Long-Term High-Precision Monitoring of Variable Stars

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Abstract Long-term and high-precision photometric and/or spectroscopic monitoring is required for the study of some variable stars: supergiants, slowly pulsating B-stars, stars with activity cycles and/or amplitude modulation, and so on. These observations require stable and dedicated instrumentation.

1. Introduction

This review examines the problem of "long-term" (i.e., at least about ten years), "high-precision" (i.e., better than about 5 millimagnitudes) "monitoring" (i.e., surveys as continuous as possible). The two characteristics, long-term and high-precision, are generally not satisfied together. Moreover, they are frequently not required by the final aim of the studies.

Thanks to the AAVSO and other groups of variable star observers, we have access to large collections of measurements. But these data are generally not high-precision measurements according to the definition given above. On the other hand, high-precision data exist, but they are generally not long-term, continuous, monitorings.

For classical periodic variable stars, such as Cepheids or RR Lyrae type variables, for example, long-term and high-precision monitoring is not necessary to determine the period (see, e.g., Goodricke 1786) and to describe the light curves. However, long-term surveys are necessary in order to describe the period variations (see, e.g., Szabados 1980), and highly precise data are required to analyze the details of the light curves (see, e.g., Gillet *et al.* 1989).

For very large amplitude variable stars, such as Mira, for example, high-precision monitoring is not required to describe the light curve. However, long-term monitoring is obligatory since the variability is not strictly periodic.

For many types of variable stars, both long-term *and* high-precision are absolutely necessary conditions in order to completely describe their subtle and complex behavior. Among the most interesting cases, let us mention:

Slowly pulsating B stars (SPB) are multiperiodic ($0.8\text{d} \lesssim P \lesssim 2.0\text{d}$), slightly evolved (luminosity class IV-III), mid B-type stars. Following the detection of the multiperiodic character of HR 3462 by Burki (1983), extensive long-term photometric campaigns have been organized with the Swiss telescope at La Silla by C. Waelkens (Leuven Astronomical Institute). These variable stars have been renamed SPBs (Waelkens 1991, 1994). They are pulsating in *non-radial, gravity modes* of low degree ($\ell = 1$ or 2), and the driving mechanism has been identified as the κ-mechanism acting on the metal opacity bump at $T \sim 2 \times 10^5$ K (Moskalik 1995).

Variable binary stars, such as RS CVn systems, are systems having one active F, G, or K subgiant and showing periodic light variations. In the case of RZ Eri, which is also an eclipsing binary, long-term (11 years) photometric monitoring revealed three types of variability: the eclipses, the starspot variability of the secondary (producing the so-called "migration waves"), and a long-term decrease of the mean luminosity of this secondary (Burki *et al.* 1992). The star is also a double-lined spectroscopic binary (SB2) system, thus radii and masses have been determined. The high precision of the survey led to the description of the processes of circularization and of synchronization in binary stars with a subgiant component.

Rapidly oscillating Ap stars (roAp) were discovered by D. W. Kurtz (1982) in South Africa. They are chemically peculiar stars, with magnetic fields of effective strengths of a few kG, and exhibiting small amplitude light variations. The periods are from 6 to 16 minutes, and the peak-to-peak amplitudes are smaller than 16 millimagnitudes. On the basis of high-precision photometric monitoring of about thirteen years, Kurtz *et al.* (1994) found that the period of HR 3831 (P = 11.67 minutes) exhibits a modulation of 0.06 second on a time-scale of 1.6 years. The most probable explanation is a cyclic modulation of the magnetic field, which is reminiscent of the solar cycle.

Stellar activity cycles are similar to the solar cycle related to the solar magnetic field variation ($P \sim 11$ y). On the basis of a long-term spectrophotometric survey of the CaII, H, and K emission lines of early F to early M dwarf stars, Wilson (1978) showed that the analog of the solar activity cycle exists on about one quarter of his sample of roughly 100 objects.

Two examples are presented hereafter: V810 Centauri, a supergiant monitored photometrically, and V473 Lyrae, a Cepheid whose variable amplitude was determined spectroscopically.

2. Reduction and precision of photometric data

In order to obtain high-precision photometric data for a long timebase, a few parameters should be controlled or determined:

- Earth atmospheric extinction coefficients
- Telescope and photometer instrumental coefficients (zero points)
- Stability of the passband of the filters
- Stability of the standard stars

In the case of *all-sky photometric measurements*, the effects of atmospheric extinction and instrumental coefficients must be correctly reduced (the Geneva photometric program follows this procedure). When only *differential photometry* is performed, the procedures can be simplified; nevertheless, the long-term homogeneity requires a good control of the stability of the instrumentation and filters.

The two fundamental equations for the reduction of the photometric data are, in the monochromatic case and to the first order,

$$m_o(\lambda) = m(\lambda,t) - k(\lambda,t) X_z, \tag{1}$$

with

$$m(\lambda,t) = -2.5 \log E(\lambda,t) + c(\lambda,t), \tag{2}$$

where $E(\lambda,t)$ is the measured monochromatic flux, $m(\lambda,t)$ is the measured magnitude, $m_o(\lambda)$ is the magnitude "outside the atmosphere," X_z is the air mass of the measured star, $c(\lambda,t)$ is the instrumental coefficient, and $k(\lambda,t)$ is the terrestrial atmospheric coefficient.

The precision of $m_o(\lambda)$ depends on the accuracy of the determination of the two coefficients $c(\lambda,t)$ and $k(\lambda,t)$. Figures 1 and 2 present the variations of the instrumental and atmospheric coefficients in the case of a very stable photometric instrumentation installed in a very good photometric site: the Swiss 70-centimeter telescope at ESO La Silla Observatory, equipped with a P7 photometer (Burki *et al.* 1995; Burnet and Rufener 1979). The main characteristics of these figures are generally not discussed in detail in photometric manuals, despite the fact that they illustrate clearly and concisely the difficulties of reaching the precision level of a few millimagnitudes.

Figure 1 shows that *the decrease of the reflectivity of the mirrors (mainly the telescope primary mirror) is about 1 millimagnitude per night of work*. This effect is essentially due to the dust deposit on the mirror surface.

Figure 2 shows that the atmospheric extinction coefficient strongly varies due to stratospheric aerosols from volcanoes and meteorological aerosols (annual variation, large values in summer). Strong variations from night to night and even during the same night are also observed. *The estimation of the flux outside the atmosphere must absolutely be done by using the atmospheric extinction value for the site and at the time the measure has been effectuated*.

As shown by Burki *et al.* (1991), the mean global precision reached in the case of the *all-sky measurements* of the Geneva photometric program is 5 to 7 millimagnitudes in the *V* magnitude range of 4 to 11. In the case of the monitoring of SN 1987A, this precision was improved to 4 millimagnitudes due to the larger number of standards measured.

Standard stars are measured during each photometric night. A good knowledge of these stars is always required. This point is even much more crucial in the differential mode (i.e., using comparison stars). A star of constant magnitude is the simplest condition to use as a standard; however, a variable star having a perfectly predictable light variation could also be used as a standard. It is important to have a large collection of standards, because some of them can be stable during many years and suddenly start to vary. One interesting such example is given in Figure 3. This standard star was constant (standard deviation of 0.0058 magnitude) from 1978 to 1991. In 1992, its luminosity increased; in addition, a pseudo-period of about 400 days was measured from 1995 on. A useful standard became an interesting variable!

3. An example of long-term high-precision photometric monitoring: V810 Centauri

The variability of V810 Centauri was discovered by Eichendorf and Reipurth (1979), who described this variable as *a long-period Cepheid-like star with a period of roughly 125 days*. It was further shown by Burki (1984, 1994) that V810 Cen's variability is multi-periodic, and that the period ratio of the two main modes (153days and 104days), 0.68, is similar to the values of the double-mode Cepheids, from 0.697 to 0.711 (Balona 1985).

V810 Cen was measured using the Swiss telescope at La Silla Observatory from 1976 until now. Since the star can be measured throughout the whole year from La Silla, it was monitored as continuously as possible from December 1989 to November 1993. The resulting light curve is presented in Figure 4a. These observations show that *the amplitudes of the pulsation modes are variable* (see Figure 4b). This analysis was done by Kienzle *et al.* (1998), by applying the Wavelet Transform method described by Foster (1996). Transient frequencies are seen, and the main modes, corresponding to the periods 153days and 104days (frequencies $\nu = 0.00654$ and 0.00962, respectively), were not permanent and stable amplitudes during the time interval of the survey. *The continuity of the monitoring is absolutely necessary* in order to correctly describe the complexity of such light variations.

4. Spectroscopic monitoring

Long-term spectroscopic monitoring is quite rare in astronomy, in part due to the fact that telescopes are rarely dedicated to this activity. Schematically, one can classify spectroscopic monitorings into three groups:

The monitoring of line intensities. Some monitoring has been organized on a very long term, as with the study of the stellar activity cycles (see the Introduction).

The monitoring of line profiles. From the variation of the lines, it is possible to identify the pulsation modes, in particular the non-radial ones which induce large line profile distortions (see, e.g. Smith 1977; Vogt and Penrod 1983). These monitorings are generally organized for a few weeks or months.

The monitoring of line centroids. This is the measure of *the radial velocity* of the star, at least in the case of those with radial pulsation. Very long-term monitoring of the radial velocity of variable stars has been organized. This is the subject of the following sections.

5. Parameters of the pulsating stars

The radial velocity curve $V_r(t)$ of a radially pulsating star is a very powerful tool for deriving some of its fundamental parameters. From $V_r(t)$, one can derive *the pulsational velocity*

$$\dot{R}(t) = -\beta(V_r(t) - \overline{V}_r) = -\beta\Delta V_r(t), \quad (3)$$

where β is the conversion factor from radial to pulsational velocity, and $\overline{V}_r$ is the mean radial velocity of the star. *The radius variation* is given by

$$\Delta R(t) = \int \dot{R}(t)dt = R(t) - R_o, \tag{4}$$

where R_o is the mean stellar radius. *The acceleration* of the surface is given by the expression

$$a(t) = \ddot{R}(t) = -g + g_{eff}, \tag{5}$$

where $g = GM/R^2$ and g_{eff} are the static and dynamical gravities, respectively.

The mean radius R_o can be calculated by applying the Baade-Wesselink (BW) method. Recall that this method requires the simultaneous determination of the light (V magnitude), color (B–V or an infrared index), and radial velocity curves. Then, *the distance, d,* to the star can be calculated from R_o and T_{eff}. An example of the calculation of $\dot{R}(t)$, $\Delta R(t)$, $\ddot{R}(t)$, R_o, and d is given by Burki and Meylan (1986) for the RR Lyrae star RR Ceti.

6. An example of long-term high-precision radial velocity monitoring: V473 Lyrae

This star's radial velocity has been monitored since 1977 from the Observatoire de Haute-Provence (France) by using the spectrovelocimeter mounted on the Swiss 1-meter telescope. V473 Lyrae is quite exceptional among the Cepheids (Burki *et al.* 1986, Burki 1994):

- This is the galactic Cepheid with the shortest known period (P = 1.490972d).
- The amplitude of pulsation varies by a factor ~15 in ~1200d (see Figure 5).
- The mean radius R_o, determined by the BW method (see section 5) is 30 ± 5 R.
- The star pulsates in a high overtone (probably the second one).
- The variations of $\dot{R}(t)$, $\ddot{R}(t)$, g, g_{eff} (see section 5) and other parameters (turbulence, temperature, etc) with $\Delta R(t)$ can be studied in the same star for various amplitudes of pulsation. For this reason, V473 Lyr is a unique "stellar atmospheric laboratory." Of course, this analysis requires long-term monitoring.

The duration (~20 years) and precision ($\sigma \lesssim 0.4$ km/sec) of the survey allow the examination of the constancy of the period of pulsation. The data have been divided into fifty-four successive ranges according to HJD and, in each range, the V_r measurements have been fitted by least-squares to a function of the form

$$V_r(t) = A_0 + \sum_{k=1}^{n} A_k \cos\left(2k\pi\nu\,(t - t_0) + \phi_k\right), \tag{6}$$

where $\nu = P^{-1}$ and n varies from 1 to 4 according to the HJD range. The value of the phase ϕ_1, equivalent to an O–C value, can be used to test the constancy of the period. Figure 6 shows that:

- A constant value (1.490972d) can be adopted for the period in the intervals noted by horizontal solid lines, corresponding to the ranges of slowly increasing pulsation amplitude.

- The period takes a smaller value (~1.490d) during the ranges of increasing ϕ_1 value, corresponding to the ranges of rapidly decreasing pulsation amplitude. Thus, *the period of pulsation of V473 Lyr decreases by about 2min during the phases of decreasing amplitude*.

The very detailed description of the complex variability of the unique Cepheid V473 Lyr would have not been possible without a high-precision, long-term and "continuous" monitoring. As shown in this review, this is true for many variable stars. These observational programs require stable and dedicated instrumentation over decades.

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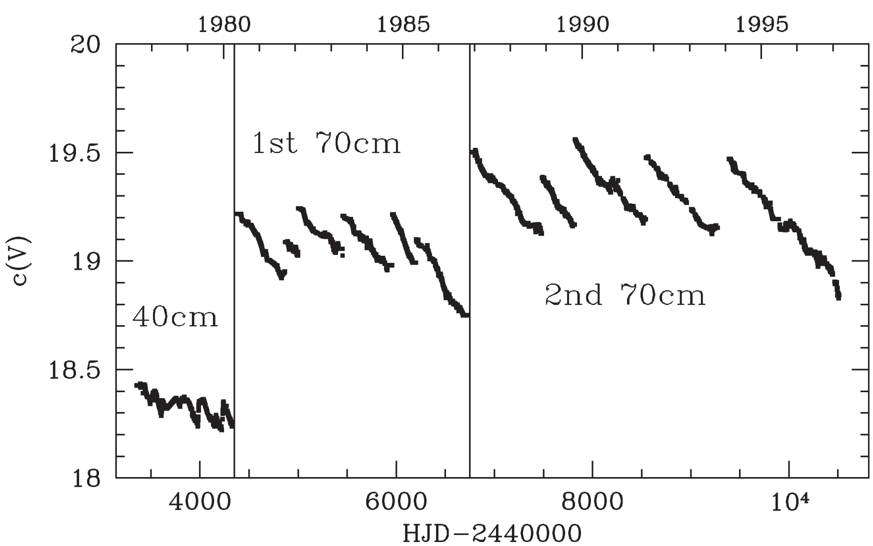

Figure 1. Variations of the instrumental coefficient in the *V* band for the Swiss telescope at La Silla Observatory. The changes of telescope and the aluminum coating of the mirror, as well as the series of cleanings of the mirrors (telescope and/or photometer) are clearly visible (for more details, see Burki *et al.* 1995).

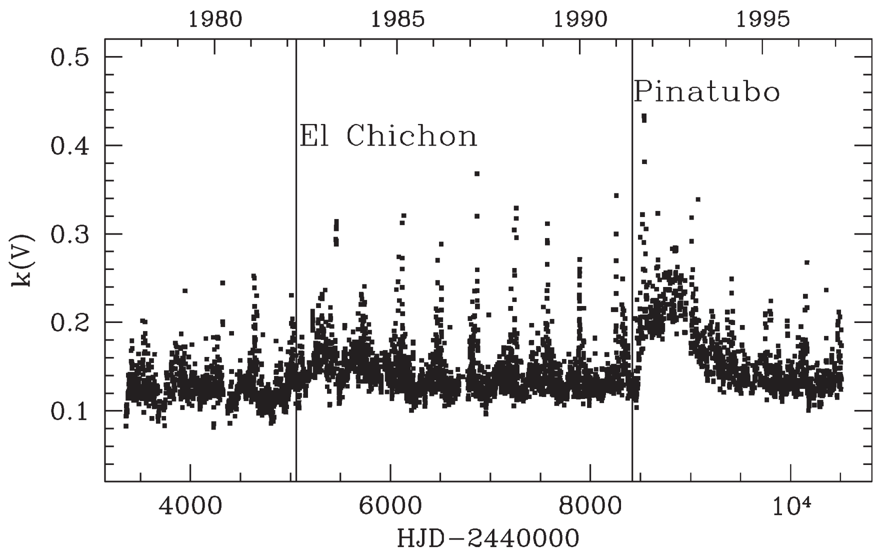

Figure 2. Variations of the extinction coefficient in the *V* band during photometric nights at La Silla Observatory. The effects of the stratospheric aerosols (sulfur dioxide transformed into sulfuric acid) from the two volcanoes El Chichon (Mexico) and Pinatubo (Philippines), and of meteorological aerosols (global annual variation due to the haze and dust content of the atmosphere above the site) are clearly visible (for more details, see Burki *et al.* 1995).

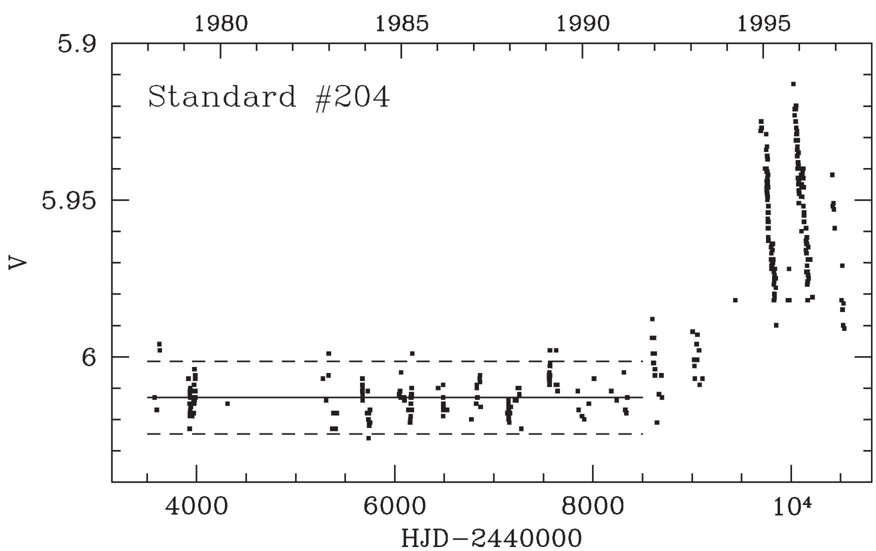

Figure 3. The long-term behavior of a standard star which became variable in 1991. The dotted lines refer to the 2-σ level.

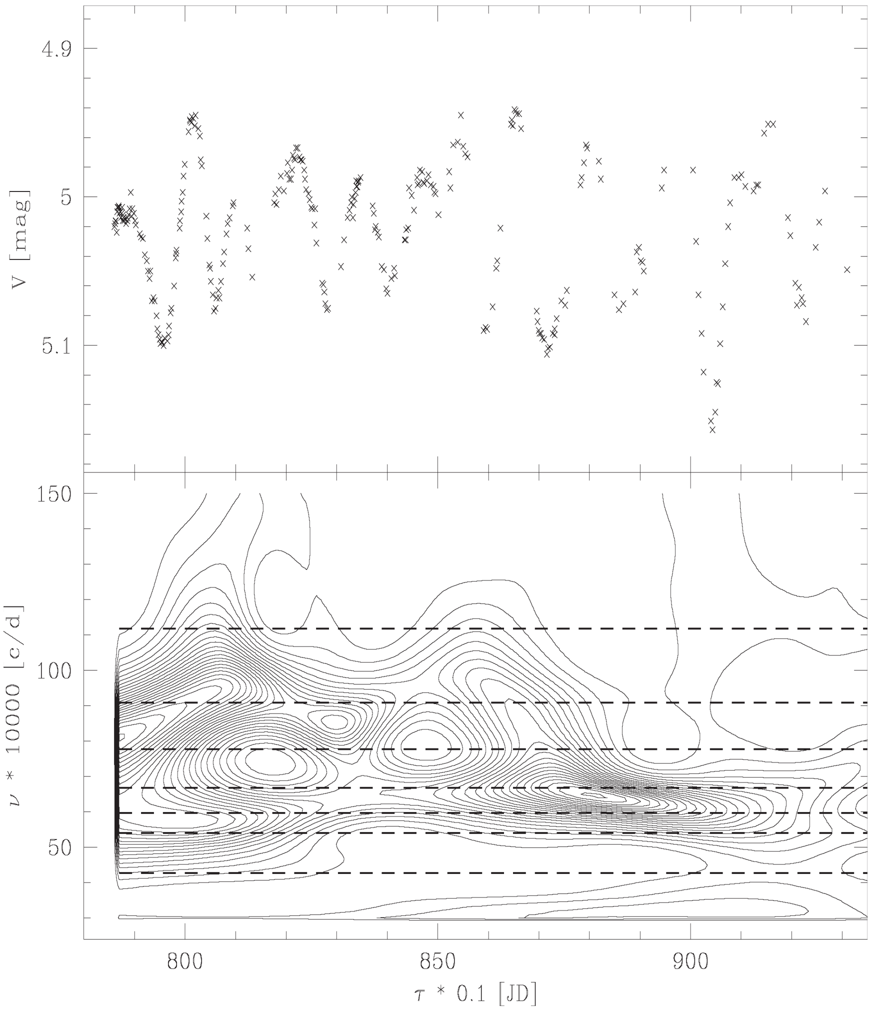

Figure 4a. (Top) The light curve of V810 Cen during a period of intense monitoring.

Figure 4b. (Bottom) The frequency-JD diagram from the *Wavelet Transform* analysis according to the method of Foster (1996). ν is the frequency and τ is relative to HJD 2,440,000.

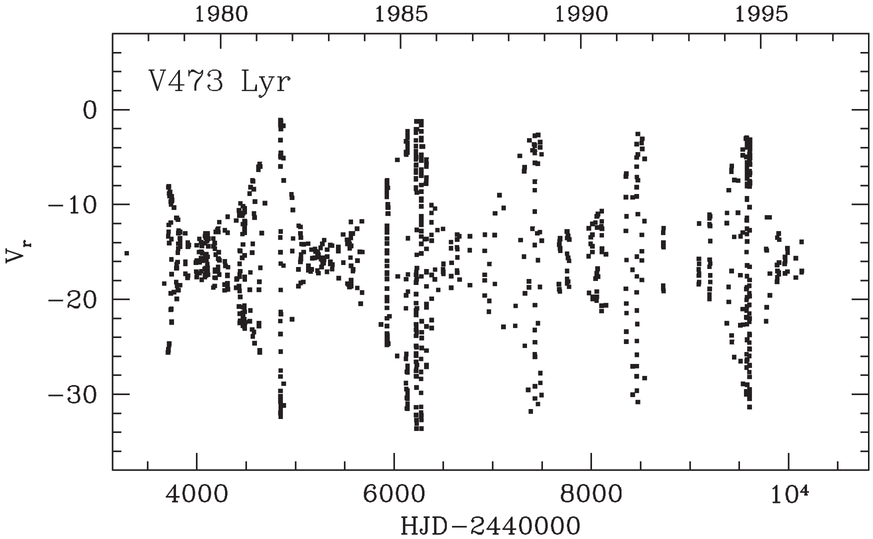

Figure 5. The long-term radial velocity monitoring of V473 Lyr. The characteristic time 1000d $\lesssim t_c \lesssim$ 1400d of the amplitude variation is clearly visible.

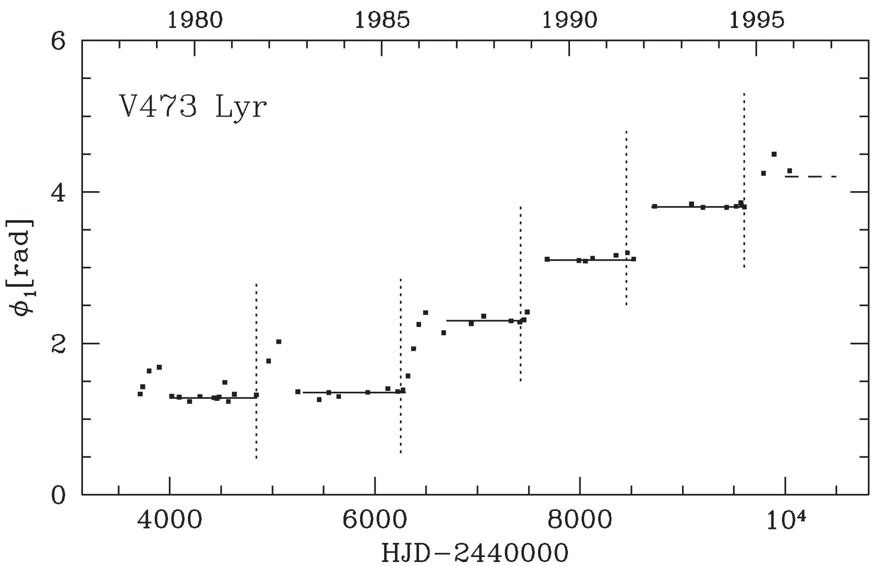

Figure 6. The variation of ϕ_1 according to equation (6). This variation is equivalent to an O–C diagram: the period is constant during the intervals of constant ϕ_1 values (solid lines). The dotted lines refer to the maxima of the pulsation amplitude (see Figure 5).