PERIODIC RADIO CONTINUUM EMISSION ASSOCIATED WITH THE β CEPHEI STAR V2187 CYG

Mauricio Tapia,[1] Luis F. Rodríguez,[2,4] Gagik Tovmassian,[1] Vicente Rodríguez-Gómez,[3] Diego González-Buitrago,[1] Sergei Zharikov,[1] and Gisela N. Ortiz-León[2]

RESUMEN

Presentamos fotometría y espectroscopía de mediana resolución de V2187 Cyg. Confirmamos que es una estrella tipo β Cephei de tipo espectral B2-3 V. Tiene variaciones sinusoidales con un período de 0.2539 días y amplitudes medias de 0.037 y 0.042 magnitudes en i y V, respectivamente. No encontramos evidencia de variaciones en los perfiles de líneas de absorción en escalas de tiempo de horas o días y tampoco líneas de emisión. Reportamos también la sorpresiva detección de emisión de radiocontinuo de esta estrella con un espectro térmico. La emisión de radio presenta variaciones con un periodo de 12.8 días. Del archivo del *Very Large Array* encontramos que ninguna de las otras 15 estrellas de tipo β Cephei que han sido observadas con este instrumento muestra emisión de radio detectable, aunque muchas de ellas se encuentran mucho más cercanas al Sol que V2187 Cyg. La emisión de radio es, entonces, un fenómeno extremadamente raro en las estrellas tipo β Cephei.

ABSTRACT

We present new optical time-resolved photometry and medium-resolution spectroscopy of V2187 Cyg. We confirm its classification as a β Cephei star based on sinusoidal light variations with a period of 0.2539 days and mean amplitudes of 0.037 and 0.042 magnitudes in i and V, respectively. We classified the spectrum of this star as B2-3 V with no evidence of variations in the profiles of its absorption lines in timescales of hours or days. The stellar spectrum is totally absent of emission lines. We detected unexpected faint radio continuum emission (between 0.4 and 0.8 mJy at 6-cm) showing a sinusoidal variation with a period of 12.8 days. The radio spectrum is thermal. We searched in the Very Large Array archive for radio continuum emission toward 15 other β Cephei stars. None of these additional stars, some of them much closer to the Sun than V2187 Cyg, was detected, indicating that radio emission from β Cephei stars is extremely uncommon.

1. INTRODUCTION

During analysis of the NRAO[5] Very Large Array (VLA) archive data of the O-type binary system Cyg OB2 #8A, the persistent presence of a faint radio source $\sim 1.3'$ to its southeast was noted. The position of this faint radio source is coincident, within $0.2''$, with the β Cephei star V2187 Cyg, (ICRS 2MASS coordinates $20^\text{h}33^\text{m}18\overset{\text{s}}{.}29; +41°17'39\overset{''}{.}4$), in the central part of the spherical OB association Cyg OB2 (Knödlseder 2000). The β Cephei stars are pulsating main sequence variables of low amplitude ($\Delta V \leq 0.2$) with early B spectral types and typical periods of several hours (Stankov & Handler 2005).

V2187 Cyg, also designated as MT91-487 (Massey & Thompson 1991) or Schulte-63 (Schulte 1956), was classified by Pigulski & Kołaczkowski (1998) as a member of the β Cephei class of vari-

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, B.C., Mexico.

[2]Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia, Michoacán, Mexico.

[3]Harvard-Smithsonian Center for Astrophysics, USA.

[4]Astronomy Department, Faculty of Science, King Abdulaziz University, Saudi Arabia.

[5]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

ables based on its observed (Kron-Cousins) I-band sinusoidal light curve with an amplitude of 0.033 magnitudes, a derived period of 0.25388 days and photometric color indices $V = 15.39$, $U - B = 0.66$, $B - V = 1.61$, $V - R = 1.14$ and $V - I = 2.14$ (Massey & Thompson 1991; Pigulski & Kołaczkowski 1998) that indicate an early-B spectral type. Its 2MASS near-infrared magnitudes are $J = 11.52$, $H = 10.97$, $K = 10.67$. Albacete-Colombo et al. (2007) list this star as an X-ray emitter.

The star is located close to the highly obscured ($A_V = 5 - 10$) central region of the Cyg OB2 association that is characterized by an extremely high projected stellar density, particularly rich in O and early-type stars. The whole association, or young galactic globular cluster, contains around 2600 O and B stars, with a total mass amounting to slightly less than $10^5 M_\odot$ (Knödlseder 2000). The age of the complex has been estimated by several authors to be in the range of $3 - 4$ million years (Torres-Dodgen, Tapia, & Carroll 1991; Herrero et al. 1999; Knödlseder et al. 2002). Cyg OB2 is also conspicuous in terms of harboring a large fraction of known massive (OB- type) binaries. Kiminki et al. (2007) report orbital and stellar parameters of 20 of these spectroscopic binary systems. More intriguing is the presence of three known X-ray sources and (variable) non-thermal stellar radio emitters close to the nucleus of Cyg OB2. They are Cyg OB2 #9, #8a and #5, all of these being O-type spectroscopic binaries (Nazé et al. 2012; De Becker, Rauw, & Manfroid 2004), the latter with at least two other less massive stellar companions (Dzib et al. 2013, and references therein).

There is no known report of radio continuum emission from stars classified as β Cephei (Güdel 2002; Wendker 2004). Their lack of radio continuum emission is consistent with what is known regarding early type stars, which makes O-type stars much stronger radio emitters than B-type stars. Thermal radio continuum in massive stars is due to free-free emission in their ionized winds, that is proportional to the mass loss rate to the 4/3 power (e.g. Blomme 2011). O-type stars have much more massive winds than B-type stars and are, thus, easier to detect in radio continuum (e.g. Bieging, Abbott, & Churchwell 1989). Non-thermal radio continuum emission can also be present in early type stars and it is known to be associated with binarity (Dougherty & Williams 2000). In a massive stellar binary, the two stellar winds collide and in the shock a fraction of the electrons is Fermi accelerated to relativistic speeds, producing synchrotron emission (De Becker 2007;

Blomme 2011). The strength of the radio emission increases with the mass loss rate and wind speed, and again O-type stellar binaries are frequently detected as radio emitters. All the non-thermal radio stellar sources listed by De Becker (2007) contain at least one O-type or Wolf-Rayet (WR) star.

In this paper we report new optical photometry in the i and V bands and time-resolved medium-resolution optical spectroscopy of V2187 Cyg. From these, we classify the star as B2-3 V and derive its basic stellar properties, which are consistent with it being a peculiar β Cephei star. To understand the nature of the radio emission from V2187 Cyg, we analyze flux densities at 6-cm from the VLA archive data at 17 epochs from 1984 to 2005, obtaining evidence of periodic variations in the radio-continuum emission. We investigate the nature of this emission and also perform a search in the VLA archives for radio emission from other β Cephei stars.

2. OPTICAL OBSERVATIONS

Medium-resolution long-slit spectroscopy was performed with the Boller & Chivens spectrograph[6] attached to the 2.1-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir (OAN-SPM), Mexico during three runs in 2011 June, 2012 July and 2012 September. We used the 1200 l/mm grating and a slit width of 250 μm, yielding a nominal spectral resolution of 1.8 Å (111 km s^{-1} at Hβ). This spectral resolution was confirmed by measuring the width of the interstellar Na D lines on all the spectra of stars. The scale on the Marconi #2 CCD chip that was used is 0.60 Å/pixel. The length of the slit is 55″, oriented east-west. Two stars were included in the slit: V2187 Cyg and the O9V star MT91-507 (Massey & Thompson 1991), located 30″ to the east, and which we used as comparison. Series of spectra in the blue ($4000 - 4900$ Å) and red ($5570 - 6800$ Å) wavelength regions were secured. Table 1 presents the details of the individual spectroscopic observations. Note that the integration times were kept relatively short in order to search for possible short-time (fractions of an hour) variations. All spectra were reduced in the standard way (except no flat-fielding was performed) using IRAF's procedures[7]. Wavelength calibrations were performed using frames of CuArNe arcs taken several times each night.

---

[6]http://www.astrossp.unam.mx/.

[7]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under contract to the National Science Foundation.

TABLE 1

LOG OF THE SPECTROSCOPIC OBSERVATIONS WITH
THE B&CH SPECTROGRAPH ON 2.1−M TELESCOPE AT SPM

Date UT	No. spectra	Spectral range (Å)	Exposure time (s)
2011 June 29-31	4	4200−5300	900
2012 July 18-27	38	5600−6800	900
2012 Sept. 13	3	4300−5400	1200
2012 Sept. 14-16	12	5600−6800	1200

We also performed a series of photometric measurements of V2187 Cyg and several nearby comparison stars within $50''$ on 60-second integration images. These were acquired in approximately 1.5-hour nightly periods from 2012 October 23 to 2012 November 7, totalling nearly 14 hours of coverage. The frames were obtained simultaneously through the Bessel V and i filters. The instrument used was a 4-channel optical/near-infrared camera (though only the two optical cameras were used for this work) named RATIR (Reionization and Transients Infrared Camera) attached to the 1.5-m telescope of OAN-SPM (Butler et al. 2012[8]). All observations were made in service mode. The typical measured full-width half maximum (FWHM) seeing was $1''5$. No attempts were made to obtain absolute photometry and only differential photometry is reported in this paper. This is referred to several local comparison, non-variable (Pigulski & Kołaczkowski 1998) stars. Digital aperture photometry was performed using DAOPHOT (Stetson 1987) with an aperture (diameter) of $3''$, large enough to allow for ocasional guiding errors. Sky subtraction was performed in a ring of radius $1''6$ and width $1''1$. For some $5−10\%$ of the usable time, thin clouds were present. The photometric uncertainties were estimated from the dispersion of the relative magnitude differences between comparison stars. These values ranged from 0.005 to 0.008 mag for i and approximately three times larger for V band. The mean V magnitude differences between the comparison O9V star MT91-507 and V2187 Cyg is 2.65, in full agreement with Massey & Thompson's (1991) photometry for these stars.

The photometric observations cover all phases of the short-period (0.25388 days = 6.1 hours) sinusoidal variations reported for V2187 Cyg by Pigulski & Kołaczkowski (1998). The star was observed for up to 1.6 hour-long segments each night during the
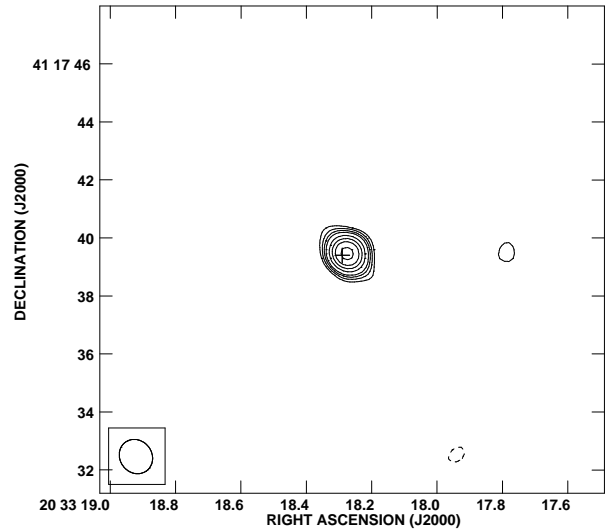
---

[8]See also http://www.ratir.org/.

Fig. 1. VLA image of the radio emission associated with V2187 Cyg at 6-cm taken on 2005 Feb 13. Contours are $−4, −3, 3, 4, 5, 6, 8, 10, 12$ and 15 times 45 μJy, the rms noise of the image. The synthesized beam, shown in the bottom left corner, has half power full width dimensions of $1''23 \times 1''10$, with the major axis at a position angle of $+38°$. The cross marks the optical position of the star.

length of our observing run (16 consecutive nights) and we managed to cover all phases, but this situation made it impossible to detect unequivocally any other photometric fluctuation in time-scales of several days.

3. RESULTS

3.1. *6-cm Flux Density as a Function of Time*

The bulk of the archive observations of V2187 Cyg comes from the high-quality set of 13 observations used by Blomme et al. (2010) to study Cyg OB2 #8A. These observations were made at 6-cm between 2005 February 15 and 2005 March 12. Figure 1 presents a representative VLA map from which

TABLE 2

FLUX DENSITIES OF V2187 CYG AT 6-CM

Epoch	JD −2440000[a]	Project	Phase Calibrator	Phase Calibrator Flux Density (Jy)	VLA Conf.	Source Flux Density (mJy)[b]
1984 Mar 04	05764.36	AA28	2007+404	4.23±0.01	CnB	0.51±0.14
1984 Mar 09	05769.17	AA28	2007+404	4.31±0.01	CnB	0.48±0.16
1993 May 01	09109.11	AS483	2007+404	3.19±0.01	B	0.68±0.16
2004 Feb 15	13051.28	AS786	2015+371	2.76±0.01	CnB	0.47±0.10
2005 Feb 05	13406.51	AB1156	2007+404	2.37±0.01	BnA	0.67±0.07
2005 Feb 06	13408.36	AB1156	2007+404	2.44±0.01	BnA	0.53±0.07
2005 Feb 08	13410.32	AB1156	2007+404	2.46±0.01	BnA	0.43±0.07
2005 Feb 11	13413.31	AB1156	2007+404	2.48±0.01	BnA	0.43±0.08
2005 Feb 13	13415.48	AB1156	2007+404	2.36±0.01	BnA	0.54±0.07
2005 Feb 18	13420.36	AB1156	2007+404	2.37±0.01	B	0.62±0.06
2005 Feb 25	13427.41	AB1156	2007+404	2.43±0.01	B	0.64±0.08
2005 Feb 27	13429.42	AB1156	2007+404	2.42±0.01	B	0.78±0.06
2005 Feb 28	13430.39	AB1156	2007+404	2.40±0.01	B	0.77±0.07
2005 Mar 01	13431.16	AB1156	2007+404	2.43±0.01	B	0.73±0.07
2005 Mar 02	13432.23	AB1156	2007+404	2.41±0.01	B	0.79±0.07
2005 Mar 08	13438.19	AB1156	2007+404	2.41±0.01	B	0.47±0.07
2005 Mar 12	13442.15	AB1156	2007+404	2.44±0.01	B	0.71±0.07

[a]At the middle of the observing run.

[b]Corrected for the primary beam response.

measurements were performed. The flux densities from these observations suggest periodic variations in the flux density. A chi-square test on these 13 data points yields a 94% confidence level for such a variability. We found four additional 6-cm observations (two made in 1984, one in 1993 and one in 2004) of good quality made. These observations are also included in Table 2.

We used the Lomb-Scargle method (Scargle 1982; Lomb 1976; Press et al. 1992) to search for periodicity in the radio continuum emission (at 6-cm) in two ways: (1) using all 17 data points available, and (2) using only the 13 points obtained in a 36-day span in February-March 2005. Both periodograms are shown in Figure 2 and suggest the same period, namely 12.8 ± 0.2 days. The false alarm probabilities, calculated assuming that the errors in the flux are Gaussian-distributed (Press et al. 1992), are 12.9% (17 points) and 14.5% (13 points). The cosine functions derived from both fits are shown in Figure 3. They are practically identical and have the same semi-amplitude of 0.18 mJy. By including measurements from earlier epochs we confirmed that the periodogram is dominated by the data from 2005. However, we note that the two measurements taken in 1984 have a clear significance to our model, since
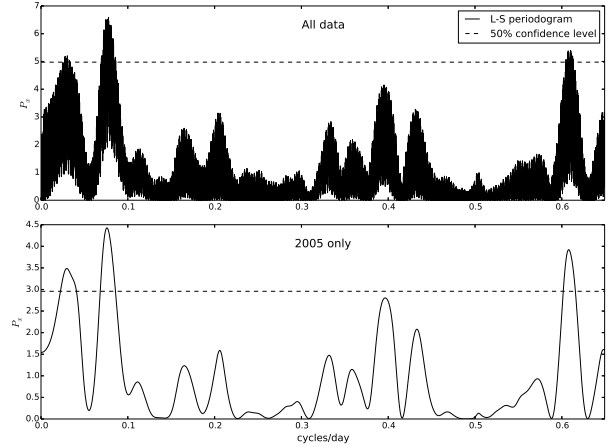

Fig. 2. Periodograms for the radio continuum data of V2187 Cyg. The upper panel is for all 17 data points; the high frequency oscillation is produced by the inclusion of data points remote in time from the 2005 observations. The lower panel is for the 13 points obtained during a 36-day span in 2005 February−March. The dashed lines indicate the 50% confidence level.

they are only separated by a few days. While these two measurements alone are not enough to firmly establish the existence of a periodicity, they certainly

TABLE 3

FLUX DENSITIES OF V2187 CYG AT OTHER WAVELENGTHS

Epoch	JD −2440000[a]	Project	Wavelength (cm)	Phase Calibrator	Phase Calibrator Flux Density (Jy)	VLA Conf.	Source Flux Density (mJy)[b]
1984 Nov 28	06032.52	AC116	20	2007+404	3.86±0.01	A	≤0.24[c]
1993 May 01	09109.11	AS483	3.6	2007+404	3.19±0.01	B	1.05±0.11
2004 Feb 15	13051.28	AS786	3.6	2015+371	2.72±0.01	CnB	1.15±0.13
2012 Jun 18[d]	16096.92	12A-007	12	2007+404	0.930±0.002	B	0.16±0.02

[a]At the middle of the observing run.

[b]Corrected for the primary beam response.

[c]Three-sigma upper limit.

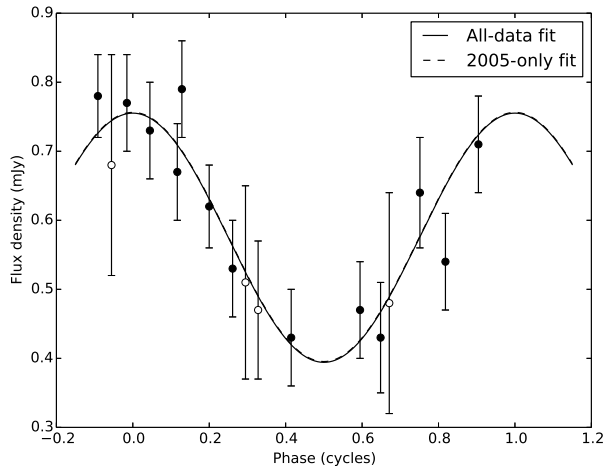[d]Observations made with the Jansky Very Large Array.

Fig. 3. VLA observations of V2187 Cyg at 6-cm. The flux densities are plotted as a function of orbital phase in the 12.78-day period, with phase 0 corresponding to the maximum radio emission. The data points from 2005 are shown as solid circles, while the data points for other epochs are shown as empty circles. The continuum line shows the cosine fit for all data points and the almost identical broken line represents the fit for the 13 data points obtained in 2005.

do not contradict our model, as one could think of possible configurations in which the two points cannot be fit by a 12.8-day sinusoid of the same amplitude (for example, if the two measurements had a flux approximately equal to the maximum value of our model and were temporally separated by 0.5 cycles, or if they had an average flux and were separated by 0.25 or 0.75 cycles).

3.2. *Radio Spectral Index*

Simultaneous observations are required to determine the spectral index. We found observations of V2187 Cyg in the VLA archive at 6 cm (4.86 GHz) and 3.6 cm (8.44 GHz) made on two epochs: 1993 May 01 as part of project AS483 and 2004 February 15 as part of project AS786. The flux densities at 4.86 GHz are given in Table 2, while those at 8.44 GHz are given in Table 3. Combining the flux densities at both frequencies measured on 1993 May 1, we obtain an spectral index of $S_\nu \propto \nu^{0.8\pm0.5}$, while for 2004 February 15 we obtain $S_\nu \propto \nu^{1.6\pm0.4}$. Both determinations are consistent with a thermal emission mechanism, most likely partially thick free-free radiation. The other two flux densities listed in Table 3 (at 20 and 12 cm) are also consistent with a thermal spectrum (i.e., weaker flux densities at the lower frequencies).

3.3. *Optical photometry*

The Discrete Fourier Transform (DFT) method[9] was used to independently confirm the present periodicity of V2187 Cyg in the i-band photometric light curve. The resulting power spectrum is shown in Figure 4. The dominant frequency in this power spectrum is 3.93866 ± 0.03503 day^{-1}, which corresponds to a period of 0.25389 ± 0.00228. This value agrees with that (0.25388 days) determined by Pigulski & Kołaczkowski (1998), obtained in mid-1996 and based on a longer time-span (44 days) light-curve.

The light-curves of V2187 Cyg in i (filled circles) and V (open circles) are shown in Figure 5. The photometric data points are plotted folded into phase, assuming a period of 0.2539 days, covering 1.2 periods. The amplitudes of the light curves appear to vary, with values ranging from 0.032 to 0.042 magnitudes in i and 0.035 to 0.050 in V from one period to the next. In particular, one of the light maxima (phases 0.85 to 1.0 on the left hand extreme of

---
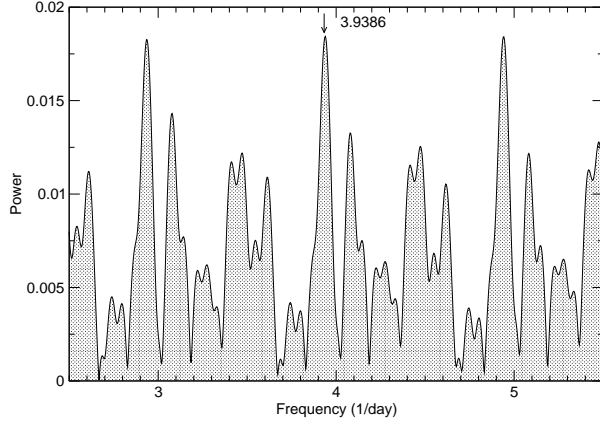[9]http://www.univie.ac.at/tops/Period04/.

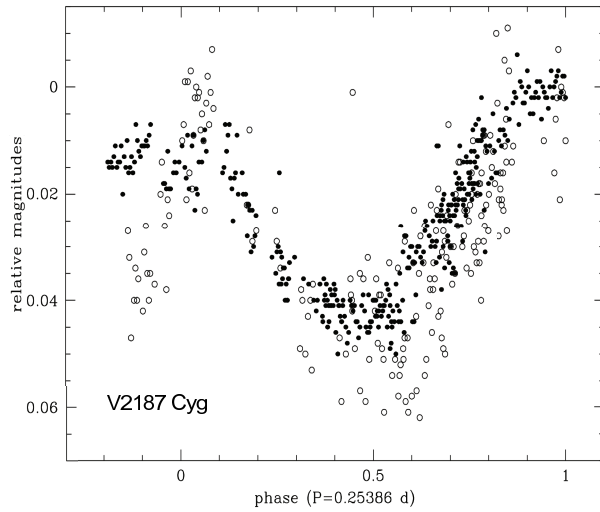Fig. 4. The power spectrum of the *i*-band variation of V2187 Cyg.

Fig. 5. Light curves of V2187 Cyg in *i* (filled circles) and *V* (open circles). The scale in the abscissa is given in terms of arbitrary phase with a period = 0.2539 days (see text). Measurements from the first observing night in this series correspond to the right hand side of the plot, while those from the last night, to the left (see text). The scale in the ordinate is expressed in relative magnitudes. Note that the significantly larger amplitude and scatter (noise) in the *V*-band and the larger number of points for phases larger than 0.3, give the false illusion of a phase shift.

the plot) on 2012 November 5−7 appears to be depressed compared to the equivalent phases on 2012 October 23−24 (on the right hand extreme of the plot). Based on these light curves, and on our determination of a B3 V spectral type, (see next subsection) we support the classification of V2187 Cyg as a member of the β Cephei class of variables.
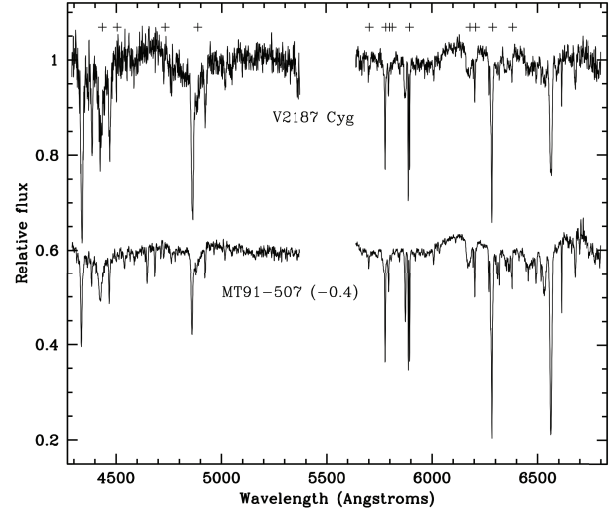

Fig. 6. Averaged normalized spectra of V2187 Cyg and MT91-507. The diffuse interstellar bands (DIBs) are indicated with plus signs at the top of the graph. Note that Hβ blends with DIB4882. The dates of each averaged short wavelength segment are 2012 Sep 13+2011 June 29-31 and for the long wavelength segment, 2012 Sep 14-16+2012 July 25-27+2012 July 18-2.

3.4. *Optical spectroscopy*

We determine spectral types for V2187 Cyg and for the comparison star MT91-507 (O8.5V, Hanson 2003; O9V, Kiminki et al. 2007) using all available spectra. The spectrum of V2187 Cyg is classified for the first time and it yields B2-3 V, based on the relative strength of the Balmer and HeI lines, using templates from Grey & Corbally (2009), though a luminosity class IV cannot be ruled out from our spectrum. As a test of consistency, we used the same classification procedure to independently classify MT91-507, yielding O9V, in agreement with the literature. No evidence of emission lines in the spectrum of either V2187 Cyg or MT91-507 was found. The combined normalized spectra (all individual spectra added for each wavelength range) of both stars are shown in Figure 6. The widths (FWHM) of the absorption lines measured on this combined spectrum of V2187 Cyg are $\sim 11 - 12$ Å for the Balmer lines and $\sim 8 - 10$ Å for the HeI lines. The latter imply rotational velocities ($v \sin i$) of around 350 km s^{-1} (Daflon et al. 2007, their Table 2). Those of MT91-507 are significantly narrower (around 9 Å and 5 Å for H and HeI, respectively).

Because of the low signal-to-noise (S/N), we found it impossible to obtain reliable values for the width of the absorption lines on individual short-integration (20 min) spectra, thus preventing us
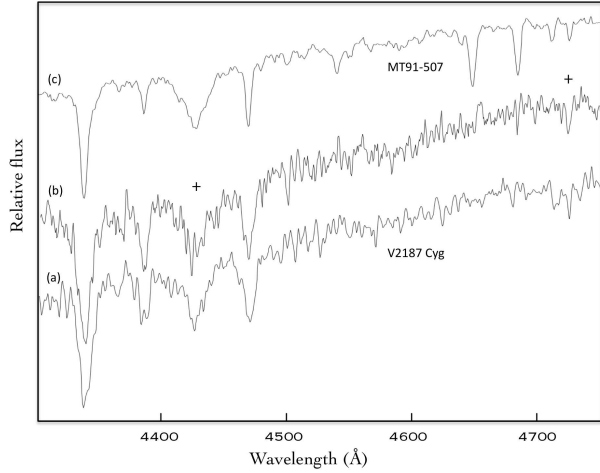
Fig. 7.   Sections of 3-day averaged spectra (boxcar-smoothed with kernel 3) of V2187 Cyg and MT91-507 with representative He and H lines at different epochs and phases ϕ (Table 4).   The absorption lines in the 4300−4750 Å segment are: Hγ, HeI 4385,4471,4538,4713 CIII 4647/50/52, HeII 4686, DIB4424,4724,4761.   The dates are (a) 2011 June 29−31 ($\phi = 0.81$); (b) 2012 September 13 ($\phi = 0.48$); (c) 2012 September 13.   The plus signs mark the DIBs.
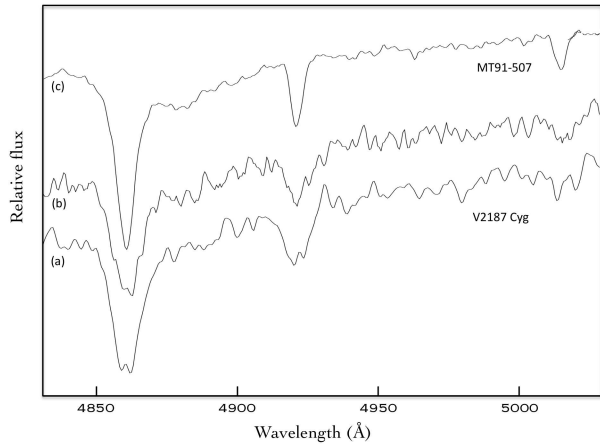

Fig. 8.   Sections of 3-day averaged spectra (boxcar-smoothed with kernel 3) of V2187 Cyg and MT91-507 with representative He and H lines at different epochs and phases ϕ (Table 4).   The absorption lines in the 4830−5040 Å segment are: Hβ, HeI 4920,5016.   The dates are (a) 2011 June 29−31 ($\phi = 0.81$); (b) 2012 September 13 ($\phi = 0.48$); (c) 2012 September 13.

from determining whether there are variations in the line profiles in time-scales comparable to the pulsation period (6 hours).   In order to search for evidence of line profile variations on timescales of days, we improved the S/N by averaging spectra of
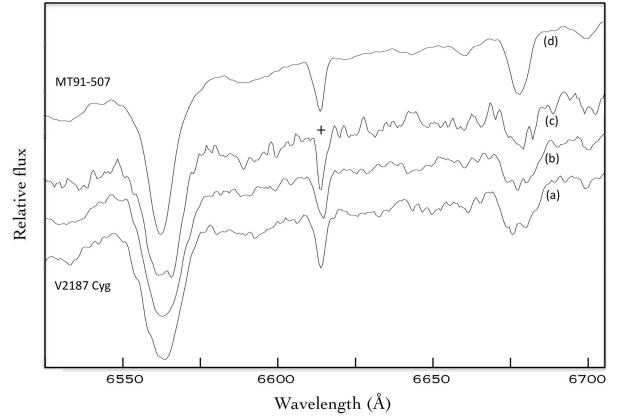

Fig. 9.   Sections of 3-day averaged spectra (boxcar-smoothed with kernel 3) of V2187 Cyg and MT91-507 with representative He and H lines at different epochs and phases ϕ (Table 4).   The absorption lines in the 6540−6700 Å segment are: Hα, HeI 6672, DIB 6614.   The dates are (a) 2012 July 18−21 ($\phi = 0.17$); (b) 2012 July 25−27 ($\phi = 0.32$); (c) 2102 September 14−16 ($\phi = 0.63$); (d) All 2011−2012. The plus sign marks the DIB.

V2187 Cyg obtained over three consecutive nights in four epochs, which correspond to four distinct phases distributed along the 12.8 days radio period.   These mean spectra, compared to those of the star MT91-507, are illustrated in Figures 7, 8, and 9.   We then measured the widths of the Balmer and HeI lines in V2187 Cyg corresponding to each of the four epochs. With typical uncertainties of ± 0.3 for the HeI lines and ± 0.1 for the H lines, the results are given in Table 4.   Although there may be a marginal evidence of variations in phase with the radio-continuum flux, the large uncertainties preclude us from reaching any firm conclusion in this regard.

4. DISCUSSION

We provide independent confirmation that this B3 V star displays the characteristics that define the β Cephei class of pulsating variables, with a visual photometric period of 0.25388 days that has remained unchanged since its discovery in 1996 (Pigulski & Kołaczkowski 1998).   The measured widths of the HeI lines suggest atypically high rotation velocities, of about 300−400 km s^{-1}.   At the same time, the star shows a 12.8-day sinusoidal variation of its 6-cm radio flux density, with a spectral index that implies a thermal origin.   This kind of emission from V2187 Cyg is unique among β Cephei stars, both in terms of its high radio flux as well as of its cyclic, variable nature, with a period some 50 times longer than the pulsation period.

TABLE 4

MEAN FWHM OF BALMER[a] AND
HELIUM[b] ABSORPTION LINES

Phase ϕ	Width (Å)			
(P=12.8 days)	V2187 Cyg		T91-507	
	H	HeI	H	HeI
0.81	12.2	9.8	–	–
0.17	12.6	9.7	–	–
0.32	12.6	9.7	–	–
0.48	11.7	8.4	–	–
-	-	-	8.9	5.1

[a]H (Hα, Hβ and Hγ).

[b]HeI ($\lambda\lambda$4438,4472,4931,5015,5875,6678).

The available $UBVRIJHK$ photometry of V2187 Cyg combined with our new spectral type B2-3 V, imply a single value for the dust extinction of $A_V = 5.7 - 5.8$, consistent with that measured towards other *bona fide* members of the Cyg OB2 association. Determining its spectroscopic distance from the Sun is subject to a large uncertainty, mainly because of the uncertainties in the calibration of the stellar absolute magnitudes that must be assumed. It is probably more instructive to assume that V2187 Cyg belongs to Cyg OB2 and is, thus, at the same distance. We adopt 1.62 kpc (true distance modulus 11.05) for the distance to Cyg OB2, as determined by VLBA astrometric parallax to two *bona fide* Cyg OB2 members (Zhang et al. 2012, Dzib et al. 2013). This value is consistent with the mean spectroscopic distance measurements ($d = 1.7$ kpc; Torres-Dodgen et al. 1991; Massey & Thompson 1991). The assumed distance implies absolute magnitudes $M_V = -1.5$ and $M_K = -0.9$ for V2187 Cyg, that correspond to a B3 main sequence star. If the assumption is correct, then V2187 Cyg cannot be a subgiant, as many β Cephei stars are. The fact that all photometric indices from 0.44 to 2.2 μm are well fitted by a single reddened star with the above properties imposes strong restrictions on a possible companion stellar object, as this would have to be much fainter than the B3 star at all these wavelengths.

Finally, we derive the value of the "pulsation constant" Q for V2187 Cyg,

$$Q = P\sqrt{\frac{\overline{\rho}}{\overline{\rho}_\odot}} \ ,$$

where P is the period and $\overline{\rho}/\overline{\rho}_\odot$ is the mean star density in solar units. For a B3V star, $\log\left(\overline{\rho}/\overline{\rho}_\odot\right) =$

-1.15 (Schmidt-Kaler 1982, § 4.1.5.2) and $P = 0.254$ days, then $Q = 0.07$ days, consistent with the values of β Cephei variables in the catalog of Stankov & Handler (2005). For a luminosity class IV, Q would be slightly smaller.

4.1. *The Nature of the Radio Emission*

The radio emission from V2187 Cyg has a spectral index suggestive of partially thick free-free emission. One possible explanation could be that we are observing the emission from the stellar ionized wind. However, the expected flux densities at centimeter wavelengths of ionized winds from massive stars and the observed values (0.4 to 0.8 mJy at 6 cm) are orders of magnitude higher than those expected for an early B-type star at a distance of 1.62 kpc (Dzib et al. 2013).

Another possibility is that V2187 Cyg is ionizing a small HII region. The expected ionizing photon rate for a B2 V star is 7.8×10^{44} s^{-1} (Panagia 1973), that at a distance of 1.62 kpc will produce a flux density of $\sim$3 mJy at 3.6 cm. In other words, V2187 Cyg can provide the photoionization required to explain the radio continuum emission. However, the optical spectra discussed here does not present evidence of the emission lines expected from an HII region.

The presence of a low-mass close companion whose neutral wind is, at some distance, ionized by UV photons from V2187 Cyg may also explain the observed radio emission. The radio flux variations with a periodicity of 12.8 days would be caused by periodic eclipses of this ionized region by the optically thick stellar wind of the primary star. Alternatively, these may be caused by periodic gas ejections by the secondary.

The main problem with the proposed mechanisms is that the optical observational results presented here do not support the presence of a binary system. In fact, no emission lines are present in the stellar spectrum, and no variations are seen in the profile of any absorption line. Furthermore, the photometry from 0.44 to 2.2 μm does not show any deviation from a single B2-3 V star reddened by $A_V = 5.8$. On the other hand, the object is also an X-ray source, which would argue in favor of a binary scenario with a compact companion.

Finally, we consider the possibility that the radio emission is a fortuituous alignment with a background source. Following Windhorst et al. (1993), the *a priori* probability of finding a 3.6 cm source of 0.4 mJy in a solid angle of 1 square arcsecond is only $\sim 2 \times 10^{-6}$, so we consider this possibility very unlikely.

TABLE 5

UPPER LIMITS TO β CEPHEI STARS OBSERVED WITH THE VLA

Star	Other Name	Position[a] α(J2000)	δ(J2000)	Epoch	Project	VLA Conf.	λ (cm)	Upper Limit (mJy)[b]
γ Peg	HD 886	00 13 14.15	+15 11 00.9	1992 Apr 14	AD288	C	3.6	≤0.20
V619 Per	SAO 23246	02 22 02.78	+57 08 25.1	1984 Sep 29	AR110	D	6	≤0.17
V595 Per	SAO 23251	02 22 08.61	+57 07 28.4	1984 Sep 29	AR110	D	6	≤0.17
V1032 Sco	Braes 930	16 53 58.60	−41 48 41.8	1990 Feb 17	AH395	A	3.6	≤0.17
V946 Sco	Braes 932	16 54 01.77	−41 51 12.1	1990 Feb 17	AH395	A	3.6	≤0.14
V964 Sco	Braes 672	16 54 18.32	−41 51 35.7	1990 Feb 17	AH395	A	3.6	≤0.17
HD 167451	SAO 161234	18 15 54.86	−13 34 27.7	1997 Oct 11	AK451	DnC	21	≤0.60
HD 172427	SAO 161713	18 40 32.18	−10 43 06.9	1995 Jan 21	AR330	DnC	6	≤0.17
NSV 13054	NGC 6910 18	20 22 58.94	+40 45 39.3	1994 Oct 11	AS544	C	6	≤0.42
NGC 6910 16	—	20 23 07.34	+40 46 55.6	1994 Oct 11	AS544	C	6	≤0.33
TYC 3156-1857-1	NGC 6910 14	20 23 07.57	+40 46 08.9	1994 Oct 11	AS544	C	6	≤0.33
TYC 3156-1028-1	NGC 6910 27	20 23 33.75	+40 45 19.9	1994 Oct 11	AS544	C	6	≤0.39
BW Vul	HD 199140	20 54 22.39	+28 31 19.2	1986 Jun 19	AH204	A	6	≤0.07
β Cep	HD 205021	21 28 39.60	+70 33 38.6	2002 Jun 02	AD467	A	3.6	≤0.15
DD Lac	HD 214993	22 41 28.65	+40 13 31.6	1992 Apr 14	AD288	C	3.6	≤0.20

[a]From SIMBAD. The position of V595 Cyg in the catalog of Stankov & Handler (2005) differs by $\sim 1'$ from that given in SIMBAD.
[b]At the 3σ level.

4.2. A search for radio continuum from other β Cephei stars

The catalog of galactic β Cephei stars of Stankov & Handler (2005) lists a total of 93 stars. More recently, Pigulski & Pojmański (2008) reported an additional 103 β Cephei stars. We searched for VLA archive observations of good quality toward these stars.

We found observations for only 14 stars in the Stankov & Handler (2005) catalog and only for two stars in the Pigulski & Pojmański (2008) catalog. The small number of stars with VLA observations in this last, more recent, catalog is due to the fact that most of the stars in it are very southern objects. Many of these observations were pointed to other objects, but included the β Cephei star in the primary beam.

We set as a criterion that the final image was expected to provide an rms noise in the range of 0.1 mJy and thus a detection at the mJy level. Of these 16 β Cephei stars, only V2187 Cyg was detected as a radio source. The upper limits for the other stars are listed in Table 5. It must be stressed that not even the prototype of the class, the third-magnitude star β Cep, with a Hipparcos measured parallax of 4.76 mas ($d = 210$ pc) could be detected at 3.6 cm, with a 3σ upper limit of 0.15 mJy.

5. CONCLUSIONS

1. We report the detection of centimeter radio continuum emission toward the β Cephei star V2187 Cyg. The 6 cm emission is faint (0.4 to 0.8 mJy) and shows a periodicity of around 12.8 days. We searched unsuccessfully for radio emission toward another 15 β Cephei stars with VLA archive observations.

2. We present extensive new optical observations of V2187 Cyg that support its classification as a β Cephei star based on sinusoidal light variations with a confirmed period of 0.25389 days and a mean amplitudes of 0.37 and 0.42 magnitudes in the i and V bands, respectively.

3. We classify the spectrum of V2187 Cyg as B3 V with no evidence of a stellar companion or any emission lines in the spectral range 4300 to 6800 Å.

REFERENCES

Albacete-Colombo, J. F., Flaccomio, E., Micela, G., Sciortino, S., & Damiani, F. 2007, A&A, 464, 211

Bieging, J. H., Abbott, D. C., & Churchwell, E. B. 1989, ApJ, 340, 518

Blomme, R. 2011, Bul. Soc. Roy. Sci. Liège, 80, 67

Blomme, R., De Becker, M., Volpi, D., & Rauw, G. 2010, A&A, 519, A111

Butler, N., et al. 2012, Proc. SPIE, 8446, id 844610

Daflon, S., Cunha, K., de Araújo, F. X., Wolff, S., & Przybilla, N. 2007, AJ, 134, 1570

De Becker, M. 2007, A&A Rev., 14, 171

De Becker, M., Rauw, G., & Manfroid, J. 2004, A&A, 424, L39

Dougherty, S. M., & Williams, P. M. 2000, MNRAS, 319, 1005

Dzib, S. A., Rodríguez, L. F., Loinard, L., Mioduszewski, A. J., Ortiz-León, G. N., & Araudo, A. T. 2013, ApJ, 763 139

Gray, R. O., & Corbally, C. J. 2009, Stellar Spectral Classification (Princeton, NJ: Princeton Univ. Press)

Güdel, M. 2002, ARA&A, 40, 217

Hanson, M. M. 2003, ApJ, 597, 957

Herrero, A., Corral, L. J., Villamariz, M. R., & Martín, E. L. 1999, A&A, 348, 542

Kiminki, D. C., et al. 2007, ApJ, 664, 1102

Knödlseder, J. 2000, A&A, 360, 539

Knödlseder, J., Cerviño, M., Le Duigou, J.-M., Meynet, G., Schaerer, D., & von Ballmoos, P. 2002

A&A, 390, 945

Lomb, N. R. 1976, Ap&SS, 39, 447

Massey, P., & Thompson, A. B. 1991, AJ, 101, 1408

Nazé, Y., Mahy, L., Damerdji, Y., Kobulnicky, H. A., Pittard, J. M., Parkin, E. R., Absil, O., & Blomme, R. 2012, A&A, 546, A37

Panagia, N. 1973, AJ, 78, 929

Pigulski, A., & Kołaczkowski, Z. 1998, MNRAS, 298, 753

Pigulski, A., & Pojmański, G. 2008, A&A, 477, 917

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992 Numerical recipes in FORTRAN, The art of scientific computing (2nd ed.; Cambridge: Cambridge University Press)

Schmidt-Kaler, Th. 1982, Landolt-Börstein: Numerical Data and Functional Relationships in Science and Technology, VI/2b, ed. K. Schaifers & H. H. Voigt (Berlin: Springer), 14

Schulte, D. H. 1956, ApJ, 123 250

Scargle, J. D. 1982, ApJ, 263, 835

Stankov, A., & Handler, G. 2005, ApJS, 158, 193

Stetson, P. B. 1987, PASP, 99, 191

Torres-Dodgen, A. V., Tapia, M., & Carroll, M. 1991, MNRAS, 249, 1

Wendker, H. J. 2004, VizieR Online Data Catalog II/199A, 2199

Windhorst, R. A., Fomalont, E. B., Partridge, R. B., & Lowenthal, J. D. 1993, ApJ, 405, 498

Zhang, B., Reid, M. J., Menten, K. M., Zheng, X. W., & Brunthaler, A. 2012, A&A, 544, A42

Diego González-Buitrago, Mauricio Tapia, Gagik Tovmassian and Sergei Zharikov: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877, Ensenada, Baja California, C.P. 22830, Mexico (mt, gag, zhar@astrosen.unam.mx).

Gisela N. Ortiz-León: Centro de Radiostronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, (Xangari), C.P. 58089 Morelia, Michoacán, Mexico (g.ortiz@crya.unam.mx).

Luis F. Rodríguez: Centro de Radiostronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, (Xangari), C.P. 58089 Morelia, Michoacán, Mexico and Astronomy Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia (l.rodriguez@crya.unam.mx).

Vicente Rodríguez-Gómez: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA.