DRAMATIC PERIOD DECREASE IN T URSAE MINORIS

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Abstract

The Mira-type long period variable T Ursae Minoris has exhibited a remarkable decrease in its period recently. Analyzing AAVSO visual observations from 1905 to 1994, we identify six distinct episodes during which T UMi has shown a different period. We discuss the various methods used to determine the changes in the period. From 1905 to 1979, its period shows small variations. However, beginning in 1979, its period has sharply decreased from 315 to 274 days. We propose that this star, with its unprecedented period decrease, may be immediately after the helium flash stage of its evolution.

Introduction

T Ursae Minoris (T UMi), at position $13^h33^m39^s$, +73°41.2' (1950), is a Mira-type long period variable star (LPV), with M4E to M6E spectra and a range of optical light variation between visual magnitudes 7.8 and 15.0. In the fourth edition of the *General Catalogue of Variable Stars* (Kholopov *et al.* 1985), its period is given as 301 days, with a note that it varied between 310 to 315 days during the years 1936 and 1978 (JD2428300 and 2443600).

Mira variables are pulsating red giants of about one solar mass, with periods ranging from 200 to 500 days, and visual amplitude of variation more than 2.5 magnitudes. Although the mean period may be stable, individual periods may vary from cycle to cycle in a Mira variable.

With unstable dense cores they represent an important stage of stellar evolution. Some Mira variables are planetary nebula progenitors, while others are directly evolving to the white dwarf stage. They appear as tracers of the chemical evolution of the galaxy, and through mass loss they play a major role in galactic evolution, enriching the interstellar medium in heavy elements. The period of light variation in these stars is an important parameter showing correlations with the shape of the light curve (Campbell 1955), infrared excess due to circumstellar dust (De Gioia-Eastwood *et al.* 1981; Jura 1986), and mass loss rate (Wood 1990; Whitelock *et al.* 1986, 1991). The period is also an indicator of the age, thus the initial mass and metallicity, the mode of pulsation, and the evolution in these stars (Feast 1989; Mennessier 1982; Willson 1982; Wood 1982; Willson 1986; Willson 1988).

Some Mira variables undergo abrupt period changes which provide direct observational evidence of the theory of shell flashes in the helium-burning shell around the hydrogen-exhausted cores of these stars. During this event, the helium shell around the dense core of the star reaches a critical mass and ignites. This influences the star's pulsation via changes in surface luminosity and radius (Wood and Zarro 1981).

Due to their intrinsic brightness, large amplitudes, and long periods, the light variations and periods of these stars are almost always determined from visual observations compiled by the AAVSO and by other variable star observer groups of amateur astronomers worldwide.

2. Data and analysis

T UMi is one of the most closely monitored Mira stars in the AAVSO observing program, with observations going back to 1905 in the AAVSO International Database. Its observed maxima and minima dates have been determined homogeneously using Pogson's method (Campbell 1926; Campbell 1955; Mattei *et al.* 1990). Each year these data are used to predict the maxima and minima of the following year that are published in the *AAVSO Bulletin*. Until the late 1980's, it had been fairly straightforward to predict maxima and minima of T UMi. However, since then we have noticed that the maxima and minima were occurring earlier than predicted, signaling a possible decrease in the period, and inspiring us to carry out this analysis.

To check the stability of the period, we used the AAVSO maxima and minima dates from JD 2416970 to 2449580 (May 1905 to August 1994). These include published values from Campbell (1926, 1955) and Mattei *et al.* (1990) through 1975, as well as more recent data from the AAVSO International Database. In addition, we compiled 5304 observations from the AAVSO archives from JD 2418400 to 2449540 (April 1909 to July 1994).

With times of maxima and minima, the analysis is already well on the way; individual periods can be estimated as the time from each maximum to the next. To this time series we applied trend analysis, fitting low-order polynomials by the method of least squares, to establish significant period changes. Knowing the times of both maxima and minima, we were also able to compute the *fall time* (the time from a maximum to the following minimum), and the *rise time* (the time from a minimum to the following maximum). We applied trend analysis to these time series also.

In classic fashion, the times of maxima were used to compute observed minus calculated (O-C) values for each observed cycle. O-C analysis, as usually applied, is *not* a valid statistical test for establishing a period change in LPVs (Lombard and Koen 1993; Percy and Csatary 1992; Foster 1993), but is an excellent indicator of *possible* change. We did find that it is inconvenient to use the published elements of T UMi to calculate the "computed" times of maxima, especially when studying the most recent data (when the period of T UMi is radically different from its published value). Therefore the elements used to compute all O-C diagrams are those determined by a least-squares best-fit straight line to the times of maxima, for the time span under study. This makes visual inspection of the O-C diagrams much easier.

To determine periods from the AAVSO archive of visual observations, we need a period search method. We chose Fourier analysis in two forms: the *date-compensated discrete Fourier transform*, or DCDFT (Ferraz-Mello 1981), and the CLEANEST algorithm (Foster 1995). The DCDFT is a reliable period detection method, but like most such methods, it gives a reliable estimate of the *average* period over a given time span, but little information about period changes. It can, however, be applied to different "episodes" of the data, to see whether the period is different from episode to episode.

CLEANEST is a new analysis method, developed at AAVSO, which finds the best way to fit the data with a smooth function which has *multiple* periods. It greatly reduces the effect of irregular observation times. Perhaps most interesting, it sometimes happens that CLEANEST includes several periods which are nearly, but not exactly, the same. This is a *cluster* of closely spaced periods, and indicates some sort of *change* in the period and/or amplitude of the signal. In such a case, not only can CLEANEST detect a changing period, it can also portray its changes over time. T UMi served as a test case for this application of CLEANEST.

Table 1. Episodes of periodicity of T Ursae Minoris.

	Interval Limits Cycles	JD 2400000+	Years	Num. Cyc.	Period DCDFT	CLEANEST	Average	SDV	SDV (Ave.)
1	2-42	16971-29930	1905-1940	41	315.4	315.4	315.41	8.11	1.27
2	43-65	29930-37038	1940-1960	23	310.0	309.8	310.22	7.15	1.49
3	66-87	37038-43968	1960-1979	22	315.4	315.2	315.00	3.15	0.67
4	88-94	43968-46072	1979-1985	7	301	301	300.57	3.69	1.39
5	95-100	46072-47790	1985-1989	5	287	288	286.33	3.93	1.76
6	101-105	47790-49540	1989-1994	6	275	274	275.40	6.73	2.75

3. Period evolution of T UMi

Based on these tests, we identified possible "episodes" during each of which T UMi exhibited a different period. In order to confirm or deny that a period change actually occurred, we applied two tests: first, we Fourier-analyzed each individual episode, by both the DCDFT and the CLEANEST algorithm, to establish the period; second, we computed the average and standard deviation of the individual periods, enabling us directly to test whether or not the period is different from one episode to another. These tests establish that the period of T UMi *is* different from episode to episode, but do *not* establish that the period remained constant during any of the episodes. In particular, during the last three episodes, the period may have changed suddenly from episode to episode, or it may have decreased smoothly. We therefore performed a trend analysis on the last three episodes, with negative results; the data do not favor one hypothesis over the other.

3.1. O-C analysis

The O-C diagram of all the maxima of T UMi (Figure 1a) reveals a sudden and dramatic change in behavior starting in 1979 (cycle 88, JD 2443970). Prior to that time, its period showed some oscillations. Three episodes of different average period are indicated by further O-C analysis (Figures 1b, 1c): cycles 2 to 42 (1905 to 1940), cycles 43 to 65 (1940 to 1960), and cycles 66 to 87 (1960 to 1979). The period from 1979 to the present also reveals episodes of different average period, with the period rapidly decreasing (Figures 1d, 1e): cycles 88 to 94 (1979 to 1985), cycles 95 to 100 (1985 to 1989), and cycles 101 to 105 (1989 to 1994). Table 1 shows the various episodes of different periods for T UMi.

3.2. Trend analysis

Fitting a 6th-degree polynomial to the sequence of periods (Figure 2a) shows the same features as indicated by O-C analysis. From cycles 1 to 87, the period changes only slightly, starting at about 315 days, dropping to about 310 days, and rising again to 315 days. From cycle 88 onwards, the period has plummeted to its current value of 274 days.

Fitting 4th- and 8th-degree polynomials to the rise and fall times (Figure 2b) shows that the vast majority of the period evolution of T UMi is due to a change in the fall time; the rise time has been far more stable over the entire century. In fact, the trend shown by the fall time mimics almost exactly the trend shown by the period itself. It is worth noting that until 1979, the fall time was significantly longer than the rise time (by about 30 days), but at present the fall and rise times of T UMi are nearly equal.

3.3. Fourier analysis

The CLEANEST spectrum of T UMi (Figure 3a) is dominated by a cluster of closely-spaced periods, which can indicate amplitude and/or frequency modulation of the signal. We have determined that, in this case, the cluster indicates frequency (period) modulation. The reconstructed time evolution of the period is shown in Figure 3b, superimposed on the individual periods. The period is reasonably stable until 1979, showing a small decrease followed by a small increase; then the period dips sharply.

We also applied the DCDFT and CLEANEST to each episode of different period. Table 1 gives the periods obtained with different methods in each of the episodes. In addition to estimating the period, CLEANEST constructs a smooth curve which models the underlying signal. In Figure 4, we show the smooth-fit curves constructed for each episode, superimposed on the data on which it is based, for the time span JD 2420000 to 2449500 (August 1913 to May 1994).

4. Implications of the recent behavior

The period of T UMi has been decreasing at a rate of 2.75 days/year since 1979. Using the AAVSO archives over 90 years, we find that this rate is twice as fast as either R Aql (1.0 d/yr) or R Hya (1.3 d/yr), two stars known to be undergoing period change due to changing luminosity produced by helium shell flash (Wood and Zarro 1981).

The longterm light curve of T UMi does not show any significant change in shape; hence, the recent dramatic decrease in the period is not due to mode switching. Yet the dramatic period decrease indicates that this star may be undergoing an evolutionary change. Wood and Zarro (1981), in their study of low-mass stars and period changes in Mira variables, point out that just before the onset of helium shell flash, the surface luminosity of a Mira variable is at maximum due to steady burning of the predominant hydrogen shell. However, just following the flash, the hydrogen-burning shell is rapidly extinguished, causing a drop in surface luminosity. This is then halted as energy released by helium burning diffuses to the stellar surface (Figures 1 and 3 in Wood and Zarro 1981).

We propose that T UMi may be at the stage just after the beginning of helium shell flash, where its luminosity and radius are decreasing significantly, as manifested by the dramatic decrease in its period.

We strongly recommend spectroscopic and multiwavelength observations at this time as the period of this star continues to decrease and it enters a rare state in its evolution.

5. Acknowledgements

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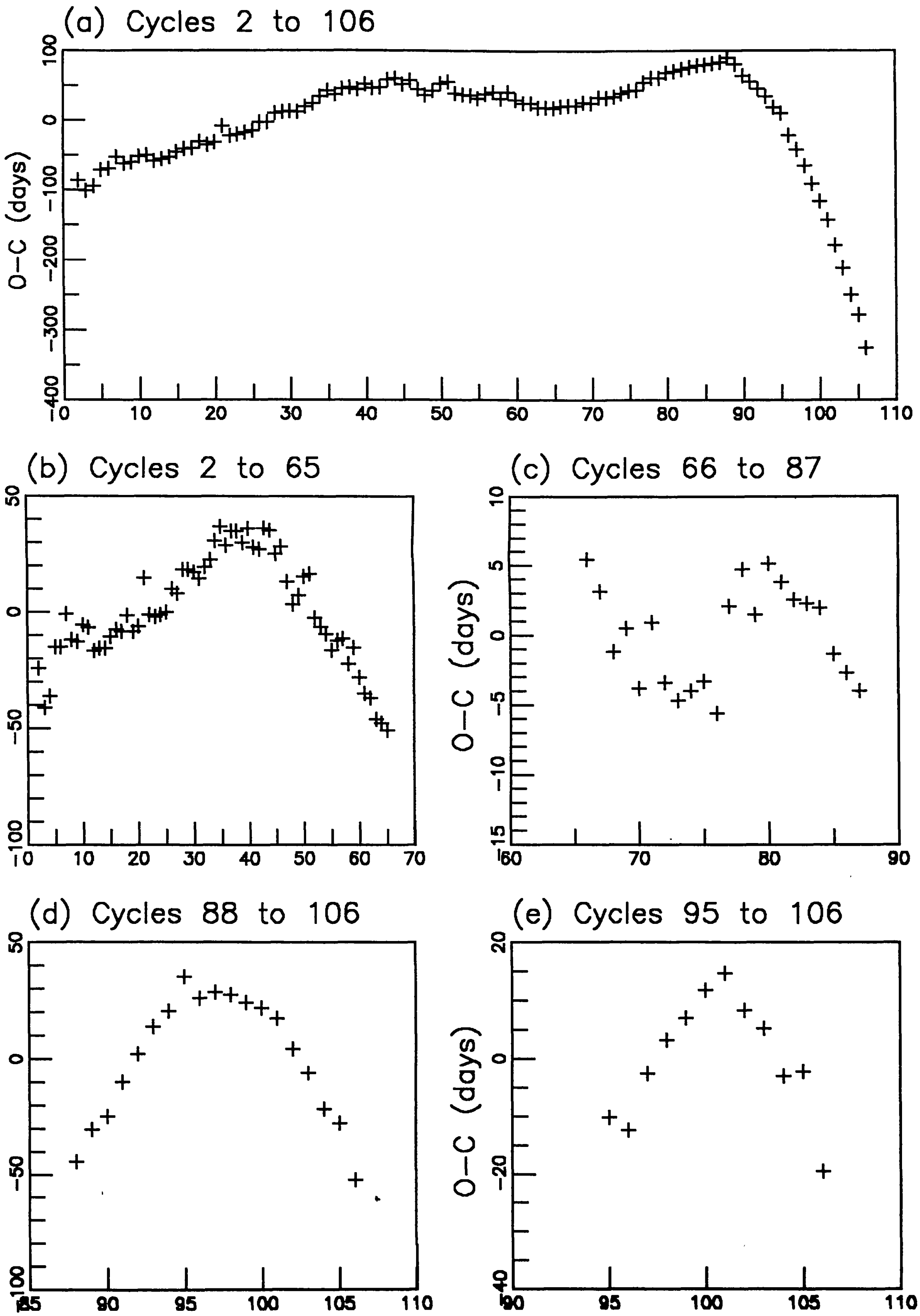


Figure 1. O-C diagrams for T UMi. (a) Cycles 2 to 106. (b) Cycles 2 to 65. (c) Cycles 66 to 87. (d) Cycles 88 to 106. (e) Cycles 95 to 106.

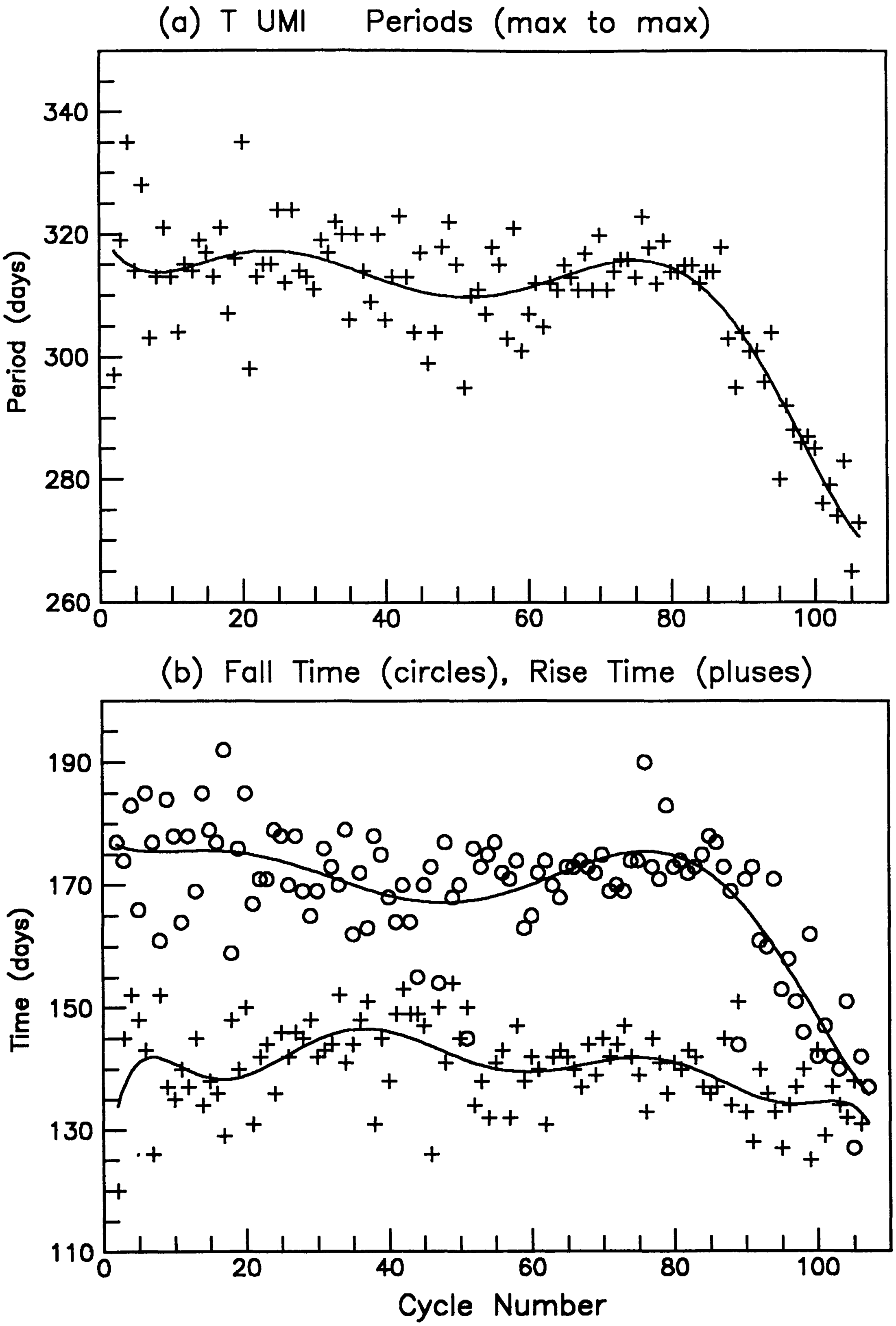
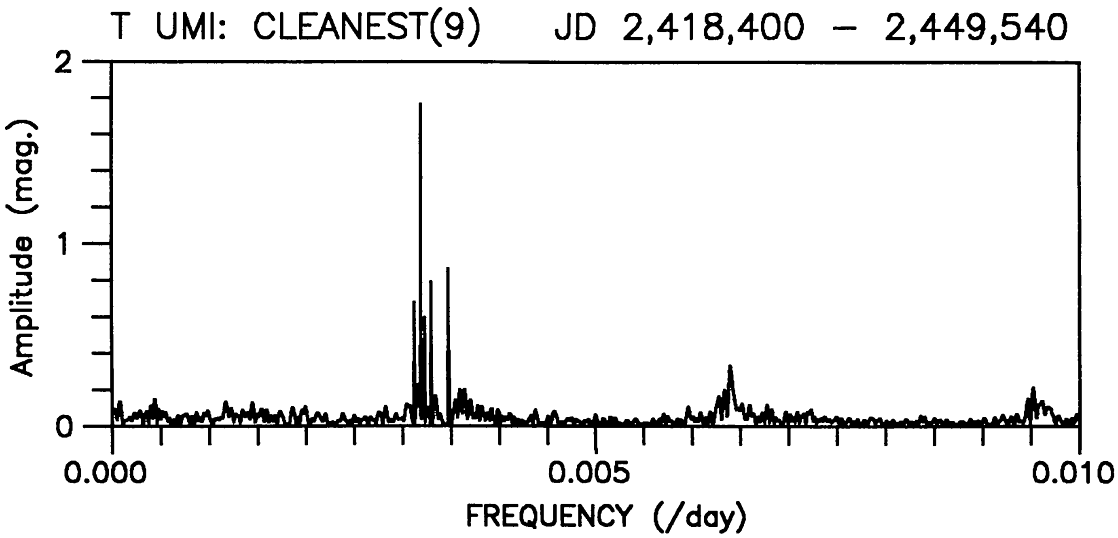


Figure 2. (a) Graph of period versus cycle of T UMi. Plus signs represent the periods from one maximum to the next. The solid curve is a best-fit 4th-degree polynomial to the data. (b) Fall time and rise time versus cycle. Circles are the fall time, from maximum to minimum; plus signs are the rise time, from minimum to maximum.



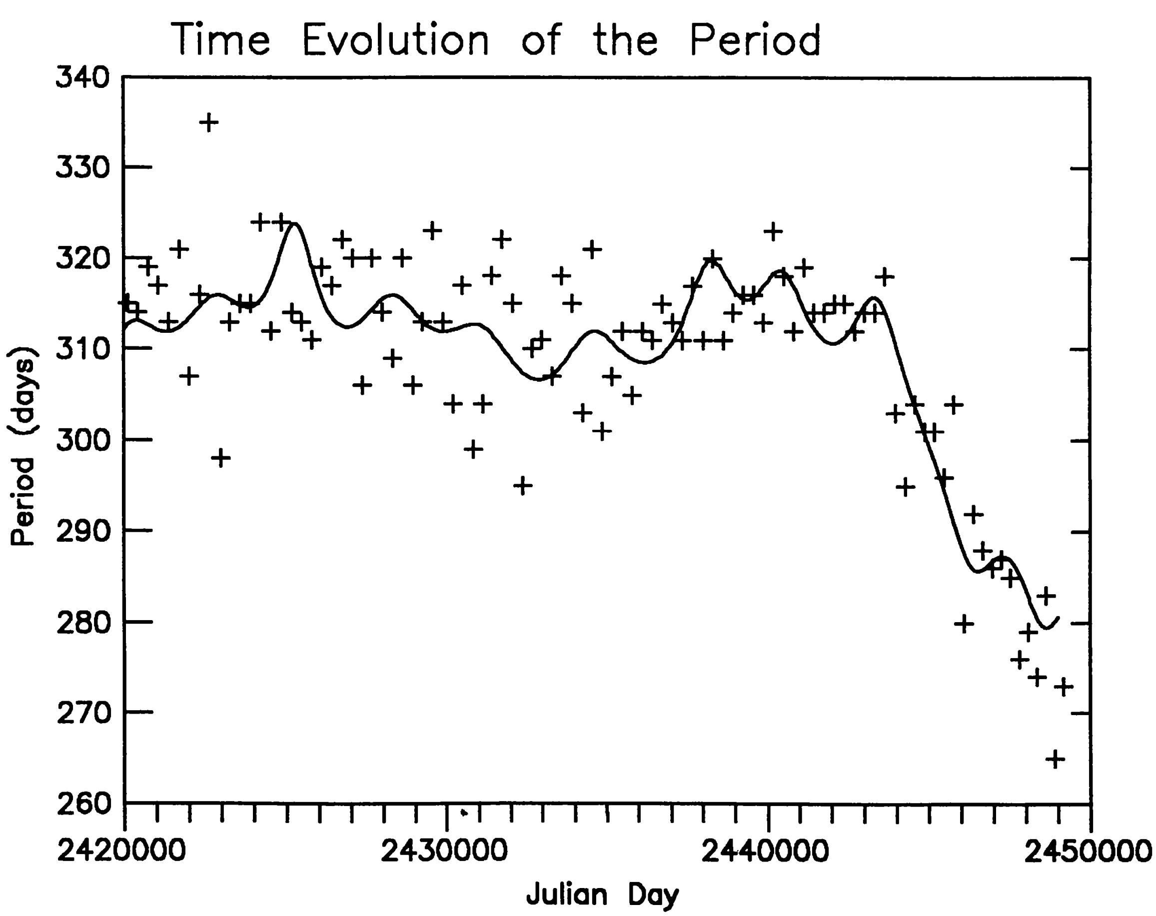


Figure 3. (a) CLEANEST-9 periodogram of T UMi data. (b) Time evolution of the period of T UMi based on the CLEANEST spectrum (solid line), superimposed on the individual periods from maximum to maximum (plus signs).

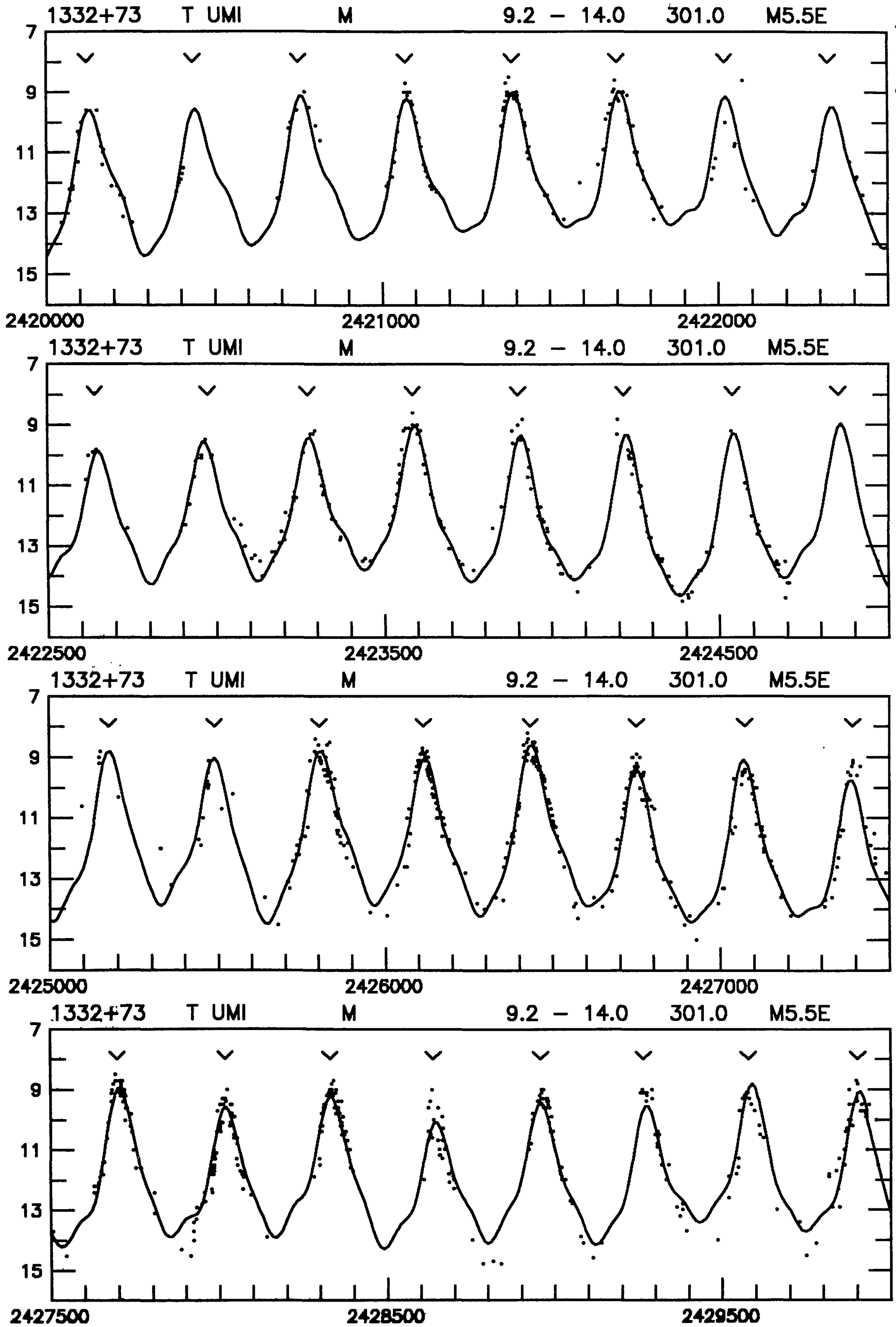


Figure 4 a–d (top to bottom). AAVSO light curve of 10-day averages of T UMi from JD 2420000 to JD 2450000. Dots are the 10-day averages, the solid line represents the smooth-fit curve computed from CLEANEST analysis, and circumflexes indicate the times of maxima.

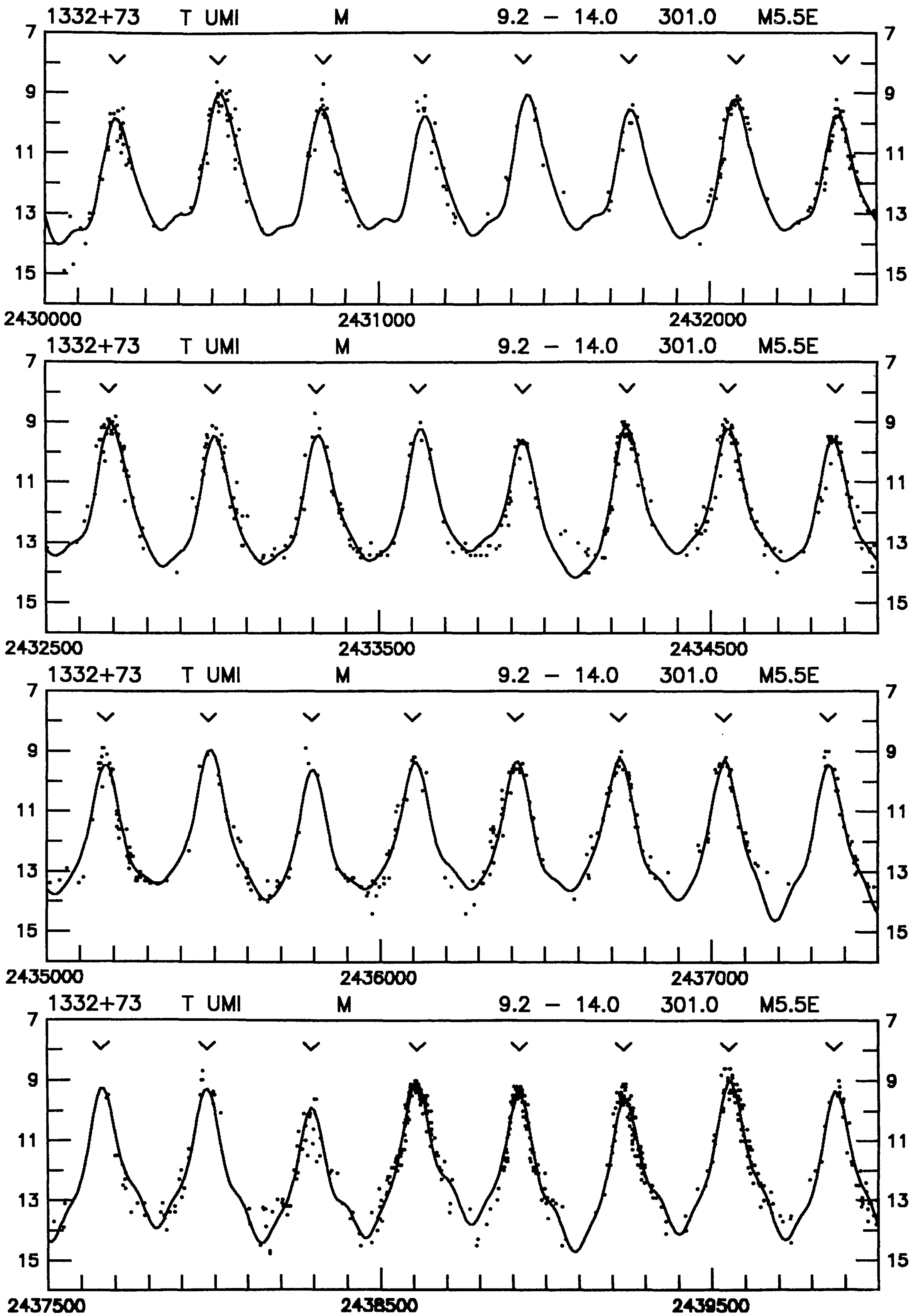


Figure 4 e–h (top to bottom). AAVSO light curve of 10-day averages of T UMi from JD 2420000 to JD 2450000 (continued). Dots are the 10-day averages, the solid line represents the smooth-fit curve computed from CLEANEST analysis, and circumflexes indicate the times of maxima.

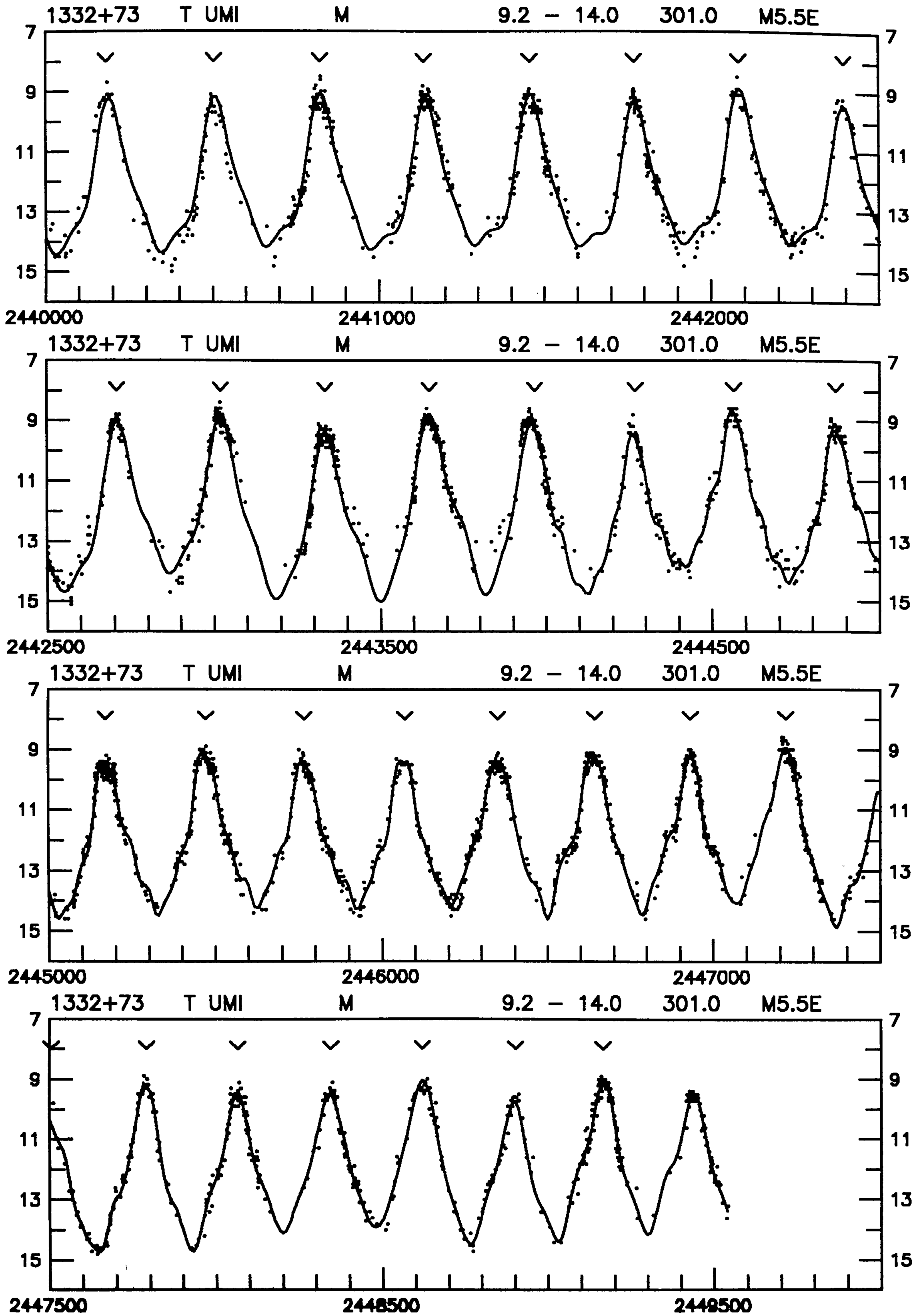


Figure 4 i–l (top to bottom). AAVSO light curve of 10-day averages of T UMi from JD 2420000 to JD 2450000 (continued). Dots are the 10-day averages, the solid line represents the smooth-fit curve computed from CLEANEST analysis, and circumflexes indicate the times of maxima.