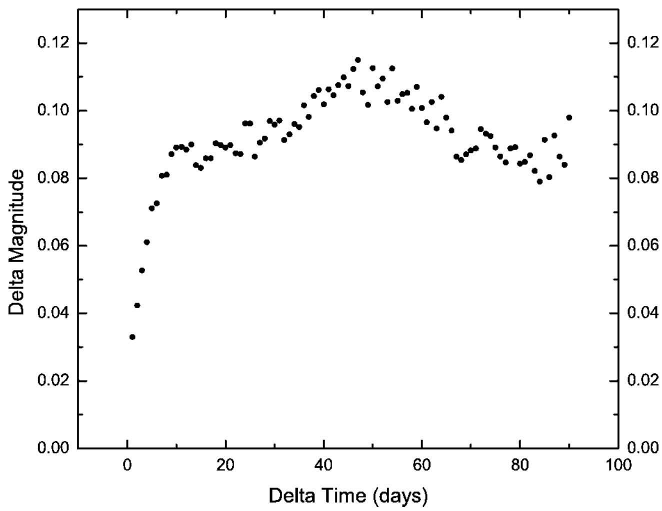

FIG. 1.—SC diagram for SU Aur. The only minima greater than a few millimagnitudes are at multiples of about 16 days. This is rather long for a rotation period but could be due to periodic obscuration by an orbiting inhomogeneity in the accretion disk.

orbital period of an obscuring inhomogeneity in the inner accretion disk.

BF Ori.—There are no significant timescales in the SC diagram or power spectrum greater than 0.01 mag. The overall level of variability on timescales greater than 10 days is 0.3 mag.

CO Ori.—There are weak inflections in the SC diagram at multiples of 15 days, with an amplitude of less than 0.05 mag (Fig. 2), and there is a peak at 15.5 days in the power spectrum (Fig. 3). The overall level of variability on timescales greater than 10 days is up to a magnitude.

UX Ori.—This is the prototype of W. H.'s "UXORs." The characteristic timescale is a few tens of days, and there is some evidence of persistent minima at multiples of 16 days (Fig. 3). This period is a bit long to be a rotation period of a young star, but it could be an orbital period of an obscuring inhomogeneity in the inner accretion disk.

AA Tau.—There are coherent minima in the SC diagram at multiples of 8.2 days, with a large amplitude of 0.25 mag. The power spectrum shows peaks at 4 and 8 days, which may reflect a nonsinusoidal light curve.

BP Tau.—There are coherent minima in the SC diagram at multiples of 8 days, with an amplitude of 0.02 mag. The overall level of variability on timescales greater than 10 days is 0.15 mag.

DE Tau.—The SC diagram shows some evidence of a timescale close to a day, but the data are sparse.

DF Tau.—There are weak minima in the SC diagram at multiples of 7 days, with an amplitude less than 0.05 mag; there are peaks in the power spectrum at 7 and 15 days. The overall level of variability on timescales greater than 5 days is 0.4 mag.

DG Tau.—There are no significant timescales in the SC

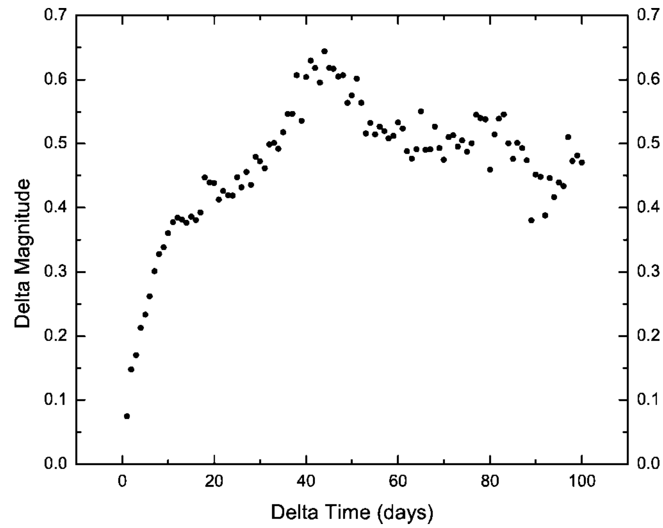

FIG. 2.—SC diagram for CO Ori. There are slight inflections at multiples of 15 days, but the amplitude is a few hundredths of a magnitude at most. The diagram shows a "profile" typical of many T Tauri stars; the Δmag rises steadily with Δt to a plateau, in this case 0.5 mag.

diagram or power spectrum; the overall level of variability on timescales greater than 10 days is about 0.15 mag.

DH Tau.—There are weak minima in the SC diagram at multiples of 7 days, with an amplitude of 0.1 mag, but the data are sparse. There are peaks in the power spectrum at 3.5 and 7.5 days, perhaps indicating a nonsinusoidal light curve.

DK Tau.—This is a classical T Tauri star. The 10 or more minima persist to large Δt, which indicates a high degree of

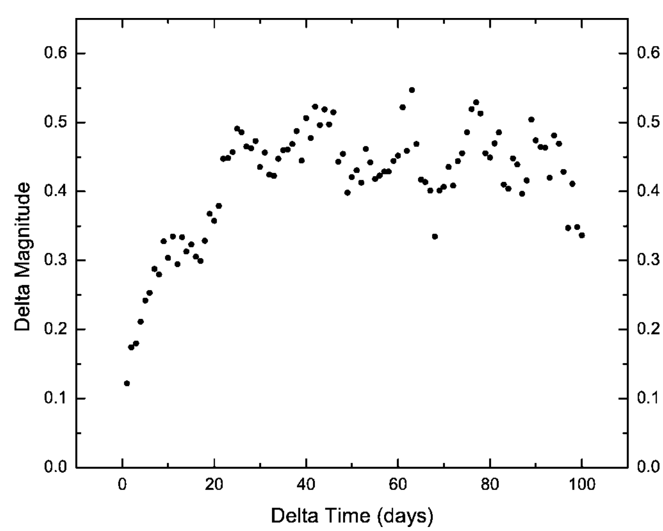

FIG. 3.—SC diagram for UX Ori, the prototype UXOR. There are slight minima, or inflections, at multiples of 16 days, but the amplitude is a few hundredths of a magnitude at most. The general form of the diagram shows that the bulk of the variability is irregular and has a characteristic timescale of tens of days; at this timescale, the diagram reaches a plateau of about 0.5 mag.

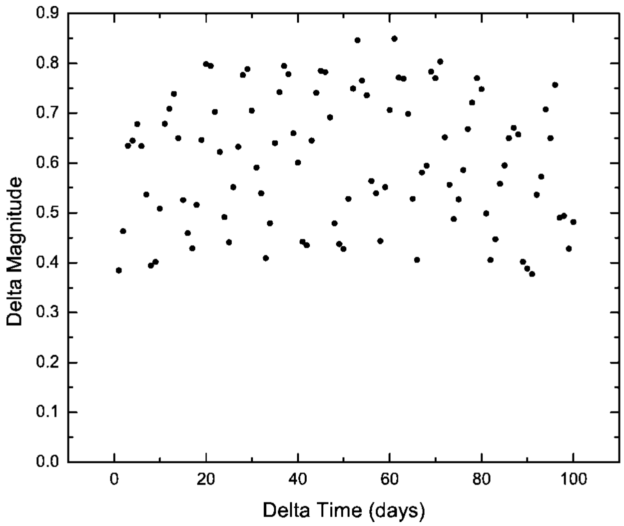

FIG. 4.—SC diagram for DK Tau. The persistence of the minima shows that the variability is coherent over 10 cycles or more; it has a period of 8.33 days and an average peak-to-peak light curve amplitude of 0.8 mag.

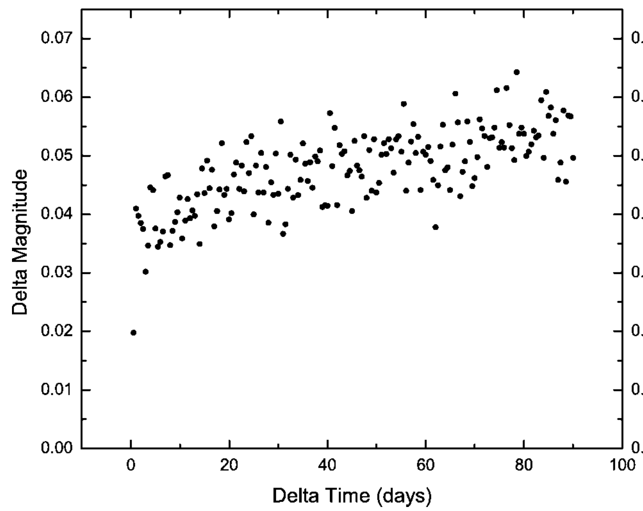

FIG. 5.—SC diagram for T Tau. There are no periodic minima at timescales (Δt) up to 90 days with amplitudes greater than 0.005 mag. The overall level of variability is small (0.04 mag) and takes place on a timescale of a few days.

periodicity (Fig. 4). The 10 minima can be used to derive a period of 8.33 days (presumably the rotation period of the star). Bouvier et al. (1993) obtained 8.4 days from Fourier analysis. The periodogram has a sharp peak at this period. The amplitude is a whopping 0.4 mag (indicating a peak-to-peak range in brightness of about 0.9 mag). The height of the minima (about 0.4 mag) is much larger than the observational error (about 0.01 mag), indicating that there are large random variations in brightness, in addition to the periodic ones.

DL Tau.—The overall level of variability on timescales of a few days or more is 0.3 mag, but there is no periodic variability greater than 0.01 mag.

DN Tau.—This is a classical T Tauri star. The minima are not distinct; there are fewer observations, and the amplitude is only 0.07 mag (indicating a peak-to-peak range of about 0.15 mag). The four minima can be used to derive a period of 6.43 days (presumably the rotation period of the star). Bouvier et al. (1993) obtained 6.0 days from Fourier analysis. The periodogram has a sharp peak at a period of 6.28 days.

GG Tau.—This star is a classical T Tauri star. Any persistent minima at multiples of a period of a few days have an amplitude $\leq$0.01 mag. This places an upper limit on the periodic rotational variability of this star. The SC diagram rises to a plateau of 0.07 mag at timescales Δt of a few days, indicating that this is the characteristic timescale of any variations.

GI Tau.—The SC diagram shows coherent minima at multiples of 7.1 days, with an amplitude of 0.1 mag; the same period appears in the power spectrum. The overall level of variability on timescales greater than 10 days is 0.4 mag.

GK Tau.—The SC diagram shows coherent minima at multiples of 4.6 days, with an amplitude of 0.1 mag. The overall level of variability on timescales greater than a few days is 0.3 mag.

IP Tau.—There are no obvious minima in the SC diagram, but the data are sparse.

IW Tau.—There is a minimum in the SC diagram at 6.5 days, but the data are sparse.

RY Tau.—The SC diagram shows a possible minimum at 11 days, with an amplitude less than 0.05 mag, but the data are sparse; there are no conspicuous peaks in the power spectrum.

T Tau.—There are no minima in the SC diagram greater than about 0.005. The overall level of variability on timescales greater than a few days is only 0.04 (Fig. 5).

V410 Tau.—The SC diagram shows coherent minima at multiples of 2.2 days, with an amplitude of 0.15 mag.

AS 310.—The SC diagram shows some evidence of a 1.5 day timescale. The overall level of variability is only 0.04 mag.

AS 441.—There are no minima in the SC diagram greater than 0.005 mag. The overall level of variability is only 0.03 mag.

AS 442.—There are no minima in the SC diagram greater than 0.01 mag. The overall level of variability on timescales greater than 20 days is 0.1 mag.

BD +65 1637.—There are no minima in the SC diagram greater than 0.001 mag—a rather stringent upper limit (Fig. 6).

Tap 9.—This is a weak-lined T Tauri star. The data are sparse, but the minima and maxima fit a period of 3.56 days (presumably the rotation period of the star). Bouvier et al. (1993) obtained 1.6 days from Fourier analysis; their period appears to be an alias of the true period. Self-correlation can therefore provide a check on periods determined by Fourier analysis.

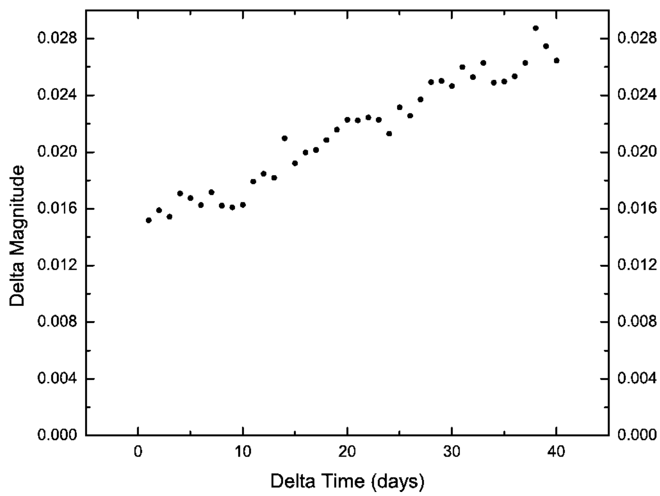

FIG. 6.—SC diagram of BD +65 1637. There are no periodic minima at timescales (Δt) up to 40 days with amplitudes greater than 0.002 mag, indicating that there is no periodic (rotational) variability greater than this value.

Tap 40.—The SC diagram shows a possible minimum at 3.2 days.

Tap 41.—The SC diagram shows possible minima at multiples of 1.3 days, with an amplitude of 0.01 mag, but the data are sparse.

5. DISCUSSION AND CONCLUSIONS

This pilot project indicates that SC provides useful information about the photometric variability of T Tauri stars and related objects.

If there is a period or characteristic timescale in the data, then SC can identify its value and its mean amplitude. It provides information about the degree of coherence from the number of minima that appear in the SC diagram. If there are several of these, then each one can be used to help refine the value of the period or timescale. See Figure 4 for a good example.

SC can provide an upper limit to the amount of periodic or cyclic variability in a star. In several stars in our project, periodic variability could be ruled out at the 0.01 mag level, and in at least one case (Fig. 6), it could be ruled out at the millimagnitude level. In the prototype T Tau (Fig. 5), the periodic component is less than 0.005 mag.

Since SC does not suffer from aliasing in the usual sense, it can sometimes be used to correct alias periods that have been determined by Fourier analysis, as in the case of Tap 9. SC is best used in conjunction with Fourier analysis, since the two methods provide different types of information and have different strengths and weaknesses.

Most of the periods that we have determined are consistent with rotation periods expected in young solar-type stars. In a few cases, the periods are of the order of weeks—too long to be rotation periods. In these cases, the variability may be due to periodic obscuration by orbiting inhomogeneities in the inner accretion disk.

The value of Δmag as Δt approaches zero is a measure of the variability on very short timescales (hours or less). Some stars, analyzed here, seem to show significant variability on such short timescales (UX Ori; see Fig. 3, for instance). Thus, the SC diagram can provide an estimate of the relative amount of variability on short and longer timescales.

Put another way, even in nonperiodic stars, the SC diagram provides a "profile" of the mean amplitude of variability as a function of timescale Δt. Figures 1–3 are good examples. In some cases, such as Figures 5 and 6, the SC diagram is flat, indicating little or no variability (although this could easily be deduced from the data or light curves, of course).

In the future, we plan a comprehensive study of a much larger sample of T Tauri and related stars, especially the classical T Tauri stars and Herbig Ae/Be stars and others whose periodicity is currently in doubt.

W. G. and J. W. were participants in the University of Toronto Mentorship Program, which enables outstanding senior high school students to work on research projects at the university. We acknowledge a research grant from the Natural Sciences and Engineering Research Council of Canada.

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