Chapter 13: Variable Stars and *O–C* Diagrams

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Introduction

In the previous chapter we stated that a *perfectly periodic* system repeats exactly the same behavior, over and over again. Every cycle is precisely like every other cycle. Some variable stars actually behave this way: Cepheid variables, for example, may repeat precisely the same brightness variations for thousands of cycles. Eclipsing binaries also sometimes repeat thousands of cycles, with exactly the same period every time.

Other variables are not quite so reliable. While they do go through an almost never-ending series of ups and downs, each cycle is a little different from every other cycle; the period will be slightly longer or shorter, and the maximum and minimum magnitudes will be slightly brighter or fainter. You probably noticed in the last chapter that the light curve of the Mira-type variable V Cas showed slight differences from cycle to cycle. It keeps brightening and dimming, so it definitely appears to be periodic, but it is not *perfectly periodic*.

In fact, all Mira-type variables behave this way. They are periodic, because they keep repeating cycles over and over again. But they are not perfectly periodic, because every cycle is a little different. For Mira-type variables, the differences from cycle to cycle are small. The period, for instance, will be a little different for each cycle, but is usually within 10% of its average value. The amplitude of each cycle (the difference between minimum and maximum brightness) will usually be within 20% of its average value. Each cycle in the light curve looks a bit different, but they all have many similarities as well, and they are usually close to the "average shape" of the light curve.

Another class of variables, known as the *semiregular variables*, show even greater differences from cycle to cycle. Not only are their periods not perfectly periodic, but these stars also sometimes "switch" from one period to another (a process known as *mode switching*). Their amplitudes change dramatically: they may suddenly increase their variability, or they may stop varying altogether (but when they do, they usually start up again soon after).

It is easy to see the differences from cycle to cycle in the light curves of Mira- and semiregular-type variables. The light curves of Cepheids show what appear to be identical cycles. But if we watch Cepheids long enough—for tens of thousands of cycles—we can detect very slight changes in their cycles as well. They too can show changes in the cycle shape, the amplitude, and the period. The differences are still there: even the Cepheids are not perfectly periodic.

Pulsating Stars

When the first Mira-type variables were discovered, it was a mystery why they were varying at all. After all, most stars, like our own Sun, are quite stable, not variable (even the Sun varies a *little* bit, but surprisingly little). In the early part of this century, the famous English astronomer Arthur Eddington studied the problem carefully. Most known ways that stars can vary could be eliminated from consideration. For example, Mira-type variables were not exploding like supernovae: their fluctuations are too regular for that. And they were not eclipsing like the eclipsing binaries: their fluctuations are not nearly regular enough for that.

Eddington went back to the basics. Stars glow like the filament of a light bulb for the same reason—because they are hot. The light output of a star depends mainly on two things: its surface temperature (how bright the light bulbs are) and its size (how many light bulbs are burning). The apparent visual magnitude of Mira itself is 100 times brighter at maximum than at minimum. To be so much brighter, it would either have to be hotter, or bigger, or both.

By studying the spectra of stars, we can get a good estimate of their temperatures. The spectrum of Mira throughout its cycle does change, and in fact Mira will show temperature changes while it fluctuates, but these temperature changes are just too small to explain the tremendous increase and decrease in brightness. That leaves only one possibility, said Eddington: Mira changes its brightness by a large amount every cycle because Mira changes its size by a large amount every cycle. Mira (and all Mira-type variables) fluctuate because they are expanding and contracting, growing and shrinking. The star is literally "vibrating." Variables that do this are known as pulsating variables.

We now know that there are many types of pulsating variables. Cepheids, for example, are very regular pulsating variables, usually with periods of a few days or more. Mira-type variables also pulsate, but their periods are almost always more than 100 days, and their pulsations are much more irregular from cycle to cycle than those of Cepheid variables. Semiregular variables pulsate with periods from as little as 30 days to over 1,000 days, and their pulsations are even more irregular than those of Mira-type variables.

Period

Eddington's "back-to-basics" approach was appropriate. After all, the stars are so far away that we have to stretch ourselves just to uncover their basic physical properties. The most important physical parameters of a star are its size (the radius) R, its surface temperature T, and its mass M.

Unfortunately, we cannot measure these basic quantities directly. The easiest to estimate is the temperature. The spectrum of the star acts almost like a thermometer to give us a good estimate of the temperature, and other clues enable us to refine this estimate. The radius can be quite difficult to determine, because the stars are so far away that we cannot really see their images directly (except in a few special cases). Still, if we know the star's distance from earth, its brightness, and its temperature, we can get a reasonable size estimate. Of all the "basic parameters," the most difficult to estimate is the mass: too often we simply have no clues, and our best mass estimate is likely to be very unreliable.

There are exceptions. Binary stars orbit each other, and their orbits are determined by the laws of gravity. The strength of gravity depends on mass, so if we know all the details of the orbital motion of a binary star, we can get a very good mass estimate. That is one of the reasons eclipsing binary stars are so important: the details of their orbital cycles enable us to determine stellar masses. Unfortunately, this can be applied only to a few stars.

Another exception is pulsating stars. The period of a pulsating star depends mainly on its basic physical parameters of size, temperature, and mass. So if we know the period, we have one more clue to help us estimate mass. In fact, the period of a pulsating star can give us clues about its mass, the strength of its gravity, and sometimes even the reactions taking place in the star's interior.

According to our theories of stellar structure, if a star is pulsating, its period in most cases will be stable. The period may change from cycle to cycle (as with Mira-type variables), but the *average* period over many cycles will remain the same. For the average period to change, we would have to change the star's mass, size, or temperature (none of which is very likely), *or* we would have to change the internal workings of the star. Such changes do occur, but they usually happen only at important stages in the star's life cycle. So when a pulsating star shows a change in its average period, it usually means that the star is undergoing an evolutionary change in its behavior, moving from one stage in its life cycle to the next.

We see that the period of a variable star is one of the most revealing aspects of its variations. It is something that we can obtain through careful observation. The average period gives us vital clues about a star's basic properties, including mass and gravity. Any period *changes* are a warning that the star may be entering an important new stage of its development. And this is true not just for pulsating variables: for any periodic variable star, the period is one of the most important and most informative of its observable parameters. Because of this, studying the periods of variable stars, and especially any changes in their periods, is an especially important part of the analysis of variable stars.

O–C

One very useful tool for finding period changes, and one which is very popular with astronomers, is to compute what is called "*O–C*" ("O minus C"). It is based on the following idea: if a star is perfectly periodic, then every period is exactly the same. In that case, we can predict its cycles in advance. If one maximum occurs on, say, JD 2,450,000, and the period is precisely 332 days (and never changes!), then the next maximum will occur on JD 2,450,332. This is not just guesswork: it is based on the way periodic systems behave. This is how scientific predictions are made: by combining a precise *theory* of behavior (perfect periodicity) with accurate parameters (the epoch, or time of maximum, and the period) determined from precise observations (made by careful variable star observers), we can predict the behavior of a star in advance. Then we can perform what may be the most powerful test in all of science: we can compare our predictions with future observations.

If the star is perfectly periodic, has a maximum at time t_o (the *epoch*), and the period is P, then we know that the *next* maximum will occur at time $t_o + P$. The next maximum after that will be at time $t_o + 2P$, then next at $t_o + 3P$, etc. In fact, if we choose t_o, our *epoch,* to be the time of maximum for cycle number *zero*, then the *computed time of maximum* for any cycle number n, which we can call C_n, is easy to calculate:

$$C_n = t_o + nP.$$

With this one formula, we can compute the times of all maxima, past, present, and future.

Of course, these times are correct only if the system is perfectly periodic. In addition to the computed times of maximum C_n, we can also directly observe the star to estimate the *observed time of maximum* for cycle number n, which we will call O_n. You have already done this in previous chapters, estimating the time of maximum either by eye, or by fitting a polynomial to the light curve data. We are now ready to compare theory (the computed times C_n) to observation (the observed times O_n), by simply taking the difference between the observed and computed times of maxima. These are the "*O–C*," or "observed minus computed" values. For each cycle number n, we have $(O–C)_n = O_n - C_n$. After we have determined the *O–C* values, we can plot *O–C* as a function of cycle number n. This gives us a powerful tool for period analysis: the *O–C diagram*.

Investigation 13.1: Constructing an *O-C* Diagram

Your teacher will assign you a system to observe by timing. For example, you may be asked to time when the street light changes from red to green, or when the next commercial starts on a TV show. What you will end up with are a set of observed times, the times at which the "important event" (whatever you are assigned to observe) has occurred. You should have observed ten occurrences (ten cycles) of this system.

1. Make a table to list all your observations, leaving space for 4 columns. Enter your actual observations in column 2.

2. Number your observations, starting with *zero* (astronomers and mathematicians often like to start numbering things at zero rather than one). These are the cycle numbers n for your observations. The observations themselves are the observed values O_n. Enter the cycle numbers in column 1 of your table. If you have observed 10 cycles, and start numbering them from zero, then your cycle numbers n will range from 0 to 9.

3. Take the observed time of your very first observation as the estimated epoch t_o.

4. Compute the difference between the first two observed times by subtracting the second from the first. Take this as your estimated period P.

5. Using your epoch t_o and period P, calculate the computed time C_n for each cycle you have observed. Enter these values in column 3 of your table.

6. For each cycle n, subtract the computed time C_n from the observed time O_n, which will give you the *O*\–*C* values. Enter these *O–C* values in column 4 of your table. **Note**: Because you took the first observation as your estimated epoch, the first *O-C* value will always be zero. Because you also took the time between the first two observations as your estimated period, the second *O–C* value will also always be zero.

7. Plot a graph with cycle number n on the x-axis and *O–C* value on the y-axis.

What does the *O–C* diagram tell you? Is this system perfectly periodic? Is your estimated period correct?

O–C Diagrams

To find out how *O–C* diagrams behave, let us construct some—for a set of six clocks. Actually, we will use seven clocks. One of them is a precise atomic clock, pre-set by the National Bureau of Standards. We will not actually test this clock, but rather we will use it to define the correct time. The other six are our "test clocks," and we will observe their behavior to construct *O–C* diagrams.

To create an *O–C* diagram, we need to define *C*, the computed time. So we will take as our *theory* that the test clocks are all perfectly periodic, with a *period* of 1 day, and that they are set correctly. Each day, we will observe the time at which our test clocks read "noon." We agree to take noontime on the first day of our test as the zero point of time (at which $t = 0$). In this case, when cycle zero begins, with each clock reading "noon" on our first test day, according to our theory it will actually be noon.

So the computed time of cycle 0 is $t_o = 0$. This is the *epoch* of our theory. With an epoch $t_o = 0$ and period $P = 1$, we can calculate the computed times C_n for any cycle n. Since we are using the same theory, epoch, and period for every clock, the computed times C_n will be the same for each; they are listed in Table 13.1 on the next page. Also listed in Table 13.1 are the observations, the actual times at which each clock read "noon." For each observation, we have listed both the clock time and the time in days since the experiment began (which is what we will use to compute *O–C*).

Table 13.1

Computed and observed times of “noon” for six clocks

Observed Time

Cycle	*Computed*	Clock #1	Clock #2	Clock #3	Clock #4	Clock #5	Clock #6
0		12:00p	12:05p	12:00p	11:58a	12:00p	12:00p
	0	0	.0035	0	-.0014	0	0
1		12:00p	12:05p	12:03p	11:58a	11:58a	12:00p
	1	1	1.0035	1.0021	0.9986	0.9986	1
2		12:00p	12:05p	12:06p	11:58a	11:56a	12:01p
	2	2	2.0035	2.0042	1.9986	1.9972	2.0007
3		12:00p	12:05p	12:09p	11:58a	11:54a	12:03p
	3	3	3.0035	3.0062	2.9986	2.9958	3.0021
4		12:00p	12:05p	12:12p	12:37p	11:52a	12:06p
	4	4	4.0035	4.0083	4.0257	3.9944	4.0042
5		12:00p	12:05p	12:15p	12:37p	11:50a	12:10p
	5	5	5.0035	5.0104	5.0257	4.9931	5.0069
6		12:00p	12:05p	12:18p	12:37p	11:51a	12:15p
	6	6	6.0035	6.0125	6.0257	5.9938	6.0104
7		12:00p	12:05p	12:21p	12:37p	11:52a	12:21p
	7	7	7.0035	7.0146	7.0257	6.9944	7.0146
8		12:00p	12:05p	12:24p	12:37p	11:53a	12:28p
	8	8	8.0035	8.0167	8.0257	7.9951	8.0194
9		12:00p	12:05p	12:27p	12:37p	11:54a	12:36p
	9	9	9.0035	9.0188	9.0257	8.9958	9.0250

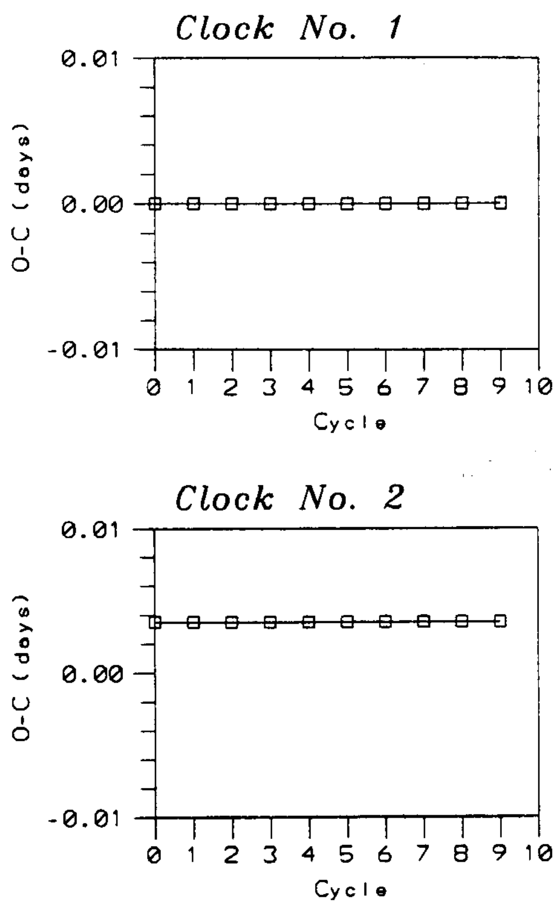
We see that Clock No. 1 fits our theory: when it reads noon, it actually is noon. Clock No. 2 is late, not reading noon until 12:05pm every day. Clock No. 3 is slow: it indicates “noon” 3 minutes later every day. Clock No. 4 is a little early until day 4, and a lot late after that. Clock No. 5 at first runs fast, marking “noon” two minutes earlier each day, until day 6; from then on it runs slow, marking “noon” a minute later every day. Clock No. 6 is not only slow, it is getting slower every day. It is easy to translate these into *O–C* values simply by subtracting *C* from *O*; these are listed in Table 13.2. We have used them to plot *O–C* diagrams in Figures 13.1a–f.

Table 13.2: *O–C* Values for Six Clocks

Cycle Number	Clock#1	Clock#2	Clock#3	Clock#4	Clock#5	Clock#6
0	0	.0035	.0000	-.0014	.0000	.0000
1	0	.0035	.0021	-.0014	-.0014	.0000
2	0	.0035	.0042	-.0014	-.0028	.0007
3	0	.0035	.0062	-.0014	-.0042	.0021
4	0	.0035	.0083	.0257	-.0056	.0042
5	0	.0035	.0104	.0257	-.0069	.0069
6	0	.0035	.0125	.0257	-.0062	.0104
7	0	.0035	.0146	.0257	-.0056	.0146
8	0	.0035	.0167	.0257	-.0049	.0194
9	0	.0035	.0188	.0257	-.0042	.0250

The first diagram (Clock No. 1, Figure 13.1a) shows what *O–C* looks like when our theory is exactly correct. All the *O–C* values are zero, because theory matches observation.

In the next diagram (Clock No. 2, Figure 13.1b), the *O–C* values still fall on a straight line parallel to the *x*-axis. However, they are all "off," by the same amount. Clock No. 2 keeps good time (it indicates noon at the same time every day), but it is a little late. In this case the theory is correct: it is perfectly periodic, and the period is correct in that it cycles in precisely 1 day; but the *epoch* is not correct—it is not "set" properly. It actually has its time of cycle zero at $t_o=0.0035$. So we have our first clue from an *O–C* diagram: **when the *O–C* values lie on a straight line which is horizontal** (parallel to the *x*-axis)**, but are all displaced from 0 by the same amount, the system is periodic, and our period is correct, but the epoch is wrong**.



Figures 13.1a (top) & 13.1b (bottom)

The next clock (Clock No. 3, Figure 13.1c) keeps indicating "noon" later and later every day. In fact, it says "noon" 3 minutes later each day. Clock No. 3 is just slow: instead of cycling in 1 day like a good clock should, it cycles in 1 day 3 minutes = 1.0021 days. Our theory is still correct in that it appears to be perfectly periodic. Our epoch is also correct: cycle 0 really did start at time 0. But the period is wrong: the true period is not *P=1* day, but *P=1.0021* days. This gives our next clue to look for in an *O–C* diagram: **when the *O-C* values lie on a straight line, but the line is not horizontal, the system is periodic but our estimated period is not correct**.

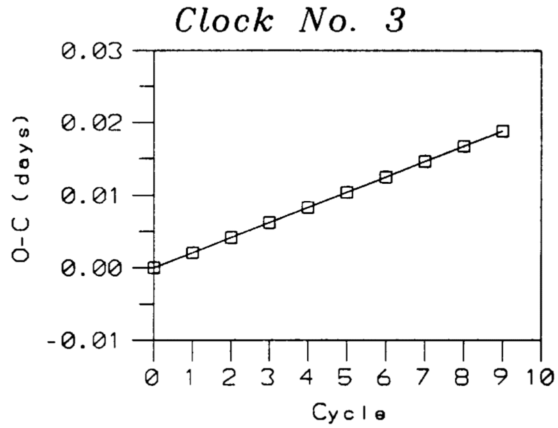


Figure 13.1c

The true period of Clock No. 3 is longer than the estimated period by 3 minutes = 0.0021 day. If we draw a straight line through the *O–C* values in Figure 13.1c, that line has a slope of 0.0021 day/cycle. Now we have another clue from *O–C*: **when the system is periodic but our period is not correct, the slope of the line through the *O–C* values is the difference between the true and estimated periods. In addition, the intercept of the line is the difference between the true and estimated epochs**.

Clock No. 4 (Figure 13.1d) was 2 minutes early until day 4, after which it was 37 minutes late. It kept good time most days, cycling in 24 hours, except from day 3 to 4, when it took an extra 39 minutes. It turns out that someone unplugged Clock No. 4 for 39 minutes between days 3 and 4. After that, the clock still has the correct period, but it is no longer set even close to being correct. In effect, it has been "re-set" by being turned off: the *epoch* has changed. Here is yet another clue from any "broken" line in an *O–C* diagram: **when the *O–C* values leave one straight line, and start another with the same slope, but which is offset, the period has remained the same but the epoch has changed**.

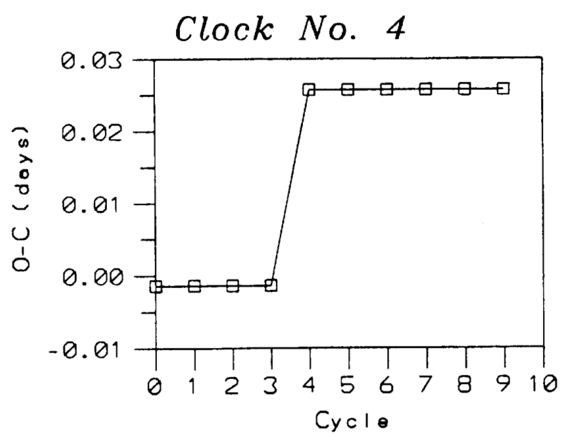


Figure 13.1d

Clock No. 5 (Figure 13.1e) was fast through day 5, reading "noon" two minutes earlier every day. This is a case of *O–C* values following a straight but not horizontal line, so the period is not correct. During these first 5 days, the period was 2 minutes less than a day, or 0.9986 day. From then on, Clock No. 5 cycled a minute later every day. The *O–C* diagram shows *another* straight line, with a different slope; this indicates a *new* period, which is 1 minute longer than a day, or 1.0007 days.

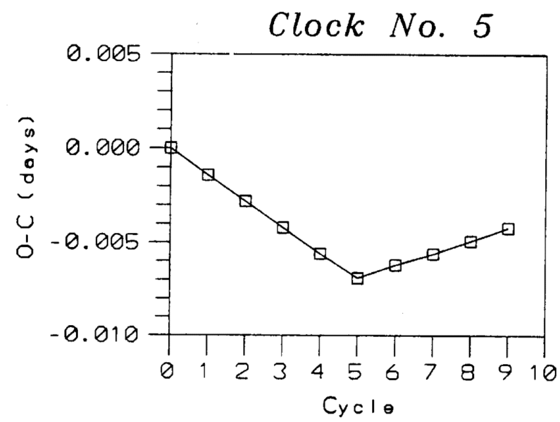


Figure 13.1e

This gives us one of the most important clues to look for in *O–C* diagrams: **when the *O–C* values change from one straight line to another which has a different slope, the period has changed. The slope of each line is the difference between its period and the estimated period**.

Clock No. 6 (Figure 13.1f) is running later and later every day, and not by the same amount. The first day it is fine, but the next day it loses 1 minute, then it loses 2 minutes, then 3, etc. This clock is *not* perfectly periodic: its period is different every day. This also gives us one of the most important things to look for in *O–C* diagrams: **when the *O–C* values do not follow a straight line, the system is not perfectly periodic**.

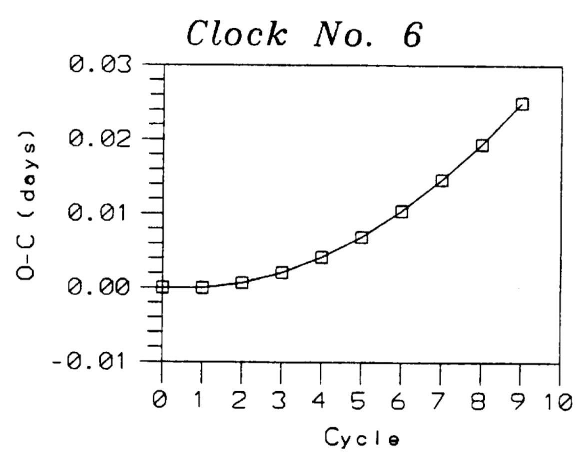


Figure 13.1f

These simple clock examples illustrate how *O–C* diagrams reveal important changes in period and epoch.

For real data, things are not always so simple. Many systems are not perfectly periodic. For Mira-type variables, for example, the period of each cycle is a little different, although the average period is stable. And for all real data, there are observational errors, no matter how precise the instrumentation. Now let us look at some real-life examples.

***O–C* Diagram Relationships**

Study the following *O–C* diagram for the Mira-type variable Z Tau (Figure 13.2). At first, the observed period is longer than the estimated period, so the *O–C* values get higher and higher. Later, the period shortens, so that near the end of the graph the *O–C* values are getting lower and lower.

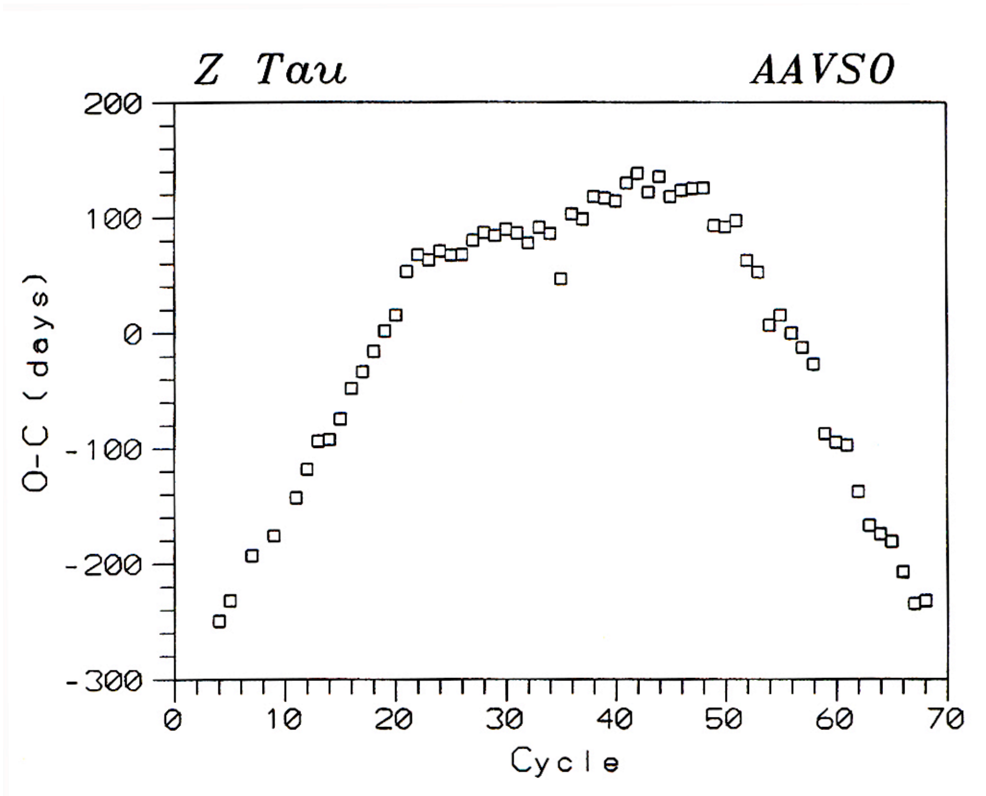


Figure 13.2

At first glance, it appears that the period of Z Tau changed slowly but steadily, decreasing by the same amount every cycle. This is similar to the behavior of Clock No.6 in our clock example. If this were the case, then the *O–C* values would fall along a parabola, which is plotted as a dashed line in Figure 13.3 on the following page. Upon closer examination, however, it is seen that a better explanation of Z Tau's behavior might be two distinct changes in period. These are plotted as solid lines in Figure 13.3 on the following page. If this interpretation is correct, then each line segment represents a different period. For the first line, from cycle 4 to about cycle 20, the slope is positive, so the period is longer than the estimated period. For the second line, from about cycle 20 to about cycle 50, the slope is also positive, but much smaller; again, the period is longer than the estimated period, but only slightly. For the last line, from about cycle 50 to the end, the slope is negative, so the period is less than the estimated period.The *O–C* diagram shows three different periodicities for Z Tau, with the observed maxima occuring from ~240 days earlier than calculated to ~140 days later than calculated.

More detailed statistical inspection of the graph shows that the *O–C* values fit the three straight lines better than they fit the parabola. So the data indicate that Z Tau has indeed shown three distinct periods, represented by the three straight lines, rather than a smoothly-changing period indicated by the dashed line.

It is also worth noting that the *O–C* values lie near to, but not exactly on, straight lines. This is to be expected; all *real* data have random errors. Also, the period of Z Tau may actually be a little different from cycle to cycle, although the average period seems to be constant over many cycles.

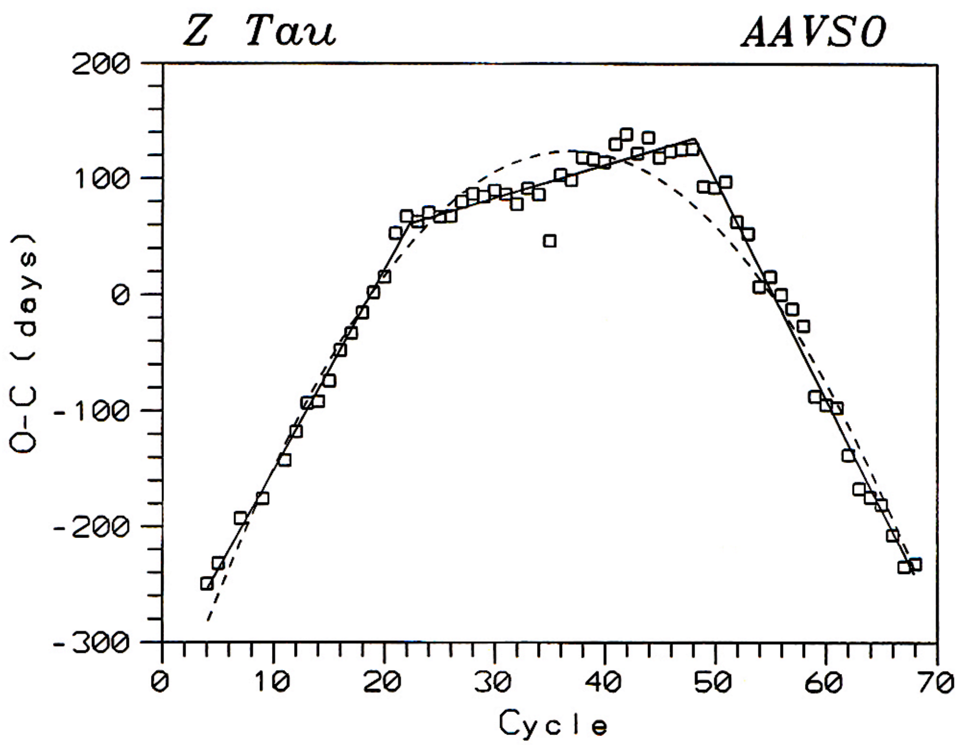
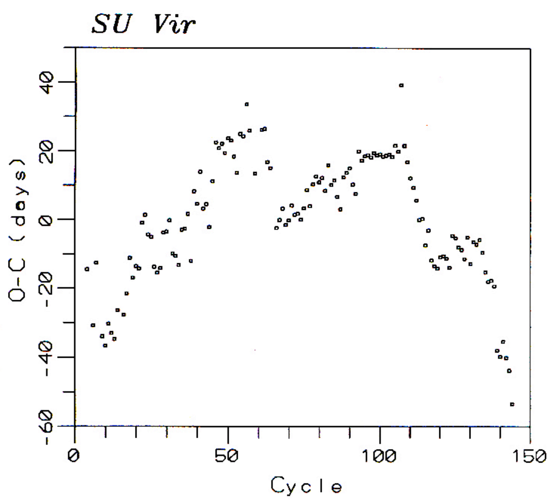
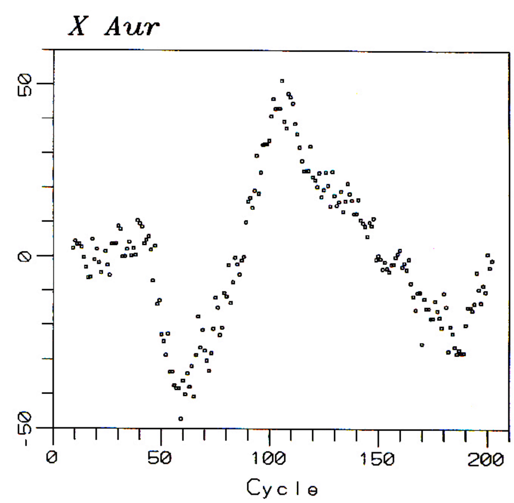


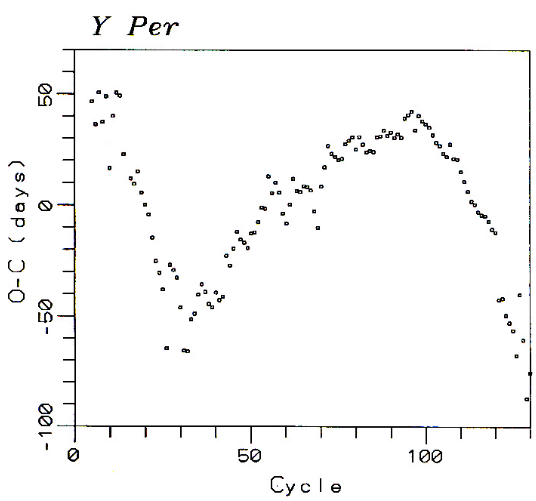
Figure 13.3

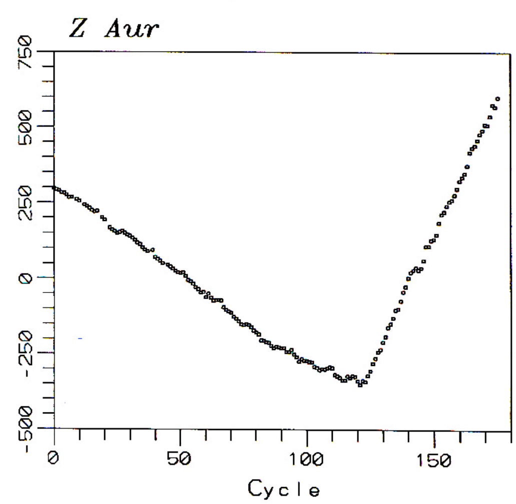
Core Activity 13.2: Understanding *O–C* with Miras

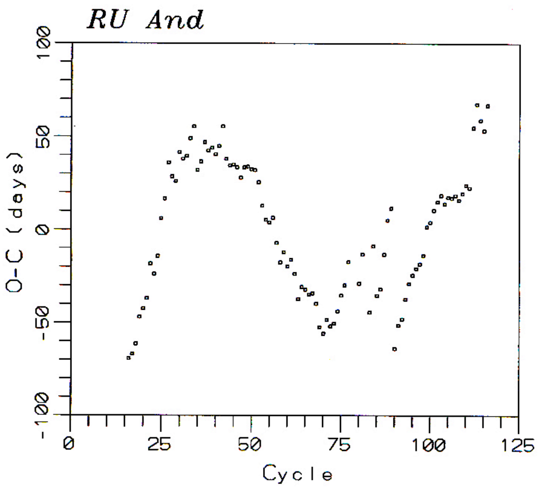
The following *O–C* diagrams have been obtained by studying the long-term behavior of eight Mira-type variable stars. Study the *O–C* diagrams and describe the differences between the predicted and observed behaviors of these stars relative to epoch and/or period.

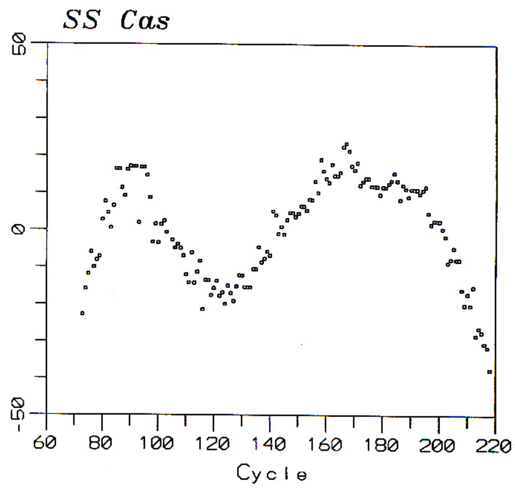


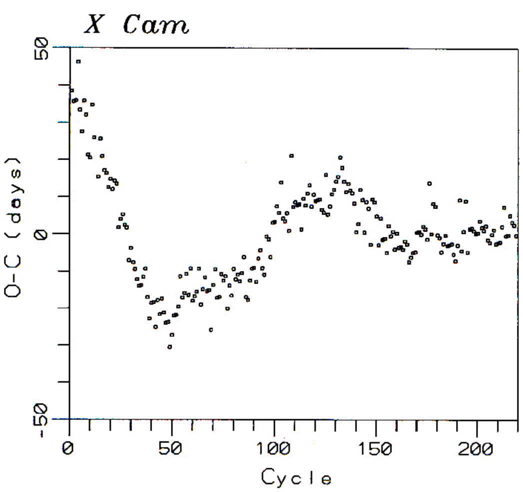


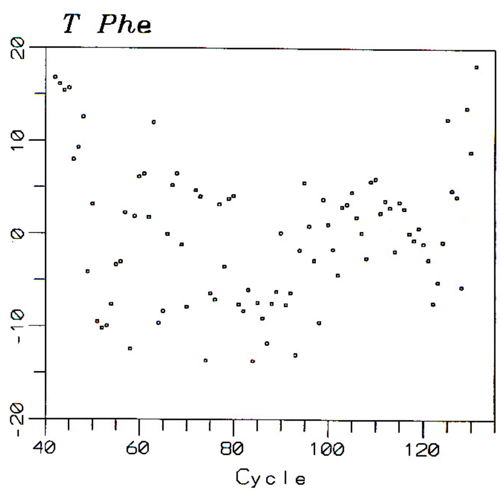





RU And
O-C (days)
100
50
0
-50
-100
0
25
50
75
100
125
Cycle


SS Cas
50
0
-50
60
80
100
120
140
160
180
200
220
Cycle


X Cam
O-C (days)
50
0
-50
0
50
100
150
200
Cycle


T Phe
20
10
0
-10
-20
40
60
80
100
120
Cycle

Core Activity 13.3: Prediction of SS Cyg

Look at the following light curve for the eruptive variable SS Cyg (Figure 13.4). Estimate the time of beginning of each eruption, the amplitude in magnitudes, and the duration in days. Predict the time of the next eruption. Access VSTAR to plot the observations for SS Cyg for JD 2449500 through 2449950. Does your predicted time for the next eruption agree with the actual time of outburst?

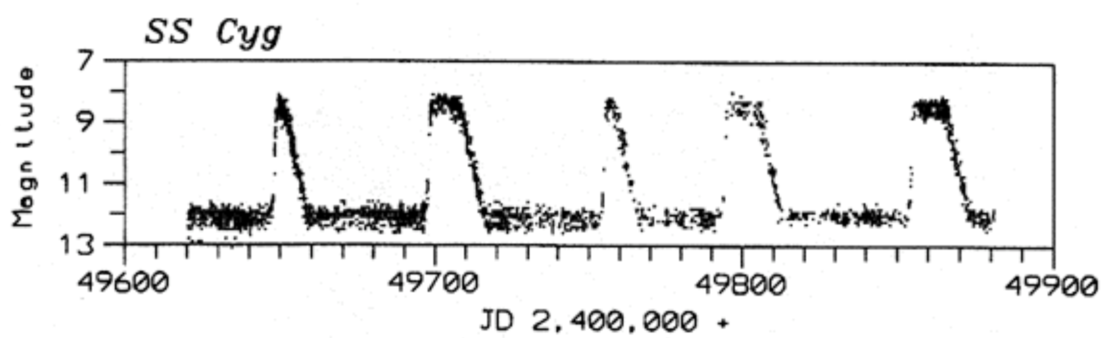


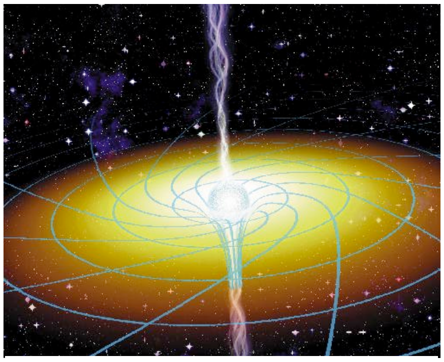
Figure 13.4

Activity 13.4: Prediction and Observation of Delta Cep

If you have observed delta Cep and determined your best estimate of the period by plotting a phase diagram, predict the times for the next few maxima. Observe delta Cep for the required amount of time and plot an *O–C* diagram for your predicted and observed results. If the diagram shows all of your *O–C* data points clustered near the 0 line on your graph, then your period determination was accurate. If you continued to observe delta Cep and noticed any changes, then the reason would be that delta Cep's period was changing.

It would be helpful at this point to write a general formula which would predict the times of maxima for delta Cep. This type of formula is called an *ephemeris* (plural: *ephemerides*) of the stars. With the formula, write a calculator or computer program to calculate the predicted times of maxima. You could write the program so that it only produces times of maxima which occur between 9:00 PM and midnight, standard time, at your location; you could also incorporate the decimal portion of the JD which corresponds to these times in your formula.

Universal Models



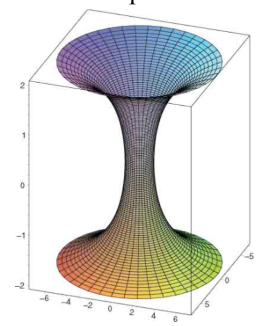
Frame Dragging – illustration courtesy of the Gravity B Probe

Cosmology is the study of the origin, evolution, and large-scale structure of the universe. Cosmological models are possible representations of the universe in simple terms. A basic assumption of cosmology is the cosmological principle. The principle states that there are no preferred places in the universe, that the universe is isotropic and homogenous. Isotropy is the property by which all directions appear indistinguishable to an observer expanding with the universe. In other words, neglecting local irregularities, measurements of the limited regions of the universe available to Earth-based observers are valid samples of the whole universe. Models are an essential link between observation and theory and act as the basis for prediction. A simple model for a two-dimensional universe is the surface of an expanding balloon, on which may be demonstrated Hubble's Law and the isotropy of the microwave background radiation, the heat left over from the explosion that initiated the universe.

Most standard cosmological models of the universe are mathematical and are based on the Friedmann universe, which assumes homogeneity and isotropy of an expanding (or contracting) universe in which the only force that need be considered is gravitation. The big bang theory is such a model. These models result from considerations of Einstein's field equations of general relativity. When the gravitational force is negligible, the equations reduce to $(dR/dt)^2/R^2 + kc^2/R^2 = (8/3)G\rho$ for energy conservation. This is known as the Friedmann equation, and ρR^3 is constant for mass conservation. R is the cosmic scale factor, ρ the mean density of matter, G the gravitational constant, and c the speed of light; k is the curvature index of space with values of +1 (closed universe in which the expansion stops, the universe contracts, and ends with a big crunch), –1 (open universe in which the expansion constantly slows down but never stops), or 0 (flat or Einstein-de Sitter universe.) Other models involving the cosmological constant, Λ, have been proposed, such as the de Sitter model, in which no mass is present; the Lemaitre model, which exhibits a coasting phase during which R is roughly constant; the steady-state theory for an unchanging universe; and those in which the gravitational constant, G, varies with time (Brans-Dicke theory). The cosmological constant is an arbitrary constant. Although it is possible for it to have any value that does not conflict with observation, it is highly probable that it is close to zero. Cosmological models involving Λ are considered nonstandard. In the standard (Friedmann) models, $\Lambda = 0$.

The Brans-Dicke theory is a relativistic theory of gravitation and a variation of Einstein's general theory of relativity. It is considered by many astronomers to be the most serious alternative to general relativity. Newton's gravitational constant is replaced by a slowly varying scalar field. The effect is to allow the strength of gravity to decrease with time. In the limit that this variation is zero, the various Brans-Dicke theories of gravitation that now exist reduce to Einstein's general relativity. Current observations limit the variation of Newton's gravitational constant to be less than one part in 10^{10} per year. This means that for local applications of a non-cosmological nature, the Brans-Dicke theory is indistinguishable from general relativity. Another model of the early universe is the inflationary universe proposed by Alan Guth in 1980. This theory describes a possible phase in the very early universe when its size increased by an extraordinary factor, perhaps by up to 10^{50}, in an extremely short period. At an age of 10^{-35} seconds, the state of the universe had to change, as the electromagnetic and strong nuclear forces "froze out" into different values. The energy released by this phase change is calculated to have caused the universe to expand, or inflate, catastrophically. The inflationary phase ended at some time before 10^{-30} seconds. After this time, the inflationary model coincides with the standard big bang description of the universe. The inflationary phase means that the observed universe is only a very small fraction of the entire universe. In addition, distant parts of the universe would have been much closer in the period before inflation than has been previously considered. The theory can explain the isotropy of the microwave background radiation, which requires distant parts of the universe to have been in causal contact in the past.

In the solution for Einstein's equations for extreme curvature of spacetime, a passage can exist between two universes or between two parts of the same universe. This structure is called an Einstein-Rosen bridge, or wormhole. Such bridges theoretically can occur in black holes for brief moments in time. Just before or just after that moment, there is no passage, only the singularity of the black hole. If you tried to race through the wormhole in the instant it opened at anything less than the speed of light, the wormhole would snap shut, trapping you and sending you into the singularity to be torn into subatomic particles, fried by radiation and crushed to infinite density. One solution to holding the wormhole open is what physicists refer to as "exotic matter." Ordinary matter has finite energy and exerts finite pressure and creates a normal, pulling, gravitational field. The opposite would be matter that has negative energy and exerts negative pressure to such an extreme level that it would produce "antigravity." Whereas ordinary matter pushes outward with pressure and pulls inward with gravity, exotic matter would pull inward with its pressure and push outward with its gravity. This concept would be similar to the inflationary universe theory. During the inflationary phase the universe underwent a rapid expansion that led to its current size and smoothness. The condition responsible for inflation is known as a false vacuum. This was the brief state of the universe when the electromagnetic and nuclear forces were indistinguishable from one another. Although not exotic matter, the false vacuum exerted a negative pressure and a repulsive gravitational field. The exotic matter necessary to create a stable wormhole would have to display the same characteristics as the false vacuum, but to a much larger degree. An Einstein-Rosen bridge could be coated with exotic matter and stabilized, maybe even become permanent.



What would a wormhole look like? It might appear spherical from the outside. The boundary would not necessarily look black, like a black hole, even though the outer structure of their spacetime geometries is similar. A black hole has an event horizon from which nothing can escape. However, you can see through a wormhole to the outside at the opposite end. Upon entering you would travel to the center of the sphere and eventually find yourself traveling away from the center, to emerge in another place outside of the wormhole. Inside the wormhole, you would be able to see light coming in from the normal space at either end of the wormhole; however, the view to either side would be distorted. The space is extremely curved. Light heading off in any direction perpendicular to the `radius' through the center of the wormhole would travel straight in the normal space inside, but end up back where it started, like a line drawn around the surface of a sphere. If you faced sideways in a wormhole you could, in principle, see the back of your head. However, the light would be distorted and your view out of focus. You would not be able to see stars through the sides of the tunnel because there is no literal tunnel wall and inside the light is trapped by the extreme curvature of space. You would not be able simply to travel through the mouth of the tunnel. It is not shaped like a funnel as represented in the two-dimensional models of the three-dimensional space around a wormhole drawn above. In these models, a circle in two-dimensional space is the analog of a sphere in three-dimensional space, and the real curved space around a wormhole is represented by a stretched two-dimensional space that resembles a funnel. You would not be able to travel through the mouth of the funnel. The funnel is a three-dimensional hyperspace in the two-dimensional analog. You would have to crawl along the surface of the two-dimensional space to get the true meaning of the nature of that space and some feeling for the three-dimensional reality. Another consideration for wormholes is Hawking radiation. Stephen Hawking's calculations show that in the space near the event horizon of a black hole, natural radiation is emitted which eventually leads to the evaporation of the black hole. In a wormhole, the Hawking radiation from one end of the wormhole can travel through normal space to the other end, enter, travel straight through, and emerge just as it left. Now there is twice as much radiation. This cycle could repeat endlessly, building up an infinite energy density which would either seal off the wormhole or prevent it from having existed in the first place.

So far there is no grand unified theory in physics. The holy grail of physics is the quest for a theory which unifies the physics of extremely curved spacetime with the probabilistic nature of quantum mechanics. This theory is necessary to fully understand the nature of the singularity of a black hole, the origin of the universe, and the validity of other mathematical cosmological models such as Einstein-Rosen bridges.

Core Activity 13.5: Prediction and Analysis of the Period of R Cyg

Access the VSTAR database and load the following observational data for R Cyg (Figure 13.5) on your screen. Determine the times of maximum brightness by fitting a polynomial to the observations. Your instructor will give you the times of predicted maxima. Plot an *O–C* diagram and determine the difference between the predicted and observed behavior for R Cyg. What is the star's behavior? Can you find any secondary relationships in the period of this pulsating red giant star?

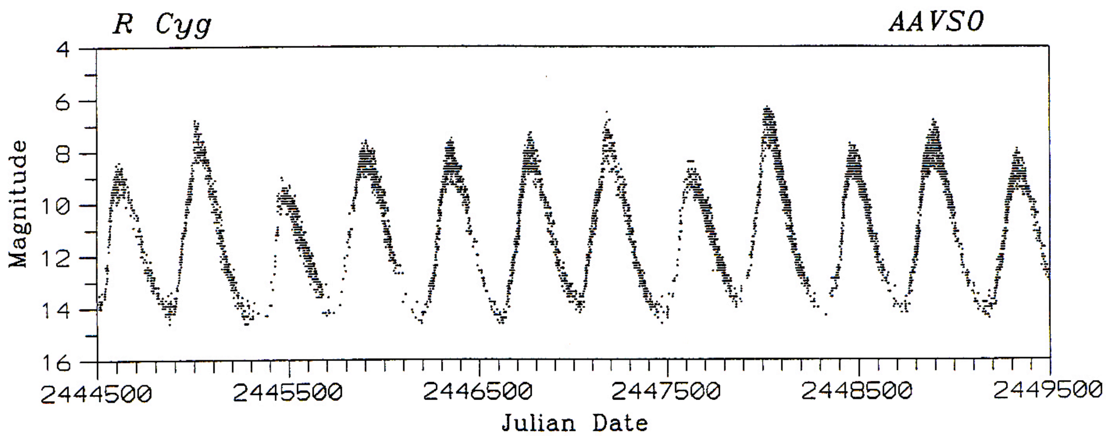


Figure 13.5

Activity 13.6: *O–C* for Eclipsing Binary Stars

You have studied pulsating variables, both short-period Cepheids such as delta Cep and long-period Miras such as V Cas. Now we will use *O–C* to study the behavior of an eclipsing binary star. Remember that for eclipsing binaries, it is the time of *minimum* brightness, rather than maximum, that is of most interest. This is because minimum corresponds to the middle of the eclipse, and the eclipse is what we are really interested in timing. In fact, a large number of variable star observers specialize in eclipsing binary stars, and design their observing programs to get accurate timings of the minimum brightness. Table 13.9 lists AAVSO data for the eclipsing binary star X Tri. Instead of containing magnitudes, it lists times of minima.

Let's construct an *O–C* diagram for the minima of X Tri. To do so, we need to estimate the period and the epoch. We will use the following values:

Epoch: t_o = JD 2442502.721

Period: P = 0.975352 day

Using this period and epoch, we can calculate the computed time C_n of any minimum.

There are a lot of minima in Table 13.9 (on the following page). Your teacher will assign each of you a small number of cycles to compute. For the cycles assigned to you, take the cycle number n and use it to calculate the computed time of minimum C_n. When all the students have completed the cycles assigned to them, collect all the class data into a large table, listing cycle number n (from Table 13.9), observed time of minimum O_n (also from the Table 13.9), and your computed time C_n.

Now subtract C_n from O_n, for each cycle, to get $(O–C)_n$ for every cycle n listed in the table. Finally, prepare an *O–C* diagram, showing cycle number n on the x-axis and *O–C* value on the y-axis.

What can you tell about the behavior of X Tri from this *O–C* diagram? Are the estimated period and epoch correct? Did the period change?

Table 13.9
Minima Timings of X Tri[1]

Cycle[2]	JD (minimum)	Cycle[2]	JD (minimum)	Cycle[2]	JD (minimum)
230	2442726.175	3197	2445608.722	5107	2447464.348
318	2442811.668	3198	2445609.694	5108	2447465.310
322	2442815.551	3233	2445643.695	5168	2447523.601
523	2443010.832	3233	2445643.697	5169	2447524.576
524	2443011.802	3508	2445910.867	5200	2447554.687
524	2443011.806	3544	2445945.845	5202	2447556.637
524	2443011.811	3619	2446018.711	5237	2447590.644
557	2443043.863	3621	2446020.646	5238	2447591.611
560	2443046.783	3621	2446020.649	5446	2447793.689
564	2443050.666	3621	2446020.652	5447	2447794.661
567	2443053.582	3622	2446021.618	5447	2447794.667
945	2443420.818	3622	2446021.618	5448	2447795.639
948	2443423.741	3622	2446021.620	5449	2447796.604
952	2443427.615	3626	2446025.508	5477	2447823.805
984	2443458.717	3659	2446057.567	5478	2447824.776
985	2443459.687	3660	2446058.540	5481	2447827.690
985	2443459.689	3690	2446087.686	5516	2447861.695
1020	2443493.687	3725	2446121.692	5520	2447865.581
1021	2443494.658	3934	2446324.737	5555	2447899.589
1262	2443728.797	3936	2446326.679	5829	2448165.784
1338	2443802.635	3974	2446363.599	5903	2448237.677
1408	2443870.641	4003	2446391.772	5903	2448237.677
1686	2444140.727	4004	2446392.745	5942	2448275.566
1687	2444141.700	4008	2446396.633	6180	2448506.792
1688	2444142.671	4042	2446429.665	6570	2448885.692
1689	2444143.641	4044	2446431.605	6573	2448888.606
1760	2444212.623	4078	2446464.635	6608	2448922.610
1762	2444214.566	4079	2446465.612	6637	2448950.781
1795	2444246.628	4322	2446701.688	6639	2448952.724
1797	2444248.567	4354	2446732.781	6641	2448954.668
1829	2444279.660	4356	2446734.726	6642	2448955.638
2075	2444518.656	4358	2446736.671	6957	2449261.673
2077	2444520.602	4389	2446766.785	7031	2449333.558
2112	2444554.600	4391	2446768.728	7348	2449641.535
2182	2444622.609	4397	2446774.559	7728	2450010.717
2419	2444852.863	4432	2446808.560	7734	2450016.550
2452	2444884.926	4668	2447037.839	7763	2450044.721
2527	2444957.790	4740	2447107.788	7764	2450045.693
2566	2444995.678	4741	2447108.761	7769	2450050.555
2845	2445266.743	4742	2447109.735	7800	2450080.669
2878	2445298.797	4742	2447109.735		

[1]Times of minima of X Tri are from AAVSO monographs *Observed Minima Timings of Eclipsing Binaries, Nos. 1,2,3,* prepared by M. Baldwin and G. Samolyk (1993, 1995, 1996).

[2]Repeated cycles indicate times of minimum from different observers.

SPACE TALK

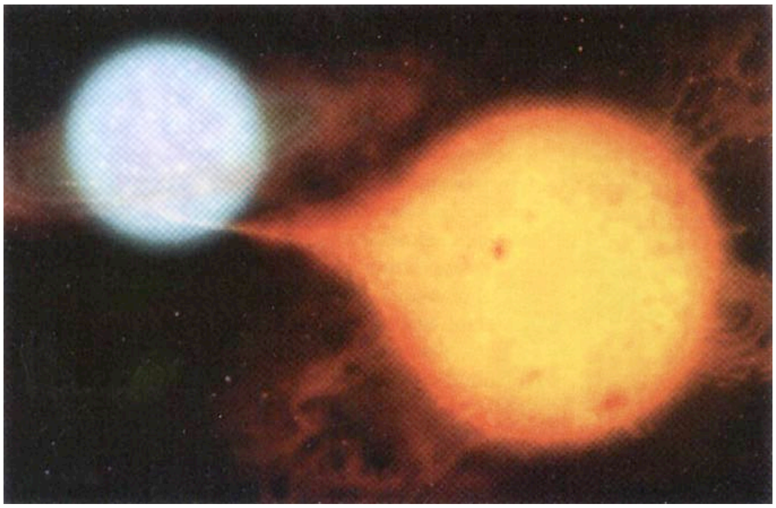
Algol (beta Persei) is the brightest eclipsing binary in the sky, and the most famous of the eclipsing variable stars. Algol means "Demon Star" in Arabic, and this suggests that its strange variability might have been known in antiquity, although there is no concrete evidence to support this conjecture. The name is from the Arabic *Al Ra's al Ghul*, which translates to "The Demon's Head." The Hebrews called the star "Satan's Head." In some other traditions, it is identified with the mysterious and sinister Lilith, the legendary first wife of Adam. Medieval astrologers considered Algol the most dangerous and unlucky star in the heavens.

Although Algol's name suggests that its light changes were known to the medieval Arabs, the first written account was made by the Italian astronomer Geminiano Montanari of Bologna in 1667. The English astronomer John Goodricke is credited with establishing the period of Algol in 1782. Goodricke proposed that the variation in Algol's brightness was due to its being eclipsed by an unseen companion, possibly a planet. In 1881, Edward Pickering, the Director of Harvard College Observatory, presented evidence which showed that Algol was an eclipsing binary star.

One peculiar feature of the Algol system, shared by other binaries of the same type, is that the fainter and less massive star has evolved to the subgiant stage, while the primary star remains a main sequence object. This is a stellar evolutionary paradox, for if the stars are of the same age, the brighter and more massive star should evolve more rapidly. Binary stars form together from the same condensing cloud of gas and dust, and therefore have to be the same age. Astronomer Fred Hoyle suggested the following solution to the dilemma. The fainter star was originally the more massive and luminous of the pair. As it began its evolutionary expansion it lost great quantities of matter to the close companion. It thus became fainter as it evolved to the subgiant stage. At the same time the companion grew more brilliant as the result of its increased mass. This is now considered to be the case. Although Algol is the most studied eclipsing binary, high-resolution spectroscopy has only recently begun to reveal the details of its behavior.

Algol is actually a three-star system 92 light-years away. The **primary** star is a bright B8 main-sequence star. The primary is eclipsed every 2.87 days by the **secondary** star, a larger, dimmer, less massive K2 subgiant with a very active surface covered with starspots. The K2 subgiant and the B8 primary are in a very close orbit. In the distance a **tertiary** F1 main-sequence star orbits the binary pair every 1.86 years. Algol varies in magnitude from 2.1 at maximum to 3.4 at primary minimum, with a period of 2.87 days. The period is slowly lengthening due to the mass transfer of material between the two stars. The primary eclipse occurs when the fainter K2 secondary passes in front of the brighter B8 star, and lasts for ~10 hours. To us, the eclipse is a partial one, due to the angle from which we observe it. There is also a shallow secondary eclipse when the B8 star passes in front of the K2 star. This can only be detected photoelectrically. The primary eclipse, however, can easily be detected with the unaided eye.

The K2 subgiant has expanded to fill its **Roche lobe**, a teardrop-shaped volume of space in which its gravity is strong enough to hold onto its loose atmospheric material. The tip of the teardrop shape points in the direction of the primary. As the K2 subgiant tries to expand further, a thin but powerful stream of gas spills from the point of the Roche lobe and crashes down onto the B8 primary star. A binary system such as this, in which one component has filled its Roche lobe and is transferring material to its companion, is called a **semidetached binary**. The speed of the stream of gas is 520 km/s when it slams into the B8 star. The stream of gas, now heated to 100,000K, strikes the B8 star's surface at a low angle and kicks a spray of gas forward and upward. This spray forms a variable, asymmetric **accretion disk** that circles the primary before settling onto the surface. The disk varies in size and shape, indicating that the gas stream varies also. The K2 star must overflow intermittently. If the B8 star were smaller, or if the stars' separation were wider, there would be room for the formation of a permanent, stable accretion disk. Instead, the surface of the B8 star gets in the way. Algol-type binaries with orbital periods greater than 5 or 6 days do have room to acquire permanent accretion disks, but Algol itself revolves in only 2.87 days.



Algol is a strong radio source. The radio emissions come from the hot corona, the layer of atmosphere directly above the photosphere surrounding the K2 star. The star probably rotates in step with its orbital period, generating a strong magnetic dynamo effect within the star, intense surface activity, and a strong radio-emitting corona. This was confirmed by **very long baseline interferometry** (**VLBI**), a method of simultaneously pointing several radio telescopes (widely separated by long distances) at an object. Radio astronomers also announced that the orbital plane of the close binary pair is oriented at a right angle to the orbital plane of the distant F1 star, contrary to theories relating to the formation of multiple star systems. Another study has reported the opposite—that all three stars lie in the same orbital plane.

In September 1990, the second-brightest eclipsing binary was discovered, and it happens to be located in the same constellation. The star is 3rd magnitude gamma Persei. The eclipses of gamma Persei occur rarely—approximately every 14.67 years. The next eclipse is expected in April of 2005. However, the star will then be in superior conjunction with the Sun, and so will not be visible from Earth. (Objects are in **superior conjunction** when they are on the opposite side of the Sun from the Earth.)

Gamma Persei consists of a cool, giant G8 primary star in orbit with a hot, main-sequence A2 secondary. It is a **composite-spectrum binary** (also called a spectroscopic binary): spectroscopic analysis shows the presence of features from two different stars. The composite nature of the spectrum was recognized in 1897 by Antonia Maury at Harvard. Gamma Persei was resolved into its two components for the first time in 1973, and it was extensively analyzed in 1987. At this time it was predicted that the A2 star would pass behind the G8 star in the fall of 1990. The eclipse occurred on the evening of September 12th, and was recorded at several observatories. The secondary star "set" more or less vertically behind the giant star's limb, so the eclipse was central, or behind the middle of the G8 star, and lasted for an entire week. The eclipse was 0.3 magnitude deep visually, so it was detectable—though certainly not conspicuous—with the unaided eye. Gamma Persei will not eclipse again for unaided-eye observers until November 2019.

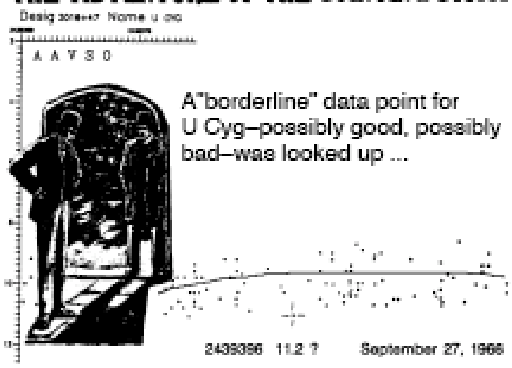
THE BIRCH STREET IRREGULARS:
MYSTERIES FOUND AND RESOLVED IN THE AAVSO DATA ARCHIVES

by Sara J. Beck, Michael Saladyga, Janet A. Mattei and the AAVSO Technical Staff

(Adapted from a paper given at the 1994 AAVSO Spring meeting.)

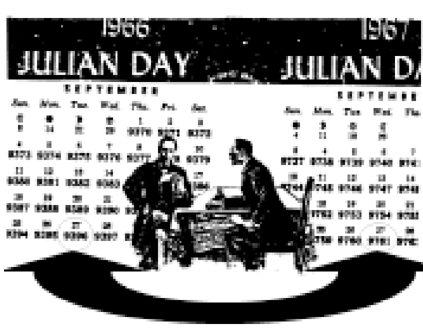
As AAVSO data are evaluated, AAVSO Technical staff and the Director run across several kinds of errors which are tracked down and rectified–a process requiring skillful investigative techniques, a good head for deduction, and dogged tenacity. With apologies to Sir Arthur Conan Doyle, author of Sherlock Holmes, here are a few of the many success stories of the detectives known as the Birch Street Irregulars. These cases also provide the new observer with an idea of some of the common pitfalls experienced by their predecessors.

THE ADVENTURE OF THE DANCING DATA

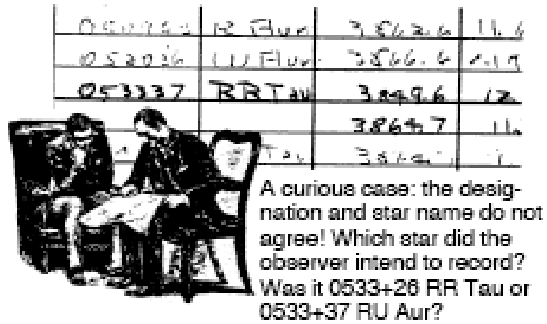


A check on the observer's report showed that the Julian Dates for not only U Cyg, but for the entire report, were off by more than 300 days compared to the month and year written in the header.

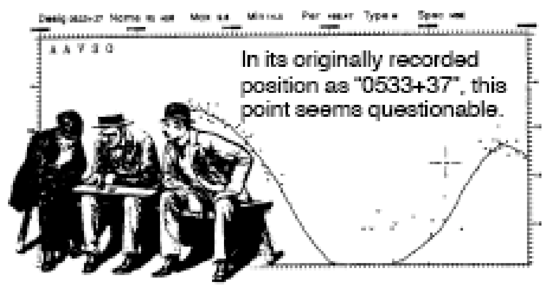
In comparing the JD calendars for the year of the report and the previous year, it became obvious that the observer had copied the JDs from the previous year's calendar.

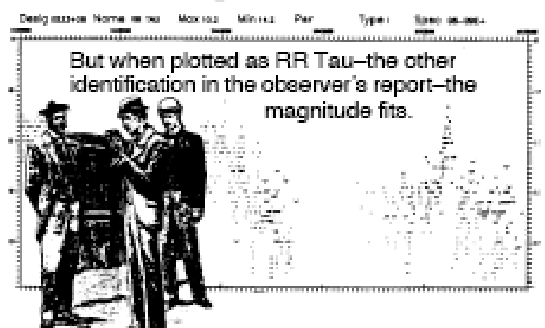


A CASE OF IDENTITY



The problem: many observations in the archives were recorded with a name and designation for two different stars. The usual causes include: (1) The observer reading the designation or name from the line above in the report form; (2) giving the wrong component letter, or none at all, in the designation; or (3) simply writing one star's name while thinking of another star (for example, WX Cet and WX Cyg).





THE ADVENTURE OF THE GREEK INTERPRETER

In this instance of star name and designation disagreeing, the observer meant to record chi Cyg, but the handwritten Greek letter chi (χ) was read as "X" by the data entry technician.

Solution: Always write out the Greek letter names. (eg. beta Per rather than β Per)