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The pulsating yellow supergiant V810 Centauri⋆,⋆⋆

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Abstract. The F8 Ia supergiant V810 Centauri is part of a long-term high-precision photometric monitoring program on long period variables started twenty years ago. Time series analysis of this unique set of 500 data points, spanning almost fifteen years in the homogeneous Geneva photometric system, is presented. Cluster membership, physical parameters and evolutionary status of the star are reinvestigated. Radial velocity data do not support the cluster membership to Stock 14. Ultraviolet and optical spectrophotometry is combined with optical and infrared photometry to evaluate the physical parameters of the yellow supergiant ($T_{\rm eff}$ = 5970 K, $M_{\rm bol}$ = -8.5, R = 420 $R_\odot$) and of its B0 III companion. From theoretical stellar evolutionary tracks, an initial mass of ∼25 $M_\odot$ is estimated for V810 Cen, which is actually at the end of its first redward evolution.

V810 Cen is a multi-periodic small amplitude variable star, whose amplitudes are variable with time. The period of the main mode, ∼156 d, is in agreement with the Period–Luminosity–Colour relation for supergiants. This mode is most probably the fundamental radial one. According to the theoretical pulsation periods for the radial modes, calculated from a linear non-adiabatic analysis, the period of the observed second mode, ∼107 d, is much too long to correspond to the first radial overtone . Thus, this second mode could be a non-radial p-mode. Other transient periods are observed, in particular at ∼187 d. The length of this period suggests a non-radial g-mode. Then, the complex variability of V810 Cen could be due to a mixing of unstable radial and non-radial p- and g-modes.

Key words: stars: individual: V 810 Centauri – stars: supergiants – stars: oscillations – stars: evolution – open clusters and associations: individual: Stock 14

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⋆ Based on observations collected at the Swiss 40 cm and 70 cm and at the Danish 1.54 m telescopes, at the European Southern Observatory (La Silla, Chile)

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1. Introduction

V810 Centauri (=HD 101947 =HR 4511, hereafter V810 Cen) is a yellow supergiant at low galactic latitude (l=295.18, b=-0.64) in the direction of Carina spiral arm.

The light variability was discovered by Fernie (1976) as a result of cepheid-like supergiants photometric survey. Eichendorf & Reipurth (1979) found a low amplitude variation (0.12 mag in V) with a "period" of 125 days (but only two successive minima were observed). Dean (1980) confirmed the variability of V810 Cen, but not the 125 d period. In a preliminary analysis of Geneva long-term photometric monitoring, Burki (1994) obtained two radial modes at 153 and 104 days with low amplitudes (0.07 and 0.04 mag respectively). However, the high residuals suggested that the amplitudes were variable and/or that additional frequencies may be present.

The pulsation interpretation of the variability was controversial. Indeed, Bidelman et al. (1963) suspected the star to be a spectroscopic binary and this was confirmed by van Genderen (1980) who proposed a B spectral type companion to account for the UV excess of the G0 Ia star. Therefore, the light variation may come from the companion variability rather than the G0 star. This issue was settled with IUE spectra from Parsons (1981). From continuum flux fitting and photometric data he found that the G supergiant should be 3.2 mag brighter (in the V band) than its B companion, thus comforting the cepheid-like pulsation hypothesis for V810 Cen. However, the spectral type of the B companion was still ambiguous: C IV and Si IV absorption lines lead to a B0-B1 Iab-Ib star while continuum flux fitting requires a B0.5-B1 III star (see Sect. 3). Since the G star luminosity relies on its companion bolometric magnitude and their magnitude difference, the variable star luminosity is also ambiguous.

The perspective of using V810 Cen as a prime candidate to understand the variability of the massive stars was strengthened by the open cluster membership. Moffat & Vogt (1975) suggested that V810 Cen is a member of the open cluster Stock 14 for which Peterson & FitzGerald (1988) derived $< E_{B-V} >= 0.26$ and $V_0 - {\rm M_V} = 12.14$. But the intrinsic luminosity, derived from the cluster distance, is 0.5 mag fainter when compared to the spectroscopic estimates from IUE data.

In the present paper we re-investigate various aspects of this long-period variable star. Sect. 2 is devoted to the discussion of the membership to the open cluster Stock 14 based on the cluster members radial velocity. IUE final archive and visual spectrophotometry are used in Sect. 4 to constrain the luminosity and effective temperature of the G0 supergiant. The variability of V810 Cen is discussed thoroughly on the basis of the Geneva photometric data, collected over 15 years (Sects. 5 to 8). Finally, a discussion of the pulsation modes is given in Sect. 9.

2. V810 Cen and Stock 14

Moffat & Vogt (1975) postulated that V810 Cen is a member of the open cluster Stock 14 (C 1141-622). This would strongly constrain the physical parameters of the supergiant. Unfortunately, as we shall see hereafter, this is probably not the case.

With the UBV photometry from Moffat & Vogt (1975), Turner (1982) and Peterson & FitzGerald (1988), collected by Mermilliod (1997) in his Cluster Database, and using the stellar evolutionary tracks from Schaller et al. (1992), the following parameters can be derived for Stock 14 : $E(B-V) = 0.26$, distance= 2.63 kpc, age= $1.4 \cdot 10^7$ yr. These values are consistent with those found by Moffat & Vogt (1975), FitzGerald & Miller (1983), Lynga (1987) and Peterson & FitzGerald (1988).

Assuming cluster membership, the absolute magnitude of V810 Cen (both components together) would be $\mathrm{M_V} = -7.88$, with an UBV intrinsic color of $(B-V)_0 = 0.526$. According to the analysis of van Genderen (1981), the blue component has an absolute magnitude of $\mathrm{M_V} = -4.25$ and an intrinsic color index of $(B-V)_0 = -0.28$ (O9-B0 type star), thus the red supergiant would have $\mathrm{M_V} = -7.84$ and $(B-V)_0 = 0.56$, corresponding to a G0Ia type star. With these values, the blue component would be close to the cluster turnoff of the main sequence, whereas the red supergiant remains close to the original position of the double system, i.e. close to the blue loop of the evolutionary track, in the core helium burning phase.

As we shall see from the analysis of the radial velocity data, it is probable that V810 Cen is not a member of Stock 14. The radial velocities of 4 bright B-type members of this cluster are known: -8 km/s (1 measurement with an uncertainty of at least 5 km/s) for HD 101994 (Buscombe & Kennedy, 1969), -6.4 ± 1.9 km/s for the eclipsing SB2 system V346 Cen, HD 101897 (Hernandez & Sahade (1978), -3 ± 12 km/s (4 measurements) for HD 101964 (Feast et al., 1957) and -10 ± 21 km/s (5 measurements, the velocity could be variable) for HD 101838 (Feast & Thackeray, 1963). A mean velocity of -6 ± 2 km/s can be adopted for the cluster in agreement with the estimation of Lynga (1987). This value relies strongly on the γ velocity of the SB2 system V346 Cen from 44 V_r measurements.

V810 Cen has 90 radial velocity data points between HJD 2 444 621 and 2 449 915 from CORAVEL spectrophotometer attached to the 1.54 m Danish telescope in La Silla. The uncertainty on each measurement is about 0.4 km/s, whereas the dispersion of the data is much larger, due to the complex pulsation of V810 Cen, which is the only component of the system measured with CORAVEL. The mean velocity is -16.7 ± 2.6 (s.d.). For further calculation, the annual means of the velocity will be used. The values of 13 annual means range from -13.2 km/s to -20.8 km/s, with standard deviations between 0.5 and 3.5 km/s.

Older measurements of the radial velocity of V810 Cen are: +11.7 km/s in 1908 (2 measurements) and +6.9 km/s in 1911 (1 measurement) from Campbell & Moore (1928), and -17.4 km/s in 1946 (10 measurements), -14.4 km/s (3 measurements) in 1947 and -10.8 km/s (2 measurements) in 1959 from Bidelman et al. (1963).

If all the radial velocity data are taken into account, the possible orbits with a γ velocity corresponding to the velocity of the cluster members ($\gamma = -6$ km/s, see Fig. 1) give values for the mass function $f(m) = (a_2 \sin(i))^3/P^2 = (m_1 \sin(i))^3/(m_1 + m_2)^2$ which are far too large: the values for m_1 (B-type component) are larger than 60 $\mathrm{M_\odot}$, if we assume an m_2 of about 25 $\mathrm{M_\odot}$. If the data obtained in 1908 and 1911 are excluded (these are 20.3 Å /mm spectra taken on photographic plates), the remaining velocities are compatible with a constant velocity (taking into account the pulsation), or with a small amplitude orbit. But the γ velocity would be close to -16 km/s instead of -6 km/s (cluster velocity). Furthermore, it is noteworthy that our recent data have a mean value (-16.7 ± 2.6 km/s) in good agreement with the mean value of the data obtained in 1946 and 1947 (-15.8 ± 4.2 km/s), suggesting that the systematic velocity of the system is indeed 10 km/s lower than the mean velocity of the cluster.

In conclusion, our radial velocity analysis allows to exclude the membership of V810 Cen to the cluster Stock 14.

3. The blue companion

The existence of a blue companion was suggested by Parsons & Peytremann (1973) and van Genderen (1980) from photometric data and conclusively proved by Eichendorf et al. (1981) and Parsons (1981) on the basis of IUE spectra.

From Si IV and C IV line profiles and intensity analysis, these authors conclude that the spectral type of this blue companion is B0-B1 Iab-Ib, i.e. a star of absolute magnitude $M_{\mathrm{V}} \simeq -6$. Furthermore, Parsons (1981) fitted synthetic spectrum on IUE data and UBVRIJKL photometry and determined a V magnitude difference between the two components of $\Delta V \simeq 3.2$ (the blue component being fainter). As noted by Parsons, there is an inconsistency between V810 Cen membership to the cluster Stock 14 and the luminosity class of the companion. Indeed, the absolute magnitude of the two components would be -7.8 (V810 Cen) and -4.6 (blue companion) if the membership is accepted and the value $\Delta V = 3.2$ taken into account. In that case, the luminosity of the blue companion corresponds to a giant and not to a supergiant (as it is indicated by Si IV and C IV lines). In order to reconcile spectral and cluster luminosity, Turner (1982) suggested that the B star stellar wind could be abnormally strong for its luminosity, as it is the case for τ Sco (B0 V) and ξ Oph (O9 V). If the same phenomenon

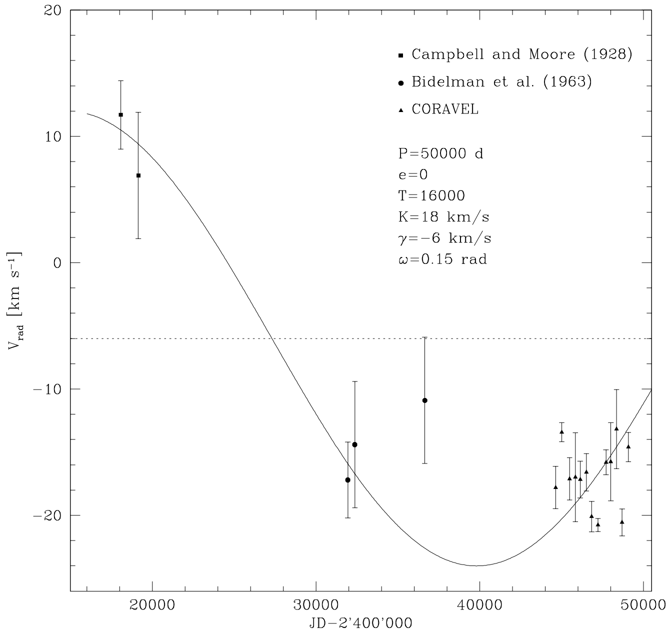

Fig. 1. Radial velocities from 1908 to 1995 collected from various sources. Only mean values are shown. The important scatter in the last set of data is due to V810 Cen pulsation. The fitted orbit (full curve) would agree with the 1908-1928 data but is physically unlikely (see text).

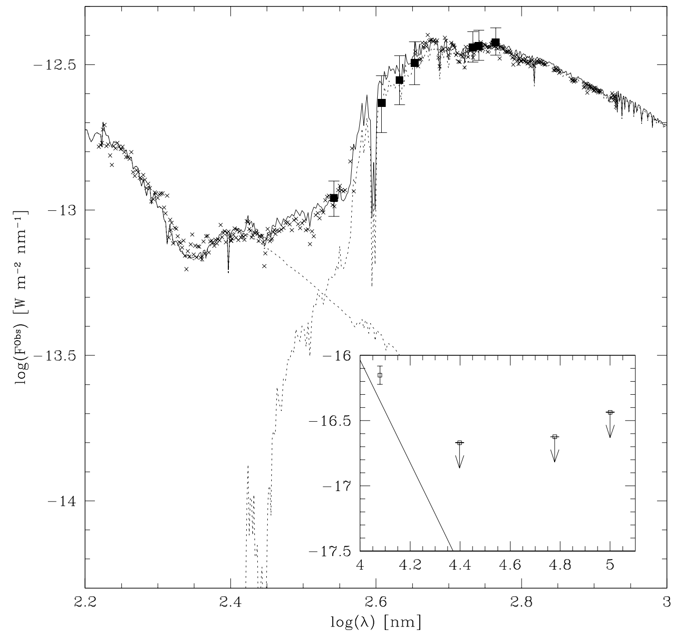

Fig. 2. Reddened and scaled Kurucz models (dashed lines) assuming a B0 III hot companion. The full line is the sum of the B0 III and F8 Ia Kurucz model. IUE and Kiehling's data (crosses), the flux derived from Geneva photometry (filled squares) and IRAS flux (open squares in the insert) are also given. The error bars are the upper and lower flux observed in Geneva photometry whereas for IRAS data they represent the estimated error. The arrows indicate upper limits for the flux.

applies here, this star could be a giant, with $M_{\rm V} \simeq -4.6$, in agreement with the membership to Stock 14.

However, as noted in the previous section, the radial velocity analysis do not support the membership to Stock 14. Thus, it appears to us that the most logical solution is to accept : *i)* the luminosity class of the blue companion, probably a giant B0 star (see Sect. 4), and its absolute magnitude $M_{\rm V} \simeq -5.1$ (Schmidt-Kaler, 1981); *ii)* the V magnitude difference between the two components, $\Delta V \simeq 3.3$ (see next section). With these values, the absolute magnitude of V810 Cen is $M_{\rm V} \simeq -8.4$ and the star is located behind the cluster Stock 14.

4. Physical parameters of the two components

Theoretical energy distributions for each of the two components, taken from the grid of stellar atmosphere models of Kurucz (1994), have been fitted to the observed UV, optical and IR spectrophotometric data of V810 Cen (both components together).

In the UV domain, three low dispersion, large aperture, spectra obtained with IUE satellite and reduced with NEWSIPS (Nichols & Linsky, 1996) are available in the IUE Final Archive (obtained from NASA Data Archive and Distribution Service), namely lwp6460, lwp28437 and swp26455. The two lwp spectra have been averaged in the 2122-3348 Å range and the strong chromospheric Si IV and C IV lines in the swp spectrum have not been used since they cannot be well described by the standard Kurucz model atmosphere.

In the optical domain, a 10 Å resolution spectrum is available in the range 3250 to 8600 Å (Kiehling, 1987). These data are accessible through the Strasbourg Stellar Data Center. Points flaged as uncertain by the author have not been used. In the IR domain, the photometric data from IRAS satellite (IRAS Points Source Catalog, 1988) are reliable only at 12 μm, whereas the fluxes at 25, 60 and 100 μm are only upper limits. In addition, the photometric measurements in the 7 colors Geneva system have been used to estimate the effect of the variability.

No detailed study of the interstellar extinction in the UV domain is available towards V810 Cen. Assuming that the star is not too far away from the open cluster Stock 14, which is at a distance of 2.7 ± 0.2 kpc according to Peterson & FitzGerald (1988), the mean Galactic extinction law of Krełowski & Papaj (1992) was adopted. This law is suited for stars at 2 to 6 kpc from the sun.

For each absolutely calibrated flux of the extracted IUE spectra an internal error estimate is given in the MXLO files (Nichols et al., 1993). The spectra have been corrected for the systematic deviations described by Bohlin (1996). From his Fig. 1, the following values for the IUE external error have been adopted: 3 %, 5 %, 2 %, and 7 % respectively in the ranges 1100-1900 Å, 1900-2400 Å, 2400-3100 Å and 3100-3300 Å . For the optical spectrum, Kiehling's external and internal error estimates have been adopted.

To reproduce the observed composite spectrum, with two model atmospheres and the mean interstellar extinction law, seven parameters should be estimated: the effective temperature, gravity and angular diameter for each star and the color

Table 1. Temperature estimates for 3 standard supergiants compared to the values derived by Evans & Teays (1996). Our temperatures are, in average, 100 K higher than Evans & Teays estimates.

Star	Sp. type	$E(B-V)$	$T_{\rm eff}$ Evans & Teays	$T_{\rm eff}$ This paper	$\Delta \log T_{\rm eff}$
α Per	F5Iab	0.04	6 270	6 430	0.011
β Aqr	G0Ib	0.03	5 560	5 660	0.008
9 Peg	G5Ib	0.13	5 110	5 170	0.005

Table 2. Parameters for various fits to IUE and visible spectra. The microturbulence is set to 4 km/s and solar metallicity is assumed. The color excess is fixed to $E(B-V) = 0.26$. Fixed parameters are quoted with an f. The best fit is achieved for a B0 III and F8 Ia couple.

Sp	$T_{\rm eff,1}$ f	$\log g_1$ f	C_1	$T_{\rm eff,2}$	$\log g_2$	C_2	χ^2
O9 V	33 000	4.0	20.286	6 070	1.2	17.204	2983
B0 V	30 000	4.0	20.160	6 040	1.0	17.198	3087
B1 V	25 400	4.0	19.893	5 960	0.4	17.182	3654
O9 III	32 000	4.0	20.249	6 060	1.1	17.202	2975
B0 III	29 000	3.5	20.119	6 010	0.7	17.190	2539
B1 III	24 000	3.5	19.812	5 905	0.0	17.171	4236
O9 Iab	32 600	4.0	20.271	6 060	1.1	17.203	2979
B0 Iab	25 000	3.0	19.898	5 910	0.0	17.171	4015
B1 Iab	20 800	3.0	19.587	5 810	0.0	17.151	9278
B2 Iab	18 500	3.0	19.387	5 760	0.0	17.143	12405

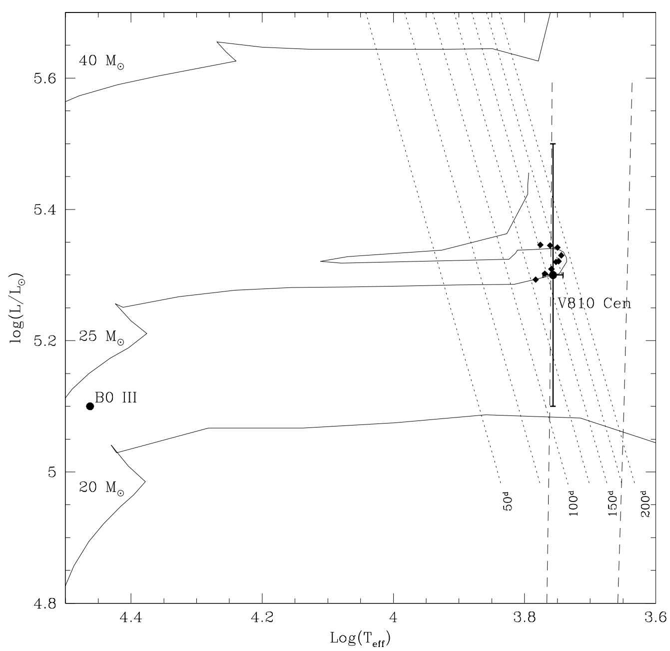

Fig. 3. V810 Cen position in the HR diagram assuming a B0 III hot companion. The "error bars" corresponds to 250 °K and 0.5 mag. Evolutionary tracks are from Meynet et al. (1994) and the instability strip (dashed lines) is from Chiosi et al. (1993). Linear non-adiabatic stability analysis has been performed on nine models (diamonds) on the 25 M$_\odot$ track (see also Table 7). Dotted lines are the iso-periods in the 50 to 200 days range (25 days step) for the fundamental mode calculated from Schaller (1990).

excess. The estimate has been performed through a standard least squares procedure minimizing the following quantity:

$$\chi^2 = \sum_i \frac{[\log(F_i^0) - \log(F_i^{th})]^2}{\sigma_i^2} \quad (1)$$

where F_i^0 and F_i^{th} are the unreddened observed and theoretical fluxes at the wavelength λ_i, and σ_i is the error estimates on $\log(F_i^{obs})$, where F_i^{obs} is the observed, reddened, flux. To compare the observed and theoretical fluxes the former has been resampled at the model frequencies. The theoretical flux is given by:

$$F_i^{th} \; = \; F_i^{mod}(T_1, g_1)\; 10^{-C_1} + F_i^{mod}(T_2, g_2)\; 10^{-C_2}$$

where $F_i^{mod}(T, g)$ is the flux from Kurucz's atmosphere models at λ_i for given values of $T_{\rm eff}$ and $\log g$. The indices 1 and 2 refer respectively to the blue and red (V810 Cen) components. The Kurucz's models used are those with the solar abundance and a microturbulence of 4 km/s, well suited for supergiants. The parameter C is related to the stellar angular diameter θ through:

$$\theta = 2 \cdot 2.06\; 10^8\; 10^{-0.5\, C} \text{ milliarcsec} \quad (2)$$

The unreddened observed flux is given by:

$$\log(F_i^0) = \log(F_i^{obs}) + \; 0.4\; A_i \quad (3)$$

where A_i is the interstellar extinction in magnitude, calculated from the extinction law of Krełowski & Papaj (1992), assuming $R = A_V/E(B-V) = 3.1$.

To estimate the accuracy of the present method, we used the spectrophotometric data from Glushneva et al. (1992) for 3 supergiant stars: α Per, β Aqr and 9 Peg. Their parameters have been derived by Evans & Teays (1996) on the basis of ultraviolet measurements (IUE data), optical and infrared photometry (BVRIJHK bands). We have adopted the same values for the gravity and the microturbulence as Evans et al. ($\log g$ = 1.5 and ξ =4 km/s for the 3 stars). Table 1 shows that our temperatures are slightly larger than Evans et al. values by 100 K on the average. However, the mean difference is small, less than 0.01 in $\log T_{\rm eff}$, i.e. less than one spectral subclass. We adopt that value of 100 K for the typical uncertainty of our temperature determinations of V810 Cen.

According to Eichendorf & Reipurth (1979) and Turner (1982) the blue component of V810 Cen is in the ranges B0-B1 in spectral type and V-Iab in luminosity class. The parameters $T_{\rm eff,1}$ and $\log g_1$ of the blue component were fixed, and the minimization of the χ^2 value was performed with the free parameters C_1, $T_{\rm eff,2}$, $\log g_2$ and C_2. The computed ranges in spectral type and luminosity class for the blue component were O9-B2 and V-Iab. In a first step, the color excess was fixed to 0.26, the mean value for the cluster Stock 14. Table 2 shows that the best fit is achieved for a blue component of type B0 III. The corresponding values for the red component are $T_{\rm eff,2} = 6\,010$K and $\log g_2 = 0.7$, corresponding to an F8 supergiant.

In a second step, the color excess was varied from 0.20 to 0.30, for the same parameters of the blue component, i.e. those of a B0 III star. As shown by the χ^2 values in Table 3, the fitting procedure is weakly dependent on the color excess value : any value of $E(B-V)$ between about 0.20 and 0.28 can be accepted.

From the relation :

$$log(R_2/R_1) = 0.5(C_1 - C_2) \qquad (4)$$

we derive the radius ratio $R_2/R_1 = 31.1$ which clearly indicates that the luminosity class of the red component is Ia. Thus, the best solution for the two components of V810 Cen is :

Blue component : B0 III, $T_{\rm eff} = 29\,000 \pm 1\,000$ K
Red component : F8 Ia, $T_{\rm eff} = 5\,970 \pm 100$ K

This solution is plotted in Fig. 2 where reddened model fluxes (dashed lines) and their sum (full line) are compared to the fluxes in the 7 Geneva passbands (full boxes, computed according to Rufener & Nicolet, 1988). Furthermore, IRAS photometry is available for the point source 11410-6212 associated to V810 Cen and it is compared to the model in the insert. The error bars, associated with Geneva photometry, are the maximum and minimum observed fluxes, while those plotted at 12 μm are the 16 % uncertainties quoted in the IRAS point source catalogue. Those data marked by an arrow are upper limits fluxes.

The absolute and bolometric magnitudes have been derived from the spectral type (Lang, 1992) for the blue component and using $\Delta V = 3.3$ for the red component (V810 Cen). The values of the stellar radii have been calculated from $T_{\rm eff}$ and $M_{\rm bol}$. Thus we have :

Blue comp. : $M_{\rm V} = -5.1, M_{\rm bol} = -8.0, R = 14$ R$_\odot$
Red comp. : $M_{\rm V} = -8.4, M_{\rm bol} = -8.5, R = 420$ R$_\odot$

Note that the ratio R_2/R_1 is 29.8, very close to the value derived above from the values of the parameter C. The two components can then be placed in the $\log L$ vs. $\log T_{\rm eff}$ diagram (see Fig. 3) together with the evolutionary tracks from Meynet et al. (1994). Initial masses of 25 ± 5 M$_\odot$ can be derived for both components.

Table 3. Variation of the χ^2 with respect to $E(B-V)$ if a B0 III companion is assumed (see Table 2). The microturbulence is set to 4 km/s and solar metallicity is assumed.

E(B-V)	χ^2	C_1	$T_{eff,2}$	$\log(g_2)$	C_2
0.20	2795	20.314	5 890	1.1	17.216
0.22	2581	20.249	5 930	1.0	17.207
0.24	2495	20.184	5 970	0.9	17.199
0.26	2639	20.119	6 010	0.7	17.190
0.28	2721	20.054	6 040	0.6	17.181
0.30	3069	19.988	6 070	0.5	17.171

As already noted by Eichendorf & Reipurth (1979), V810 Cen is located near the blue edge of the instability strip (in Fig. 3 the limits of the strip for the fundamental mode, dashed lines, are from Chiosi et al. (1993)).

With the values of the absolute magnitude of both components and of the mean visual apparent magnitude (V = 5.021), we derive for V810 Cen a distance of 3.3 to 3.5 kpc (for E(B-V) in the range 0.28 to 0.24). Thus V810 Cen is located 0.6 to 0.8 kpc behind the stellar cluster Stock 14. Is this location in contradiction with the color excess values (0.26 for Stock 14, 0.20-0.28 for V810 Cen) ? The answer is no, because Stock 14 is non-uniformly reddened. For the member stars of the cluster, Peterson & FitzGerald (1988) found a standard deviation of 0.021 on the individual values of $E(B-V)$. This value corresponds to a 3σ interval in $E(B-V)$ of 0.19-0.32. Moreover, the two stars of Stock 14 which have the lowest reddening, $E(B-V)$=0.18 (star 26) and 0.21 (star 27) according to Turner (1982), are located in the sky very close to V810 Cen (stars 33, 34 and 35, are also close, but cannot be used because of their unreliable photometric data).

5. The photometric data

V810 Cen was measured 512 times in the seven filters of the Geneva Photometric system (Golay, 1980; Rufener, 1988) from JD 2 444 544 (Nov. 1980) to 2 450 051 (Dec. 1995) with a lack of observations from 2 446 638 to 2 447 861 (see Fig. 4a and b). These data come from the successive Swiss telescopes (40 cm and 70 cm) at ESO La Silla Observatory (Chile), equipped with the P7 photoelectric photometer (Burnet & Rufener, 1979). The data reduction has been made according to the method described by Rufener (1988). Only the 499 measurements having weights in magnitude (Q) and in colors (P) larger than 0 have been used.

The photometric data are available in electronic format at the CDS via anonymous ftp to cdsarc.u.strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 4 displays the mean magnitude values and rms for the 7 filters for V810 Cen and 3 standard stars. The corrected rms value σ_0 for V810 Cen is given by $\sigma_0^2 = \sigma^2 - [(1/3)(\sigma_{s1} + \sigma_{s2} + \sigma_{s3})]^2$, where σ is the rms of V810 Cen (σ_0 differ from

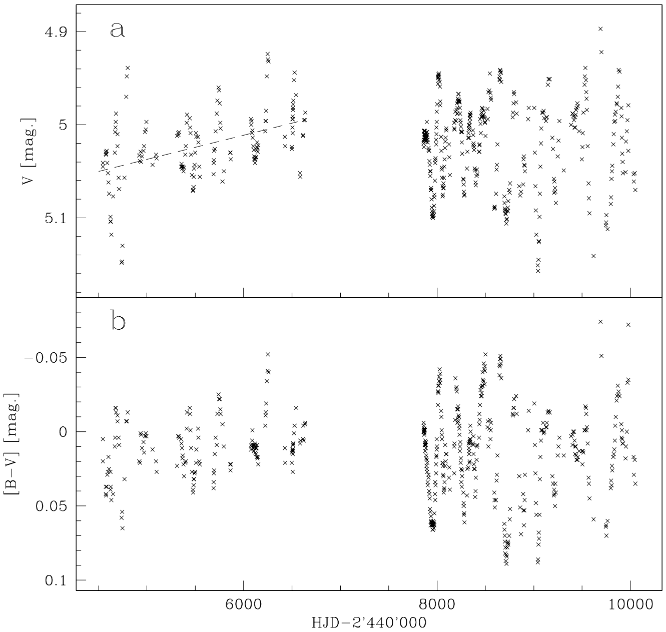

Fig. 4a and b. Geneva photometric data for V and [B-V]. The dashed line in **a** shows the long-term brightening of 0.0091 mag/y.

σ by less than 0.001). At this stage, the essential characteristics of the variability of V810 Cen is : *i)* an increase of σ_0, thus of the global amplitude from G to B1 filters; *ii)* an amplitude in U smaller than in B1, B and B2. This apparent decrease of the amplitude in U is due to the constant flux from the B-type component, which contribute significantly to the total flux only in this filter.

Our monitoring of V810 Cen can be characterized as follows :

– Three measurements have been obtained in February and March 1976, and in February 1977 (HJD from 2 442 817 to 2 443 182).

– From October 1980 to July 1986 (HJD from 2 444 544 to 2 446 639), the air mass of the measurements was restricted to values smaller than about 1.7. Thus the star was measured each year, only between November and July. On the average, 25 measurements per year were obtained.

– From December 1989 to October 1991 (HJD from 2 447 860 to 2 448 559), a peculiar observational effort was done in order to have a monitoring as continuous as possible (the star is observable during the whole year from La Silla). On the average, 9 measurements per month were obtained. These data are shown in Fig. 6a. Variations with a characteristic time in the 100-150 days range are clearly exhibited. In addition, the amplitude is variable.

– From November 1991 to December 1996 (HJD from 2 448 590 to 2 450 051), the monitoring was less intensive. Due to several periods without data, the average number of measurements per month is 3.

6. The photometric variability

Three methods have been used to analyze the variability of V810 Cen :

– The Date Compensated Discrete Fourier Transform **DCDFT** described by Ferraz-Mello (1981). This method avoids the missmeasurement of the amplitudes and mean magnitude encountered when the classical Discrete Fourier Transform (Deeming, 1975) is applied to unevenly spaced data (see Foster, 1995, 1996a).

– The **CLEANEST** method of Foster (1995). The spurious peaks in the Fourier analysis induced by the data sampling are eliminated by an iterative deconvolution process. The iteration has been stopped when the residual peaks in DCDFT were below the 1% confidence level limit according to Foster (1996a).

– The Weighted Wavelet Z-transform method (**WWZ**) of Foster (1996b). Schematically, the data are weightened with a gaussian function (with $\sigma \simeq 200$ d to 300 d in our present case) centered at a given time τ. The Fourier Transform is then performed for successive τ values and the WWZ maximum ($\mathrm{WWZ_{max}}$) indicates the dominating frequency $\nu(\mathrm{WWZ_{max}})$ (noted hereafter $\nu_{\max}$). The amplitude of $\nu_{\max}$ is estimated by the means of the Weighted Wavelet Amplitude statistics ($\mathrm{WWA_{max}}$). The WWZ method allows to analyze the changes in amplitude or/and frequency of the light curve.

In order to check the period and amplitude variabilities, the data have been splited into two samples: sets 1 and 2 span the ranges in HJD 2 444 544–2 446 639 and 2 447 860–2 450 051 respectively (see Fig. 4a and b). A careful examination of the data shows that the observed variations cannot be simply described as a stable, multiperiodic function. The main characteristics of the variability of V810 Cen during our survey are the following :

– **Long-term variation** : the mean luminosity of the star increased regularly from February 1976 to July 1986 (see Fig. 4a and b). The rate of brightening was roughly 0.009 mag/year. Since November 1991, the mean luminosity remained constant.

– **Modes at ∼156 and ∼107 days** : Figs. 5a and b present the DCDFT for both sets. We note two main peaks at frequencies 0.0064 and 0.0093 d^{-1}. The frequency difference is close the 1 y^{-1} alias ($\simeq 0.00274\ \mathrm{d}^{-1}$), suggesting that one of these may be an alias. However both of them are real because they are kept by the CLEANEST iterative method.

– **Other modes** : the CLEANEST spectra (Figs. 5c and d) reveal a third period at 115 d for set 1, and five new periods at 89, 129, 167, 185 and 234 days for set 2. These peaks appear thanks to the better time sampling of the second set.

Table 4. Weighted mean value and rms of the 499 measurements of the 7 magnitudes of V810 Cen in the Geneva Photometric System. The rms is also given for 3 standard stars measured during the same nights than V810 Cen.

	Filter	U	$B1$	B	$B2$	$V1$	V	G
	λ_0 [Å]	3464	4015	4227	4476	5395	5488	5807
V810 Cen	Mean mag.	6.797	6.155	5.035	6.323	5.785	5.021	6.005
V810 Cen	corrected rms (σ_0)	0.055	0.081	0.070	0.062	0.046	0.044	0.040
HD 93540	rms (σ_{s1})	0.0070	0.0061	0.0057	0.0058	0.0050	0.0043	0.0048
HD 94510	rms (σ_{s2})	0.0083	0.0065	0.0060	0.0058	0.0048	0.0040	0.0048
HD 102350	rms (σ_{s3})	0.0068	0.0056	0.0047	0.0049	0.0044	0.0035	0.0046

Table 5. Frequency, period and amplitude estimate from CLEANEST for set 1 (HJD 2 444 544–2 446 639) and 2 (HJD 2 447 860–2 450 051).

	Frequency [c/d]	Period [d]	Amplitude [mag.]
Set 1	0.00641±2e-05	156.0±0.5	0.028±0.002
	0.00964±2e-05	103.7±0.2	0.028±0.002
	0.00873±3e-05	114.6±0.4	0.019±0.002
Set 2	0.00668±2e-05	149.8±0.2	0.036±0.002
	0.00912±3e-05	109.6±0.2	0.024±0.002
	0.01119±3e-05	89.4±0.2	0.020±0.002
	0.00541±3e-05	184.8±0.5	0.024±0.002
	0.00597±2e-05	167.4±0.4	0.025±0.002
	0.00428±4e-05	233.5±1.3	0.015±0.002
	0.00777±5e-05	128.7±0.5	0.013±0.002

A curve of the form :

$$f(t) = \sum_{i=1}^{n} A_i \cos[2\pi\nu_i(t - t_0) + \phi_i] \quad (5)$$

has been fitted to the observations in sets 1 and 2 and the resulting amplitudes are given in Table 5. The residual standard deviation is 0.019 mag for both sets, a quite large value compared to the accuracy of our measurements (0.004 mag, see Table 4). As we shall see in the following, this is due to amplitude or/and period variation.

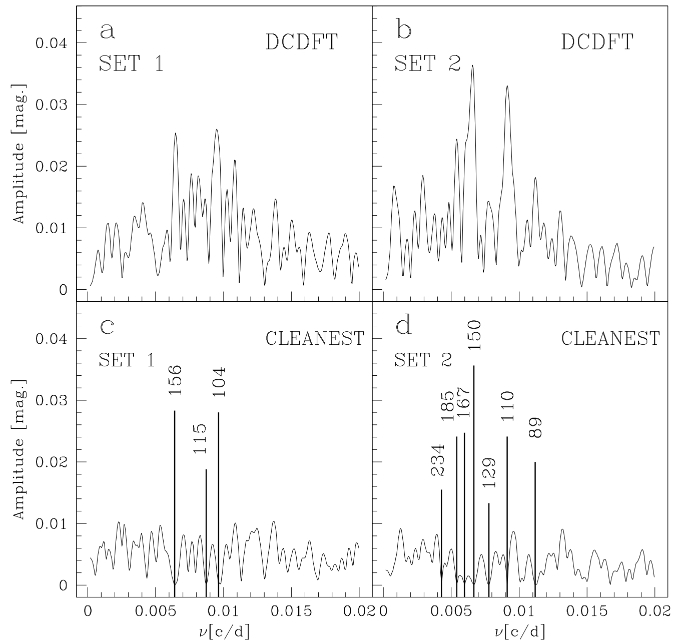

Fig. 5. a,b Date-compensated discrete Fourier transform (DCDFT) amplitudes for sets 1 and 2. **c,d** CLEANEST for sets 1 and 2, it is a combination of the subtracted periods and amplitudes (vertical bars each labeled with their period) and the DCDFT of the residuals (full line). CLEANEST has been applied until all the peaks of the DCDFT *power* are below the 1 % confidence level limits (computed according to Foster, 1996a).

7. Analysis of the mode variations

The data density is large enough in set 2 (see Fig. 6a) to allow an analysis of the variations of the frequencies and/or amplitudes of the dominant modes. Two kinds of analysis have been done :

– DCDFT method is performed in five successive intervals. In each of them (see Fig. 6a), the three most important modes have been identified and their frequencies and amplitudes are plotted as full symbols in Figs. 6b and c (the decreasing amplitude are symbolized with triangles, squares and dots respectively).

– WWZ method described previously is applied to the entire interval. In our case, the WWZ method gives reliable results only for the mode with the largest power ($\mathrm{WWZ_{max}}$). The variations of the dominating frequency $\nu_{\max}$ and its amplitude $\mathrm{WWA_{max}}$ are shown as solid lines in Figs. 6b and c.

The main points revealed by this analysis are :

1. The mode at ∼107 d (~ 0.0093 d^{-1}) is the most important one before HJD 2 448 400, while the mode at ∼156 d (~ 0.0064 d^{-1}) dominates afterwards (with short exceptions around HJD 2 449 500, 2 449 580 and 2 449 950). At the end of our survey, it appeared that the mode at ∼107 d was again the most significant one (see Fig. 6b).
2. The amplitude of the most important mode varies almost continuously. However, a stable amplitude at ∼0.06 mag was observed in the HJD interval 2 448 700–2 449 100, for the mode at ∼156 d (see Fig. 6c).
3. The DCDFT analysis (Fig. 6b) shows that a mode at $\sim 0.0045 - 0.0055$ d^{-1} (period between 225 and 180 d) is always present, but is never the most important one.

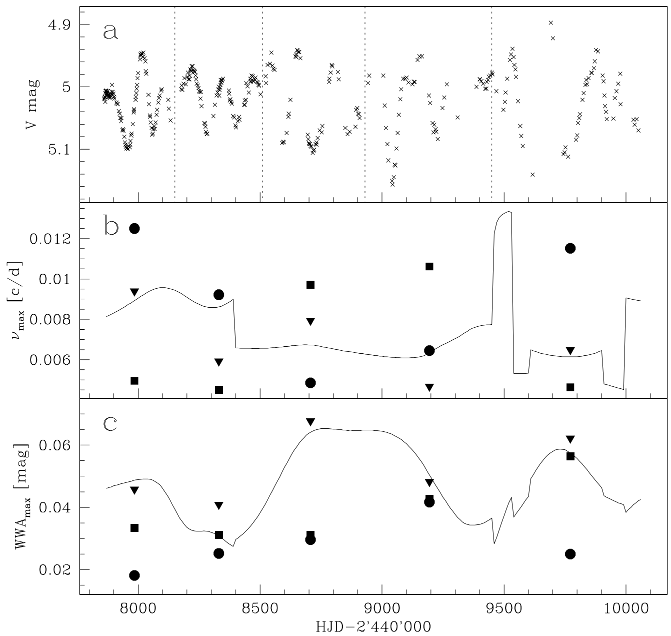

Fig. 6. a,b V-band photometry for data set 2, with subset division (vertical dotted lines). **c,d** dominating frequencies (WWZ maximum) for a given "mean time" τ and its corresponding amplitude WWA (full lines). Triangle, square and dot symbols (sorted according to decreasing amplitude) are the tree main frequencies found with DCFT analysis for each subset shown in *a*.

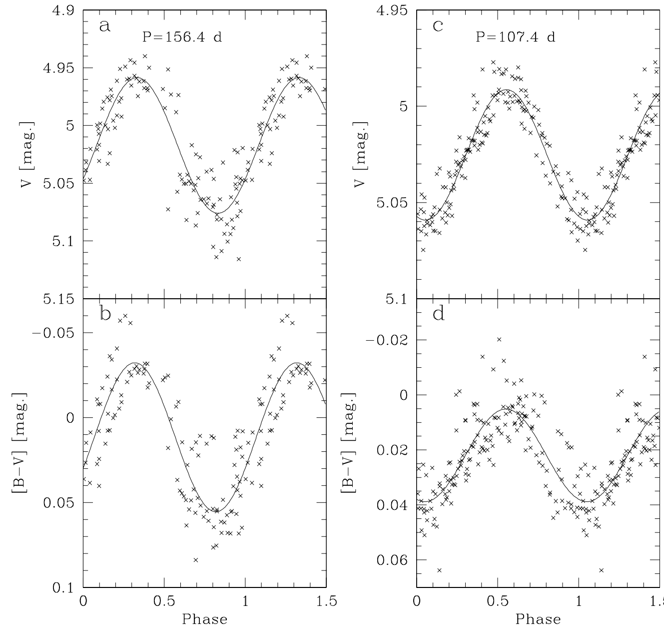

Fig. 7a–d. Light and color curves of the two main modes at 107.4 d (time interval: HJD 2 447 850-2 448 400) and 156.4 d (time interval: HJD 2 448 400-2 449 400).

In conclusion, **V810 Cen is a multi-periodic small amplitude variable star, whose periods and amplitudes are variable with time**. The periods of the two dominant modes are ~156 and ~107 d. The 7 years intensive survey (1989-1996) also reveals a third mode, with a period in the range 180-225 d.

8. The light and color curve parameters

The amplitude ratios and the differences in phase between the light V and color $[B-V]$ curves are interesting for the variability description, in particular for the mode identification. Because of the multiperiodic character of the light curve and of the amplitude variation described in the previous sections, the amplitude and phase of the principal modes have been fitted in various time intervals through Eq. (5), setting the number of frequencies (n) to 3.

According to Fig. 6, the parameters of the mode at ~107, ~156 and ~187 d have been calculated respectively in the time intervals in HJD 2 447 850–2 448 400, 2 448 400–2 449 400 and 2 447 850–2 450 100. The results are given in Table 6. The light and color curves for the two principal modes at ~107 and ~156 days are shown in Fig. 7a–d. As we see, the light and color variations are clearly *in phase*, i.e. the star is bluer when brighter. This is an indication of cepheid-like pulsation nature. However, it must be noted that, taken into account the uncertainties on $\Delta\phi$ in Table 6, the values of the phase difference $\phi_V - \phi_{B-V}$ can be slightly negative, zero or slightly positive. According to Balona & Stobie (1979, 1980), this indicates that these two modes can be radial ($\Delta\phi < 0$), but could also be non-radial, with odd ($\Delta\phi = 0$) or even ($\Delta\phi > 0$) values of the spherical harmonic order l.

The third mode, at ~187 days, shows a clearly positive value of $\Delta\phi$. This might indicate a non-radial quadrupole mode ($l = 2$). However, due to the amplitude and period changes in the modes of V810 Cen, the mode identification must not be made on the basis of $\Delta\phi$ values only (see next section).

When the time interval is short enough and the monitoring sufficiently dense, very good fitted light and color curves can be achieved. This is illustrated in Fig. 8a and b, for the interval in HJD 2 447 850–2 448 150 (the first interval in Fig. 6a). The solid curve in Fig. 8a and b represents a fit with 3 modes, the most important one being at $\sim$ 107 d. The residual standard deviation of the observed values around the fitted curves are 0.0050 mag in V and 0.0046 mag in $[B-V]$. Thus, in that case, the three modes describe completely the variability of V810 Cen (see Table 4).

9. The origin of the variability

9.1. Comparison with supergiants and cepheids calibrations

– **The Period–Luminosity–Colour PLC relations**. The largest amplitude period (~156 d) is in very good agreement with the empirical PLC relations for yellow supergiants. Taking the parameters derived in Sect. 4, $M_{\rm bol} = -8.5$ and $T_{\rm eff} = 5970$ K, the relation from Maeder & Rufener (1972), $\log P = -0.346 M_{\rm bol} - 3\log T_{\rm eff} + 10.60$, gives $P = 163$ d. Furthermore, assuming an evolutionary mass of ~20 $M_\odot$ (see the end of this section), the relation from Burki (1978), $\log P = -0.38 M_{\rm bol} - 3\log T_{\rm eff} - 0.5\log M + 10.93$, gives $P = 152$ d.

Table 6. Parameters of the highest amplitude variability modes according to Eq. (5) in various time intervals.

Period [d]	Frequency [c/d]	HJD interval	V Amp. A_V	$[B-V]$ Amp. A_{B-V}	A_V/A_{B-V}	$\Delta\phi = \phi_V - \phi_{B-V}$
107.4	0.00931	2 447 850-2 448 400	0.034 ±0.001	0.017±0.001	2.01	-0.003 ±0.014
156.4	0.00639	2 448 400-2 449 400	0.059 ±0.003	0.044±0.003	1.34	-0.014 ±0.018
186.7	0.00536	2 447 850-2 450 100	0.022 ±0.002	0.014±0.002	1.52	0.071 ±0.038

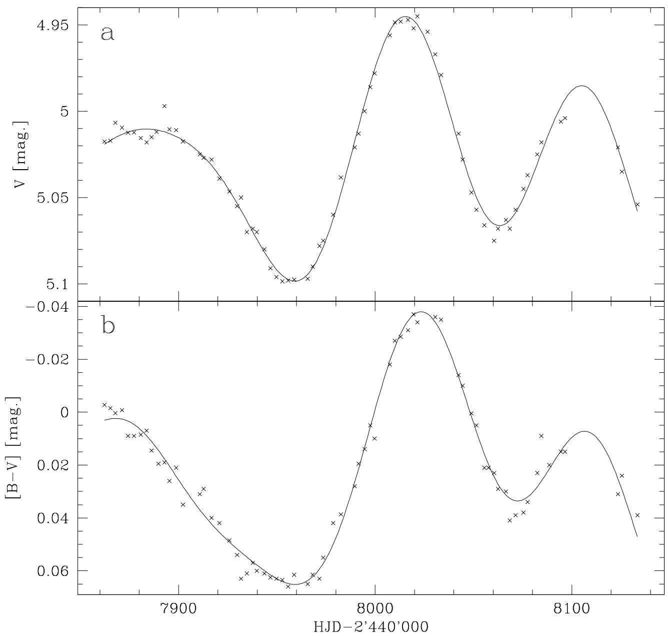

Fig. 8a and b. Three-frequency fit (0.00942 c/d, 0.00488 c/d and 0.01232 c/d) for V and $[B-V]$ (*a* and *b* respectively). Data are re-sampled in 3 days wide bin to homogenize the sampling.

The agreement is not so good with the Period–Luminosity relation for galactic cepheid stars (Gieren et al., 1993) : $M_{\rm V} = -1.371 - 2.986 \log P$ (scatter : 0.26). Using the $M_{\rm V}$ value obtained in Sect. 4, the predicted period is 226 d. This discrepancy with the observed period (∼156 d) is quite normal since V810 Cen is not located in the center of the cepheid instability strip, but rather in its blue border. For that reason, a color term is necessary in the PLC relation for supergiants (see Burki, 1978). Thus, **the observed main mode is in agreement with the observations concerning pulsating supergiants**.

– **The Period–Radius relation for cepheids**. Gieren et al. (1989) have established such a relation on the basis of 101 classical cepheids in the period range 3–45 d, studied from the visual brightness technique : $\log R = 1.108 + 0.743 \log P$ (scatter σ = 0.071). It is noteworthy that, despite the very large value of its main period (∼156 d), which is well outside the period range covered by the classical Galactic cepheids, the radius of V810 Cen found in Sect. 4 ($\log R$ = 2.62) is in agreement with this global relation for cepheids ($\log R$ = 2.74), the difference being only 1.6 σ. This agreement is **a strong support for a cepheid–like pulsation of this main mode, i.e. a fundamental radial mode**.

9.2. *Theoretical periods of the the radial modes*

– **Stellar models with "standard" mass loss rate**. Lovy et al. (1984) and Schaller (1990) have calculated the pulsation periods for the fundamental radial mode and the first two overtones, from a linear non-adiabatic analysis. Schaller's analysis is based on the massive supergiant models from the grid of evolutionary tracks of massive stars by Schaller et al. (1992). In these models, the dependence of the mass loss rate on L and $T_{\rm eff}$ is that given by de Jager et al. (1988), called hereafter the "standard" mass loss rate. Schaller (1990) derived a theoretical PLC relation, $\log P = -0.38 M_{\rm bol} - 3 \log T_{\rm eff} + 10.60$, for the fundamental radial mode which predicts a period P_0 = 140 d for V810 Cen. This value is valid for models cooler than $\log T_{\rm eff} = 4.1$ and in the phase of helium burning.

– **Stellar models with "high" mass loss rate**. Meynet et al. (1994) have calculated a new grid of evolutionary stellar models, by adopting a "high" mass loss rate, i.e. a rate enhanced by a factor of two with respect to the "standard" mass loss rate. Various comparisons with observations of high-mass stars support the high-mass loss grid of stellar models (see Maeder & Meynet, 1994). The linear non-adiabatic pulsation code of Schaller (1992) has been applied to various 25 $M_\odot$ models, at the edge of the first redward evolution, close to V810 Cen position. The result of these calculations is presented in Table 7 for the lower (redward evolution) and upper (blueward evolution) tracks. A fundamental mode period of 157 d is obtained for the blueward evolution at $\log T_{\rm eff}$ = 3.750 and $\log L/L_\odot$ = 5.342, that is 0.004 dex away from values derived in Sect. 4 for V810 Cen ($\log T_{\rm eff}$ = 3.78, $\log L/L_\odot$ = 5.3). Due to a strong mass loss at the beginning of the blueward evolution, the mass has decreased to 20 $M_\odot$.

9.3. *Interpretation of the main modes*

– **The observed main period at ∼156 d**. This observed period is in good agreement with the theoretical prediction for models with "high" mass loss rate (157.2 d). Thus, **the main observed period of V810 Cen (∼156 d) can be explained by a pulsation in the radial fundamental mode of a supergiant with an initial mass close to** $\sim 25\,M_\odot$. The evolutionary mass of V810 Cen must be $\sim 20\,M_\odot$.

– **The observed second period at ∼107 d**. The predicted periods of the first two radial overtones (P_1 = 82.0 d, P_2 = 56.3 d, see Table 7) are much too small to explain this period. The period ratio of the observed two dominant modes is 0.69, while the predicted ratios are P_1/P_0 = 0.52, P_2/P_0

= 0.36, P_2/P_1 = 0.69. This last value could suggest that V810 Cen pulsates in the first and second radial overtones. However, in that case, the fundamental radial period would be ∼350 d. This period would require a very high luminosity, $M_{\rm bol} \simeq -9.5$, which is difficult to postulate for a F8 Ia star. Since, in addition, this very large period is not observed, we conclude that **the observed second main period cannot be a radial mode and, thus, a non-radial p-mode is the most natural explanation**.
– **The observed third period at ∼187 d**. This period is larger than the main mode at ∼156 d. With the hypothesis that the main mode is the radial fundamental pulsation, we have to conclude that **the observed third period cannot either be a radial mode and, thus, a non-radial g-mode is to be postulated**. Non-radial g-modes have already been suggested in supergiants by Maeder (1980) or de Jager et al. (1991), and are probably present in the case of yellow hypergiants like ρ Cas (Lobel et al., 1994).

As noted above, the period ratio of the observed two dominant modes is 0.69, thus very close to the values of the double-mode cepheids pulsating in the radial fundamental mode and first overtone with P_1/P_0 in the 0.696–0.711 range (Balona, 1985). However, V810 Cen has a high mass, and therefore its P_1/P_0 value is lower than the ratio observed for "low mass" double-modes cepheids (see Table 7). The similarity between the observed value of 0.69 and the 0.696–0.711 range for double-modes cepheids is at the origin of a wrong conclusion, i.e. V810 Cen is a double-mode cepheid in addition to its supergiant characteristics (Burki, 1994).

An alternative interpretation associating the ∼187 d period to the radial fundamental has also been considered; then the other modes would be non-radial p-modes. However, this alternative is unlikely because, if the fundamental mode is excited, it should have the highest amplitude and this is not the case for the ∼187 d period (the highest amplitude mode is the ∼156 d period). Furthermore, the (marginally significant) positive phase shift does not support that hypothesis neither and there are strong evidences for the *radial nature* of the ∼156 d period.

Our present conclusion, based on a very long-term photometric monitoring, is that V810 Cen could be a supergiant star exhibiting the three types of pulsation modes : **radial fundamental mode** (main mode at ∼156 d), **non-radial p-mode** (second mode at ∼107 d) and **non-radial g-mode** (third mode at ∼187 d). If this conclusion is correct, V810 Cen would be the first known case of a star showing such a diversity of pulsational characteristics.

10. Conclusion

Radial velocities, spectrophotometry and Geneva photometry data have been used to discuss the evolutionary status and pulsation modes of the yellow variable supergiant V810 Cen and its B-type companion.

Radial velocities have been collected from the CORAVEL database as well as from the literature. They do not support the Stock 14 membership hypothesis of V810 Cen. To be consistent with the spectrophotometric data, the star has to be beyond Stock 14, at 3.3 to 3.5 kpc from the sun.

IUE and visible spectrophotometry together with Kurucz atmosphere models have been used to estimate the physical parameters of the red supergiant : $T_{\rm eff} = 5\,970 \pm 100$ K, $M_{\rm V} = -8.4, M_{\rm bol} = -8.5, R = 420$ R$_\odot$, spectral type F8 Ia. This star is about 3.3 mag brighter than its B0 III companion. Thus, the observed variability is due to the red supergiant.

The derived temperature and luminosity place the star at the blue edge of the classical cepheids instability strip. The initial mass was $\sim 25\,{\rm M}_\odot$ while the evolutionary mass ought to be close to $\sim 20\,{\rm M}_\odot$.

The high-precision long-term photometric monitoring in the Geneva system reveals various types of variability :

– A long-term increase of the luminosity from February 1976 to July 1986.
– A multimode pulsation behavior, with periods and amplitudes variable with time (in the range 0.02 to 0.06 mag). The main modes are :
  – A dominant ∼156 d period, identified as the fundamental radial mode. Its period value is in good agreement with the fundamental radial period derived from theoretical non-adiabatic linear pulsation analysis.
  – The second mode with a period of ∼107 d, which is most probably a non-radial mode, may be a p-mode.
  – The third mode with a period of ∼185 d, which could be a non-radial g-mode.
– Various other secondary modes have been detected during a time interval of high density measurements, at 89, 129, 167, 185 and 234 d.

Are radial and non-radial p- and g-modes simultaneously present in V810 Cen ? This is a quite fundamental question because this supergiant would then be the first known star exhibiting such a pulsational behavior. In our opinion, to answer this question, new hard and long-term work has to be done in the four following directions : *i)* New linear and non-linear non-adiabatic stability calculations have to be done, based on well-adapted supergiant models; *ii)* High resolution (R≃40 000) long-term spectroscopic monitoring must be organized in order to follow the line profile variations; *iii)* A long-term radial velocity monitoring would help to determine the parameters of the orbit and of the components; *iv)* The photometric long-term monitoring must be continued in parallel to the spectroscopic survey.

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Table 7. Periods and growth rates (η) from linear non-adiabatic stability analysis of stellar model with "high" mass loss rate. Positive η indicate unstable modes.

	$\log(T_{\rm eff})$	$\log(\frac{L}{L_\odot})$	$\frac{M}{\rm M_\odot}$	P_0 [d]	η_0	P_1 [d]	η_1	P_2 [d]	η_2	P_1/P_0
Redward evolution	3.783	5.293	22.3	107.88	-0.213	50.92	0.134	33.29	-0.346	0.47
	3.769	5.302	22.2	112.51	-0.018	56.93	0.141	39.92	-0.176	0.51
	3.759	5.309	22.2	123.04	0.008	64.54	0.146	44.67	-0.159	0.52
	3.752	5.320	22.1	129.62	0.040	69.98	0.148	47.77	-0.177	0.54
	3.748	5.321	21.7	132.03	0.068	72.66	0.143	49.37	-0.192	0.55
Blueward evolution	3.744	5.330	20.6	137.43	0.095	76.51	0.130	52.11	-0.224	0.56
	3.750	5.342	16.6	157.17	0.127	81.99	0.090	56.25	-0.489	0.52
	3.761	5.345	14.9	165.45	0.246	79.22	0.052	53.16	-0.829	0.48
	3.776	5.346	13.7	179.70	0.041	79.33	0.230	52.18	-1.900	0.44

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