PERIOD CHANGES IN RV TAURI STARS: OBSERVATIONS AND SIMULATIONS

John R. Percy
Alexandra Csatary
Ingrid Zorgdrager
Erindale Campus
University of Toronto
Mississauga, Ontario
Canada L5L 1C6

Received: June 30, 1993

Abstract

We have determined the times and magnitudes of minimum brightness of two RV Tauri stars (SS Gem and V Vul) using data from the AAVSO and from the literature. We have used these to construct (O-C) diagrams. These are dominated by cyclic features with time scales ranging from several to several hundred pulsation periods. By constructing simulated (O-C) diagrams, we have shown that the observed (O-C) diagrams could be explained by the accumulation of random, cycle-to-cycle fluctuations in period, as in the case of most Mira stars.

1. Introduction

RV Tauri stars are pulsating yellow supergiants with light curves characterized by alternating deep and shallow minima. They are believed to be in the post-asymptotic giant branch (AGB) phase of evolution - a rather transient phase lasting only a few thousand years. If this is the case, then RV Tauri stars should be contracting on this time scale, and should show decreasing periods of pulsation if the period changes are due solely to evolution.

The most comprehensive study of period changes in RV Tauri stars is by Erleksova (1971), who compiled data and presented (O-C) diagrams for 21 such stars. In each case, the (O-C) diagram was interpreted in terms of a series of abrupt period changes, which appeared to be as often positive as negative. Zsoldos (1988) found that the (O-C) diagram of AC Her shows regular cyclic behavior which, when fitted with a sine curve, gives a period of 9320 days, and an amplitude of 3.69 magnitudes. Percy *et al.* (1991) investigated the period changes in U Mon and R Sct, using a century or more of data; they found abrupt period decreases in each star which, when averaged over the interval of observation, were in good agreement with the values predicted by pulsation-evolution theory. There were also small cyclic oscillations in the (O-C) diagram of U Mon.

Because of the variety of forms and interpretations of RV Tauri star (O-C) diagrams, further studies of them would be useful. There are several RV Tauri stars in the AAVSO visual observing program, and these observations should be analyzed. In the present paper, we investigate the period changes in SS Gem and V Vul, using data from the AAVSO and from the literature. These relatively bright variables were discovered to be variable early in this century. According to the *General Catalogue of Variable Stars* (Kholopov *et al.* 1985), both are RVa stars (i.e., no long-term magnitude variations) with periods of 89.31 and 75.7 days, respectively. Zsoldos has published UBV photometry of these stars, from which he has determined light and color curves; from these and earlier observations, he has also derived (O-C) diagrams for these stars (SS Gem: Zsoldos 1991; V Vul: Zsoldos 1993; the latter paper also discusses AC Her and R Sge).

The resulting (O-C) diagrams are not simply explainable in terms of evolutionary effects; we therefore considered other explanations. The (O-C) diagrams of most Mira stars can be explained in terms of random cycle-to-cycle period fluctuations. We therefore simulated (O-C) diagrams for RV Tauri stars using this model. The observed and simulated (O-C) diagrams are qualitatively similar.

2. SS Geminorum

The data used in the present study are AAVSO visual observations from JD 2438020 to 2447640, kindly provided by Dr. J. A. Mattei (1992). These conveniently cover the interval which is sparsely covered in the (O-C) diagram by Zsoldos (1991). Dates and magnitudes of minimum brightness were determined systematically by IZ; a few were independently determined by JRP to ensure that the results were consistent. The (O-C) diagram, based on a period of 89.16 days and an epoch of JD 2414610.01 (the same parameters used by Zsoldos), is shown in Figure 1. The larger symbols represent primary minima; the smaller symbols represent secondary minima plus half a cycle. Note that we and Zsoldos have both used the double or formal period (the interval between adjacent deep minima).

The most conspicuous features in Figure 1 are the cycles with length about 3600 days and amplitude about 6 days. A similar wave-like structure is visible in Zsoldos' (O-C) diagram, but the cycle lengths are much longer: 7000 to 15400 days. It is clear that the (O-C) diagram is not periodic, nor can it be fitted by straight line segments as would be the case if the period changes were abrupt.

3. V Vulpeculae

The data used in the present study are: (1) AAVSO visual observations from JD 2424000 (1924) to 2446000 (1984), kindly provided by Dr. J. A. Mattei (1992), (2) minima derived from visual observations published by Ahnert (1948), (3) photographic observations by Payne-Gaposchkin *et al.* (1943), and (4) photoelectric observations by Kameny (1953), Preston *et al.* (1963), and DuPuy (1973). Dates and magnitudes of minimum brightness were determined systematically by AC, with a few being determined independently by JRP to ensure that the results were consistent. The (O-C) diagram, based on a period of 37.86 days and an epoch of minimum of JD 2414902 (approximately 1899) is shown in Figure 2. Note that we have used the "single" period (the time between adjacent minima, believed to be the pulsation period), as did Percy *et al.* (1991) for U Mon and R Sct.

As expected, the (O-C) diagram is very similar to that of Zsoldos (1993) except that, since Zsoldos used the double period, the cycle number in Figure 2 is twice that in Zsoldos' (O-C) diagram. Zsoldos used a more complete set of sources of earlier observations, but did not have access to the AAVSO data. The most conspicuous feature of the (O-C) diagrams is a "cycle" with a time scale of 15000 days and an amplitude of 30 days. The diagram cannot be fitted by a small number of straight line segments as would be the case if the period changes were abrupt.

4. Simulations

It has been known for decades (Eddington and Plakidis 1929; Sterne and Campbell 1937) that the (O-C) diagrams of Mira stars can be explained, in most cases, in terms of the accumulation of random, cycle-to-cycle period fluctuations.

Percy *et al.* (1990), Isles (1992), Koen (1992), and Lloyd (1992) have recently applied this model to up to 400 Miras observed over many decades.

The approach used by these authors was a quantitative and therefore powerful one, namely, to analyze the statistical properties of the (O-C) diagrams. Our approach is a qualitative, but still illuminating one, namely to simulate a variety of (O-C) diagrams based on the model. We used a "typical" period of 50 days, and generated (O-C) diagrams covering 300 cycles. The calculated times of minimum (C) were determined by assuming a constant period of 50 days (the initial period). The "observed" times of minimum (O) were the sums of the lengths of the cycles up to that time. Each cycle length was taken to be the previous cycle length, plus r.f where r is a random number between -1 and +1, and f is a multiplier which was given values of 4, 2, 1, 0.5, or 0.25 on different runs. Several dozen (O-C) diagrams were generated. The multiplier f determines the scale of the (O-C) fluctuations; values between 2 and 4 (average cycle fluctuations of 1 to 2 per cent) produced (O-C) diagrams whose scale agreed with typical observed (O-C) diagrams. Note that, in Figure 3, the assumed period is the initial period rather than the average period, so the average slopes of the diagrams are not zero. Note also that the instantaneous period is not constrained to remain close to the initial period. Incidentally, our approach is similar to the classical statistical phenomenon known as a "random walk".

An alternative approach would have been to constrain each cycle length to be the initial period plus r.f. This would be realistic if the pulsation were driven from below by a highly-periodic oscillation, to which other processes in the envelope of the star (convection cells, for instance) added a random component. We will investigate this alternative in a future paper.

5. Discussion and Conclusions

The observed (O-C) diagrams of SS Gem and V Vul are dominated by cyclic features with time scales ranging from several to several hundred pulsation periods. Given the limited time span of the observations, longer cycles would not yet be detected. The observed (O-C) diagrams cannot be fitted by a small number of straight line segments, so the period changes cannot be considered to be abrupt. They also cannot be interpreted in terms of a consistently increasing or decreasing period (either continuous or abrupt), as might be the case if the period changes were due to evolution. Certainly they differ from the (O-C) diagram of U Mon (Percy *et al.* 1991), even though U Mon, SS Gem, and V Vul have quite similar periods and effective temperatures (Wahlgren 1992).

The simulated (O-C) diagrams show a wide variety of features, including "cycles" of different lengths and apparently abrupt period changes. These could appear as evolutionary changes in some cases, especially if studied over a limited interval of time. The model can therefore explain most of the features of observed RV Tauri star (O-C) diagrams, except perhaps the very regular cyclic behavior of AC Her.

Lombard and Koen (1993) have identified problems with the use of the (O-C) diagram as a means of identifying period changes in stars with significant intrinsic scatter in period; they suggest more sophisticated methods of analysis. To some extent, our present qualitative approach circumvents these problems. On the other hand, different physical processes may produce (O-C) diagrams which are qualitatively similar.

Finally, it is interesting to note that Ashbrook *et al.* (1954) applied a similar stochastic model to the light curve of the red supergiant variable mu Cep, and were able to generate synthetic light curves which closely resembled the observed ones (and the observed (O-C) diagrams of SS Gem and V Vul!).

6. Acknowledgements

We thank the many AAVSO observers whose work made this research possible, and we thank the AAVSO HQ staff for providing the data. Alexandra Csatary was a participant in the University of Toronto Mentorship Program, which enables talented senior high school students to work on research projects with university faculty. Ingrid Zorgdrager's work was supported by the SEED summer employment program of the government of Canada.

References

Ahnert, P. 1948, *Astron. Nachr.,* **276**, 241.
Ashbrook, J., Duncombe, R. L., and van Woerkom, A. J. J. 1954, *Astron. J.,* **59**, 12.
DuPuy, D. L. 1973, *Astrophys. J.,* **185**, 597.
Eddington, A. S., and Plakidis, S. 1929, *Mon. Not. Roy. Astron. Soc.,* **90**, 65.
Erleksova, G. E. 1971, *Peremennye Zvezdy,* **18**, 53.
Isles, J. E. 1992, in *Variable Star Research: An International Perspective,* eds. J. R. Percy, J. A. Mattei, and C. Sterken, Cambridge University Press, 231.
Kameny, F. E. 1953, *Astron. J.,* **58**, 217.
Kholopov, P. N. *et al.* 1985, *General Catalogue of Variable Stars,* Fourth Edition, Moscow.
Koen, C. 1992, in *Variable Stars and Galaxies,* ed. B. Warner, Astronomical Society of the Pacific Conference Series, **30**, 127.
Lloyd, C. 1992, in *Variable Star Research: An International Perspective,* eds. J. R. Percy, J. A. Mattei, and C. Sterken, Cambridge University Press, 242.
Lombard, F., and Koen, C. 1993, *Mon. Not. Roy. Astron. Soc.,* **263**, 309.
Mattei, J. A. 1992, observations from the AAVSO International Database, private communication.
Payne-Gaposchkin, C., Brenton, V. K., and Gaposchkin, S. 1943, *Ann. Harvard Coll. Obs.,* **113**, 1.
Percy, J. R., Colivas, T., Sloan, W. B., and Mattei, J. A. 1990, in *Confrontation between Stellar Pulsation and Evolution,* eds. C. Cacciari and G. Clementini, Astronomical Society of the Pacific Conference Series, **11**, 446.
Percy, J. R., Sasselov, D., Alfred, A., and Scott, G. 1991, *Astrophys. J.,* **375**, 691.
Preston, G. W., Krzeminski, W., Smak, J., and Williams, J. A. 1963, *Astrophys. J.,* **137**, 401.
Sterne, T. E., and Campbell, L. 1937, *Ann. Harvard Coll. Obs.,* **105**, 459.
Wahlgren, G. M. 1992, *Astron. J.,* **104**, 1174.
Zsoldos, E. 1988, *Inform. Bull. Var. Stars,* No. 3192.
Zsoldos, E. 1991, *Astrophys. Space Sci.,* **181**, 203.
Zsoldos, E. 1993, *Astron. Astrophys.,* **268**, 149.

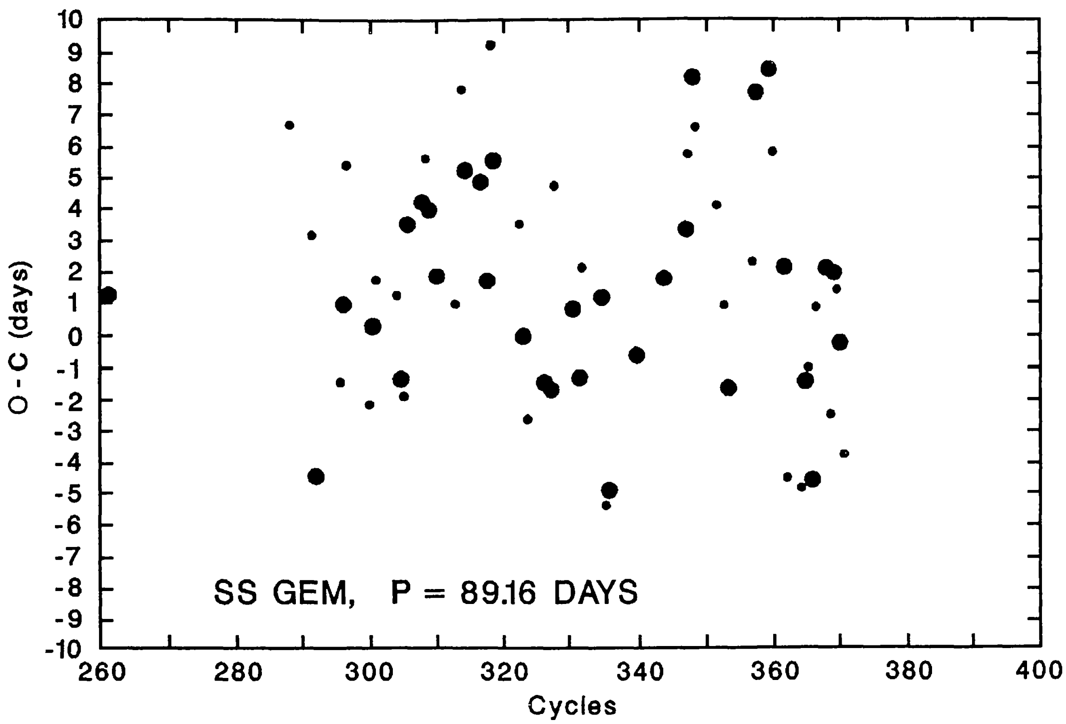


Figure 1. The (O-C) diagram of SS Gem, based on AAVSO visual observations, and assuming a period of 89.16 days and an epoch of JD 2414610.01. The larger symbols refer to primary minima, the smaller to secondary minima plus half a cycle.

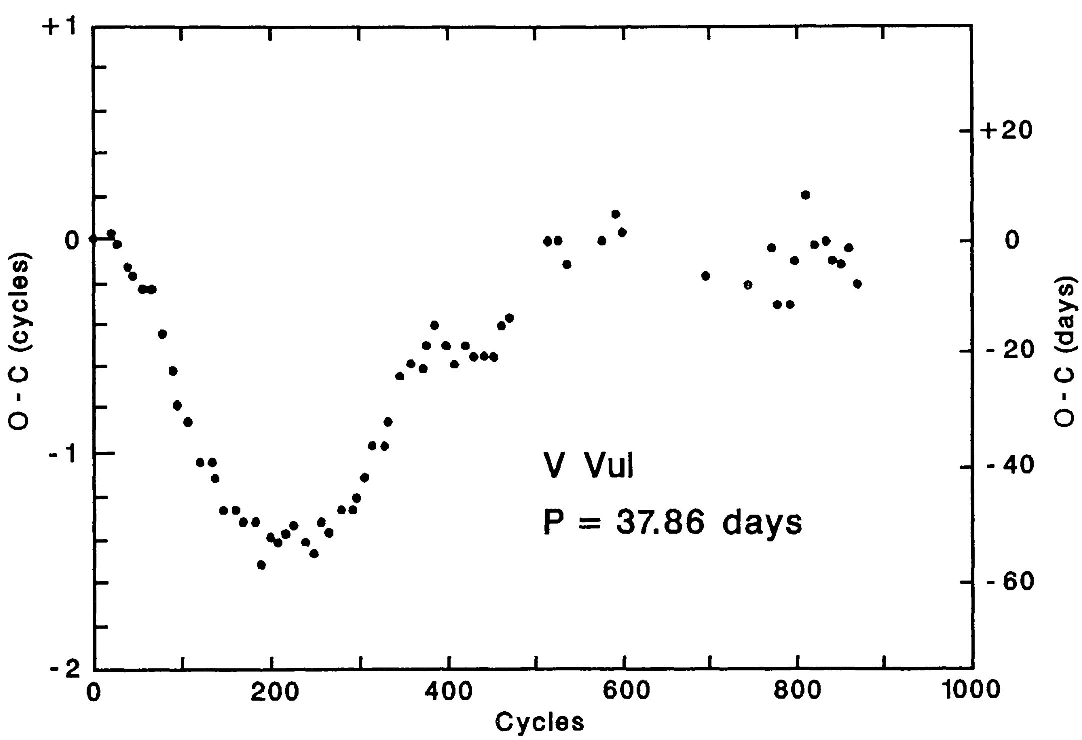
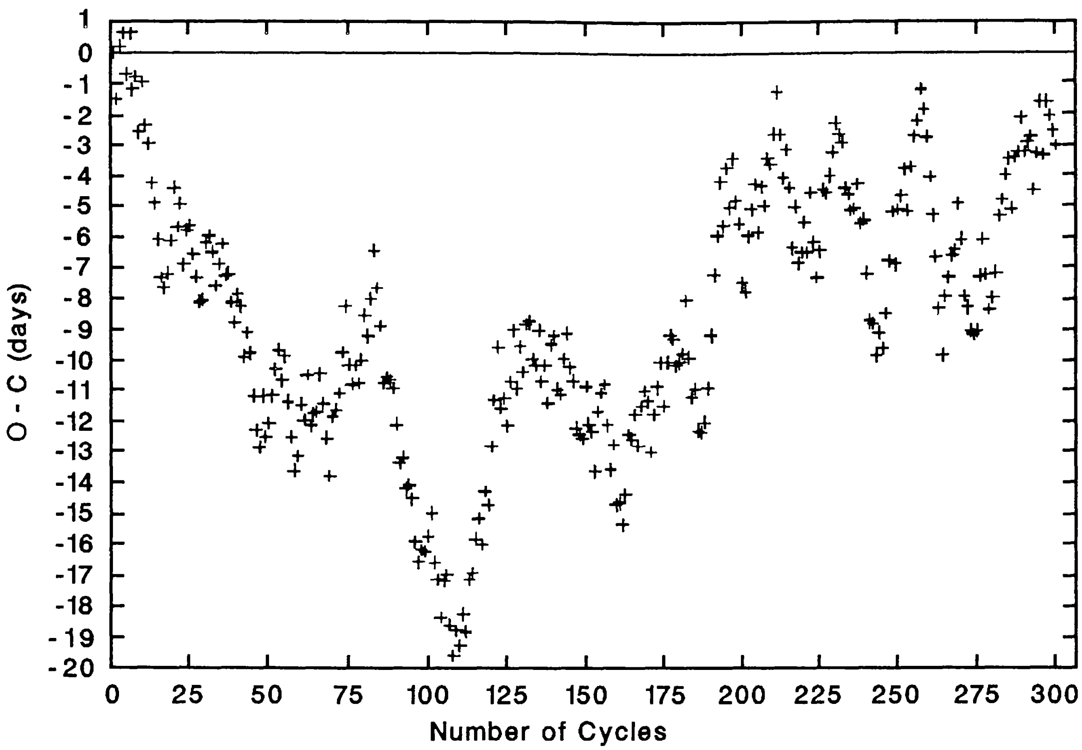


Figure 2. The (O-C) diagram of V Vul, based on AAVSO visual observations and on other sources mentioned in the text, and assuming a period of 37.86 days and an epoch of JD 2414902. This period is the "single" period (the interval between adjacent minima), believed to be the pulsation period.



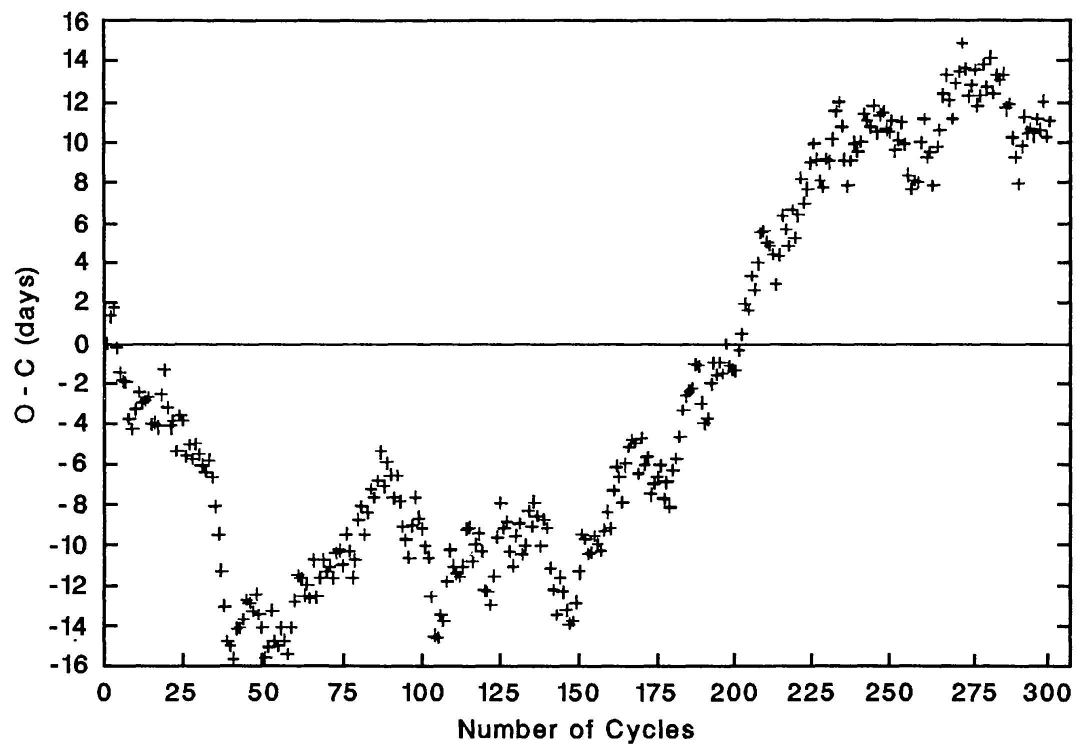
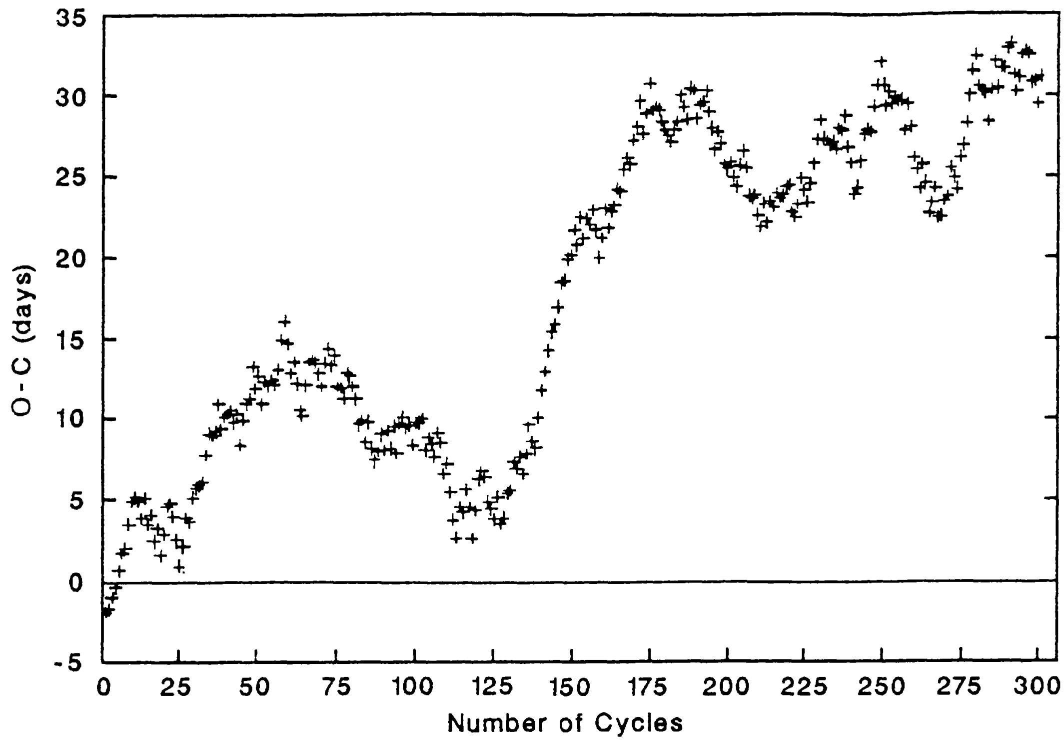


Figure 3. Simulated (O-C) diagrams for an RV Tauri star with a period of 50 days, assuming that the period changes are due to random, cycle-to-cycle fluctuations. In these cases, the average fluctuation is about 1 day or 2 per cent. These diagrams differ only in the random numbers which were generated in each run.



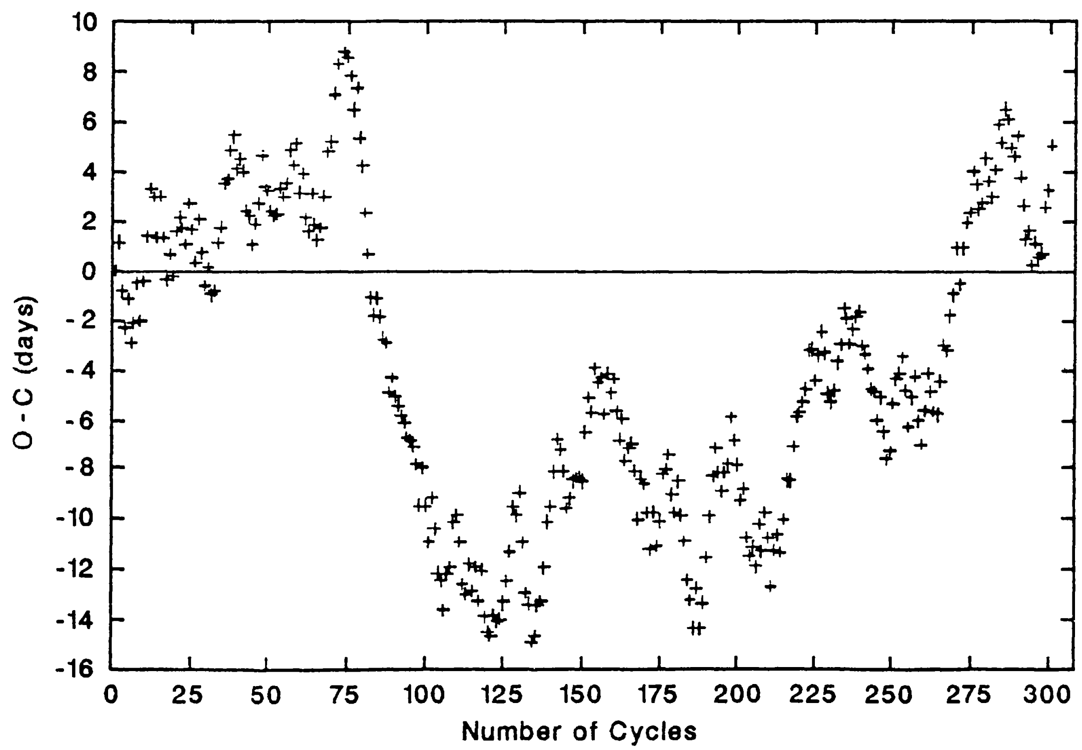


Figure 3 continued. Simulated (O-C) diagrams for an RV Tauri star with a period of 50 days, assuming that the period changes are due to random, cycle-to-cycle fluctuations. In these cases, the average fluctuation is about 1 day or 2 per cent. These diagrams differ only in the random numbers which were generated in each run.