Inner disc rearrangement revealed by dramatic brightness variations in the young star PV Cep

M. Kun, E. Szegedi-Elek, A. Moór, Á. Kóspál, P. Ábrahám, D. Apai, Z. T. Kiss, P. Klagyivik, T. Yu. Magakian, Gy. Mező, T. A. Movsessian, A. Pál, M. Rácz and J. Rogers

Konkoly Observatory, Konkoly Thege ut 15-17, H-1121 Budapest, Hungary
Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA, Leiden, the Netherlands
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
V. A. Ambartsumian Byurakan Astrophysical Observatory, 0213 Aragatsotn prov., Armenia

Accepted 2011 January 11. Received 2010 December 20; in original form 2010 June 16

ABSTRACT

Young Sun-like stars at the beginning of the pre-main-sequence (PMS) evolution are surrounded by accretion discs and remnant protostellar envelopes. Photometric and spectroscopic variations of these stars are driven by interactions of the star with the disc. Time-scales and wavelength dependence of the variability carry information on the physical mechanisms behind these interactions. We conducted multi-epoch, multiwavelength study of PV Cep, a strongly variable, accreting PMS star. By combining our own observations from 2004 to 2010 with archival and literature data, we show that PV Cep started a spectacular fading in 2005, reaching an $I_C$-band amplitude of 4 mag. Analysis of variation of the optical and infrared fluxes, colour indices and emission line fluxes suggests that the photometric decline in 2005–2009 resulted from an interplay between variable accretion and circumstellar extinction: since the central luminosity of the system is dominated by accretion, a modest drop in the accretion rate could induce the drastic restructuring of the inner disc. Dust condensation in the inner disc region might have resulted in the enhancement of the circumstellar extinction.

Key words: stars: formation – stars: individual: PV Cep – stars: pre-main-sequence.

1 INTRODUCTION

Eruptive young stars, defined by their episodically increased optical and infrared brightness, form a small subclass of Sun-like PMS stars. Traditionally they are divided into two groups: FU Orionis-type stars (FUors) exhibit an initial brightening of 5 mag during several months or years, followed by a fading phase of up to several decades or a century. The other group, EX Lupi-type stars (EXors) are characterized by relatively short, recurrent outbursts which last some weeks to months, and the time between the eruptions ranges from months to years. In both classes the outbursts are believed to be powered by enhanced accretion from the circumstellar disc on to the star. In the standard picture the inward spiralling material piles up close to the inner edge of the accretion disc, and falls on to the stellar surface as a result of a gravitational and thermal instability (Zhu et al. 2009).

In 2003, the outburst of the low-mass young stellar object V1647 Ori triggered a large number of observations from X-ray to far-infrared wavelengths. Based on these ground-based and space-born measurements it was suggested that this object fits into neither the FUor nor the EXor class. It was outlined that the outburst – unlike in other young eruptive stars where enhanced accretion is the main physical driver behind the brightening – consisted of the combination of two effects of comparable amplitude. They are an intrinsic brightening related to the appearance of a new, accretion-related hot component in the system, and a dust-clearing event which reduced the extinction along the line of sight (e.g. Acosta-Pulido et al. 2007; Aspin, Beck & Reipurth 2008). The simultaneity of the accretion and extinction changes suggests that they might be physically linked, and the changing accretion luminosity causes changes in the inner disc structure. Another example for such combined processes may be V1184 Tau (Alves et al. 1997) whose optical and infrared photometric observations have shown that the large photometric decline was associated with variation in the inner disc structure (Grinin et al. 2009). That the variable extinction may have an important role in the brightening refines the picture of the FUor/EXor phenomenon, moreover such rearrangements of the inner disc structure have a potentially high importance for the evolution of the terrestrial zone of circumstellar disc.
The target of our multiwavelength variability study PV Cep is an eruptive young star, which was originally classified as member of the EXor class by Herbig (1989), on the basis of its large outburst in 1977–1979 (Cohen et al. 1981). Currently the star undergoes significant brightness changes which we have been monitoring for years. Our first observations indicated that PV Cep might be another example for accretion-induced structural changes, and this motivated our further detailed study of the object. The role of variable circumstellar extinction was also apparent in the dramatic brightness decline observed in the near-infrared between 2008 April and June by Lorenzetti et al. (2009). Several further observed properties distinguish PV Cep from EXors, and indicate that the object may be more similar in nature to V1647 Ori. Such properties are e.g. the time-scale of the outburst (~2 yr), the A-type absorption spectrum observed at the beginning of the outburst (Cohen et al. 1981), the class I spectral energy distribution (SED; Connelley, Reipurth & Tokunaga 2008), the associated high-mass circumstellar disc (0.76 M⊙; Hamidouche 2010), variable reflection nebula (Gyulbudaghian & Magakian 1977; Cohen 1980), molecular outflow (Levreault 1984; Arce & Goodman 2002; Hamidouche 2010) and parsec-scale optical jet (Neckel et al. 1987; Gómez, Whitney & Kenyon 1997; Reipurth, Bally & Devine 1997).

We carried out a comprehensive optical and infrared photometric and optical spectroscopic monitoring of PV Cep during the low-brightness state in 2008–2010, and we have a few additional measurements from 2004, 2005 and 2006. In this paper we combine these data with archival and new near- and mid-infrared data, obtained in 2004–2010, to better understand the nature of PV Cep and the nature of physical processes which affect the inner disc structure and evolution.

2 OBSERVATIONS

2.1 Photometry

Photometric observations in the VR, IC bands spanning the time interval between 2004 September 22 and 2010 November 23 were performed with six instruments on five telescopes. Most of the data were obtained with the 60/90/180 cm Schmidt telescope of the Konkoly Observatory, equipped with a Photometric AT 200 camera, and with the 1-m Ritchey–Chretien–Coude (RCC) telescope of the Konkoly Observatory, equipped with a Princeton Instruments VersArray:1300B camera. PV Cep was also observed with the IAC-80 telescope of the Teide Observatory (Spain) between 2009 October 25 and November 7. More detailed description of these instruments is given in Acosta-Pulido et al. (2007). In 2008 August and 2009 October we obtained VR images with the Calar Alto Faint Object Spectrograph (CAFOS) instrument installed on the 2.2-m telescope of the Calar Alto Observatory (Spain). Exposure times were between 90 and 180 s per image. The IC = 11.70 ± 0.04 mag on 2004 September 22 was derived from a CCD image obtained with the 2.6-m telescope of Byurakan Observatory, Armenia, and shown in the paper of Movsessian et al. (2008). The image of PV Cep was saturated, and its magnitude was derived by fitting the point spread function (PSF) to the unsaturated wing of the stellar image. On 2010 April 8 we used the Electro Multiplying (EM) Andor Technology iXon™ EM + 888 camera at the RCC telescope of the Konkoly Observatory. We obtained a series of 100 exposures in the IC band with exposure times of 20 s per image in EM mode (the nominal EM gain was 50). The image processing was made with the software tools written by Pál (2009). All the other images were reduced in IRAF. In order to transform instrumental magnitudes into the standard system, we calibrated 16 stars in the field of view of the 1-m telescope (7 × 7 arcmin²) in VR, IC bands. Calibration was made during six photometric nights. Standard stars in NGC 7790, published by Stetson (2000), were used as reference. Equatorial coordinates and derived VR, IC magnitudes with uncertainties of the comparison stars are listed in Table 1. The results of the photometry for PV Cep are presented in Table 2 and plotted in Fig. 1. The photometric errors were derived from quadratic sums of the formal errors of the instrumental magnitudes and those of the coefficients of the transformation equations. The telescope used for each observation is shown in the last column of Table 2.

### Table 1. Comparison stars.\(^a\)

| N  | RA (2000) (hms) | Dec. (2000) (°′″) | V(ΔV) (mag) | R_C(ΔR_C) (mag) | I_C(ΔI_C) (mag) |
|----|----------------|------------------|-------------|----------------|----------------|
| C1 | 20 46 28.89    | +67 59 05.4      | 14.072 (0.012)| 13.595 (0.012) | 13.200 (0.008) |
| C2 | 20 46 26.50    | +67 58 11.8     | 14.608 (0.005)| 13.948 (0.004) | 13.495 (0.005) |
| C3 | 20 46 10.44    | +67 55 44.2     | 15.134 (0.005)| 14.205 (0.004) | 13.637 (0.004) |

\(^a\)The full table is available as Supporting Information with the online version of this paper.

### Table 2. Results of the photometry of PV Cep.\(^a\)

| ID (245 4000+) | Date               | V (ΔV) (mag) | R_C(ΔR_C) (mag) | I_C(ΔI_C) (mag) | Telescope |
|--------------|--------------------|-------------|----------------|----------------|-----------|
| –329         | 2005 October 27    | 14.58 (0.16) | 13.28 (0.06)   | 11.78 (0.06)   | RCC       |
| –327         | 2005 October 29    | 15.08 (0.04) | 13.39 (0.04)   | 11.90 (0.11)   | RCC       |
| –326         | 2005 October 30    | 15.43 (0.06) | 13.59 (0.04)   | 11.98 (0.06)   | RCC       |
| –325         | 2005 October 31    | 15.14 (0.07) | 13.36 (0.01)   | 11.84 (0.16)   | RCC       |

\(^a\)The full table is available as Supporting Information with the online version of this paper.
inner disc rearrangement in PV Cep

The spectrum of a He–Ne–Rb lamp was regularly observed for wavelength calibration. Broad-band VRcIc photometric images were taken immediately before the spectroscopic exposures for flux calibration. We reduced and analysed the spectra using standard IRAF routines. A further R-100 spectrum, obtained on 2004 August 7, and shown in fig. 2 of Kun et al. (2009), is also available.

2.4 Spitzer data

We observed PV Cep using the Spitzer Space Telescope between 2004 October and 2005 August with the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS) and the Multiband Imaging Photometer (MIPS) instruments. In addition, we used further archival data from IRAC and MIPS. Moreover, we conducted a monitoring with the IRAC instrument during the post-helium phase in 2009 September and 2010 January. A log of all Spitzer observations of PV Cep is presented in Table 3. The data reduction procedures are described in Appendix A, available as Supporting Information with the online version of this paper. The results of Spitzer photometry are shown in Table 4.

3 RESULTS

3.1 Photometric variations

3.1.1 Light curves of PV Cep in 2004–2010

The light curves of PV Cep in the V, Rc, Ic, J, H, Ks and IRAC 3.6 and 4.5 μm bands between 2004 May and 2010 November are shown in Fig. 1. Based on the shape of the Ic curve we divided the covered period into five segments, indicated by shading and Roman numbers. Segment I, hereafter referred to as the bright state, is the interval between 2004 July and 2005 October. Segment II, the fading phase, is the period between 2005 October and 2007 October, when the star faded significantly in each photometric band. Segment III, the transient peak, covers the brightening between 2007 October and 2008 February, and the subsequent sharp decline until 2008 June. Segment IV is the low-brightness state between 2008 June and 2009 September 16.

Table 3. Log of Spitzer observations of PV Cep.

| Instrument | Wavelength | Date | AOR  | Program |
|------------|------------|------|------|---------|
| IRAC       | 3.6, 4.5, 5.7, 8.0 μm | 2004 October 29 | 11571712 | 3716    |
| IRAC       | 3.6, 4.5, 5.7, 8.0 μm | 2005 August 3 | 11571968 | 3716    |
| IRAC       | 3.6, 4.5, 5.7, 8.0 μm | 2006 November 26 | 18955008 | 30760   |
| IRAC       | 3.6, 4.5, 5.7, 8.0 μm | 2007 February 26 | 19962624, 19962880 | 30574   |
| IRAC       | 3.6, 4.5 μm | 2009 September–2010 January | 35591168–35678720 | 60167   |

Table 4. Spitzer photometry for PV Cep. All fluxes are colour corrected and given in Jy.  

| Date          | F3.6 μm | F4.5 μm | F5.7 μm | F8.0 μm | F24 μm | F70 μm |
|---------------|---------|---------|---------|---------|--------|--------|
| 2004 October 29 | 4.47 (0.09) | 6.98 (0.14) | 8.34 (0.17) | 11.85 (0.23) |
| 2006 November 26 | 1.84 (0.04) | 3.99 (0.08) | 5.45 (0.11) | 8.16 (0.17) |
| 2007 February 26 | 27.12 (1.04) | 35.22 (2.13) |
| 2009 September 16 | 3.54 (0.03) | 5.97 (0.02) |

The full table is available as Supporting Information with the online version of this paper.

© 2011 The Authors, MNRAS 413, 2689–2695

Monthly Notices of the Royal Astronomical Society © 2011 RAS
and 2009 August, when the optical brightness slowly decreased further, reaching a minimum of $I_C = 15.86$ on 2009 August 18. After this date, in segment V, the optical and infrared fluxes, except the $K_s$-band flux, started rising, and large, short-term brightness fluctuations appeared in the optical light curves. We refer to this interval as the \textit{rising phase}. The total amplitude of the $I_C$ light curve is about 4 mag over the period 2005 November and 2009 September.

### 3.1.2 Colour–magnitude diagrams

In order to get insight into the origin of the observed variations we plotted colour–magnitude diagrams. Fig. 2 (left) shows that the fading in 2005–2006 was nearly grey in the $R_C$ and $I_C$ bands. Its reason may be that in minimum, whatever is the origin of the decline, the star itself is too faint to be detected, only the light scattered from the disc atmosphere, thus bluer in colour, can be observed. The transient peak shows different colour variation: the star became redder and brighter and then bluer and fainter. This colour behaviour is characteristic of UX Orionis (UXor) type variables close to the light-curve minima (e.g. Bibo & Thé 1991), and is attributed to the increasing proportion of scattered light when the star is obscured by a circumstellar dust clump. This diagram suggests that the optical source in the dim phases (segments II and IV of the light curve) was the starlight scattered from the disc atmosphere. During the low-brightness phase (filled circles) PV Cep was redder when fainter: this behaviour can result from either enhanced extinction or vanishing hotspots on the stellar surface due to the decreasing accretion rate. In the rising phase the star turned brighter and redder, indicating that instead of the scattered light direct light from the central star could be detected. The data obtained in 2010 indicate that the star completed a full loop in this diagram from 2008 April to 2010 April.

The near-infrared data in Fig. 2 (right) show that the fading in 2005–2006 was accompanied by a slight decrease of the $H - K_s$ colour index, indicative of decreasing emission from the dust sublimation zone of the disc, whereas an extinction change of $A_V \approx 7$ mag can account for the photometric variations around the transient peak in 2008. The different colour behaviour suggests the different nature of the two brightness drops. The strong decrease of

![Figure 2](https://academic.oup.com/mnras/article-abstract/413/4/2689/964360/Downloaded-from-academic.oup.com/mnras/article-abstract/413/4/2689/964360)

\begin{center}
\textbf{Figure 2.} Left: $R_C$ magnitude as a function of the $R_C - I_C$ colour index. Consecutive data points are connected by dotted lines. The arrow indicates the colour dependence of the interstellar extinction. The typical error bars are shown in the upper left-hand corner. Right: $K_s$ magnitude as a function of the $H - K_s$ colour index based on all data obtained between 2004 and 2010 (Connelley et al. 2008; Lorenzetti et al. 2009). Consecutive data points are connected.
\end{center}

\begin{center}
\textbf{Figure 3.} Flux changes of PV Cep between the different segments of the light curve, as a function of the wavelength. The dotted line shows the flux ratios corresponding to an increase of the extinction by $A_V = 5$ mag (assuming $R_V = 3.1$; Cardelli, Clayton & Mathis 1989).
\end{center}

the $H - K_s$ colour index at the bottom of the diagram, measured in 2009 October, clearly suggests the fall of the inner disc emission during the low-brightness phase.

### 3.1.3 Variations in the mid- and far-infrared

The \textit{Spitzer} data obtained in the bright, fading and rising phases of the light curve (Table 4) allow us to inspect the wavelength dependence of variations in the mid- and far-infrared regions. We plotted in Fig. 3 the flux ratios between the different segments of the light curve as a function of wavelength. In addition to our own measurements, the bright state data also include $H$ and $K_s$ data from Connelley et al. (2008), and the fading phase data set contains $JHK_s$ data measured on 2007 May 13 (Lorenzetti et al. 2009), as well as the \textit{Akari} IRC (Ishihara et al. 2010) fluxes at 9 and 18 $\mu$m, and \textit{Akari} FIS catalogue data (Yamamura et al. 2010) at 65, 90, 140 and 160 $\mu$m, each obtained between 2006 May 8 and 2007 August 26. The wavelength dependence of variations is obviously different from that of the dust extinction: the excess emission in the bright state with respect to fading phase had an optical, a near- and mid-infrared and a far-infrared component, indicative of changing emission from both the central star and various parts of the disc. The optical and near-infrared excess components are separated by a minimum in the $H$ band. The wavelength interval 10–65 $\mu$m was unaffected by the fading, while the system also dimmed in the 70–90 $\mu$m region. The $F_s(2006)/F_s(2009)$ curve shows that both the star and the inner disc continued fading after the transient peak.

### 3.2 Variations in the nebula RNO 125

RNO 125 was fan shaped and bright in the bright state (Movsessian et al. 2008), and the bright head of the cometary nebula was centred on the star (Fig. 4, upper left). A dark band appeared between the star and the nebula during the fading phase (Fig. 4, upper right). The nebula quickly faded and exhibited a strongly changing shape after the transient peak. Similar phenomenon was observed in 1977–1979 (see fig. 1 of Cohen et al. 1981). The nebula was barely visible in our images during the low-brightness phase and at the beginning of the rising phase (Fig. 4, lower left). The head of the nebula started brightening in 2010 (Fig. 4, lower right).
can be summarized as follows. (1) The equivalent width of the H\(\alpha\) line remained nearly unchanged during the photometric decline, i.e. the flux of the H\(\alpha\) emission and the continuum flux underwent equal fading, suggesting that the star and the H\(\alpha\) emitting region were attenuated by a circumstellar dust structure. (2) The fluxes of the forbidden lines decreased only slightly during the decline of the stellar flux (the equivalent widths strongly increased), indicating that the formation regions of these lines were unaffected by the changes leading to the fading. (3) The decline of the Ca\(\text{ii}\) line fluxes was significantly larger than that of the underlying continuum: their equivalent widths were halved between 2004 and 2008. Since these lines are accretion tracers (Muzerolle, Hartmann & Calvet 1998), the accretion rate of PV Cep declined between 2004 August and 2008 August.

### 3.4 Physical properties of PV Cep

#### 3.4.1 Mass and luminosity

Given that the amplitude of the photometric variations was smallest in the H band (Fig. 3), we estimated the luminosity of PV Cep from the \(H\) magnitude measured in the low-brightness state on 2008 June 18, assuming that the total flux in the \(H\) band originated from the photosphere. We adopted a distance of 325 pc for PV Cep (Straizys et al. 1992), an effective temperature \(T_{\text{eff}} = 5500\) K, corresponding to the spectral type G8–K0 found by Magakian & Movsessian (2001), a total extinction \(A_V = 12.0\) mag, obtained by reddening the near-infrared colour indices (Lorenzetti et al. 2009) on to the \(T\)-Tauri locus of the \(J - H\) versus \(H - K\), diagram (Meyer, Calvet & Hillenbrand 1997), and applied the bolometric correction tabulated by Hartigan, Strom & Strom (1994) and unreddened colour index \(V - H = 1.69\) for the spectral type G8 (Kenyon & Hartmann 1995). We obtained \(L_* \approx 17 L_\odot\), and a stellar radius \(R_* \approx 4.0 R_\odot\). Plotting the results on the Hertzsprung–Russell diagram (HRD), together with the evolutionary models of Palla & Stahler (1999), results in a mass of 2.4 \(M_\odot\) and age of <1 Myr.

#### 3.4.2 Disc accretion rates

We estimated the low-brightness state disc accretion rate of PV Cep from the luminosity of the Ca\(\text{ii}\) line, measured in 2008 August (Table 5), using the empirical formula of Dahm (2008). We obtain \(L_{\text{acc}} \approx 41 L_\odot\), and \(M_{\text{acc}} \approx 2.6 \times 10^{-6} M_\odot\) yr\(^{-1}\). The corresponding values for the bright state, estimated from the flux change of the Ca\(\text{ii}\) 8542 line, are about twice higher. The results show that the accretion rate of PV Cep is significantly higher than typical PMS accretion rates (\(~10^{-8} M_\odot\) yr\(^{-1}\); e.g. Gullbring et al. 1998; Dahm 2008) both in the high- and low-brightness states, and the accretion luminosity is higher than the photospheric luminosity.

### 4 Possible nature of the variations

The decreased fluxes of the Ca\(\text{ii}\) emission lines of PV Cep between 2004 and 2008 suggest that the fading was associated with...
decreasing accretion rate. The factor of 2 drop of the accretion luminosity, derived from the Ca II 8542 lines, however, can account for only $\lesssim 1$ mag variation in the optical region. To explain the whole amplitude of $\sim 4$ mag, enhanced circumstellar extinction also has to be invoked. The excess extinction could arise from the changes in the inner disc structure. Since $L_{\text{acc}} \gg L_\text{s}$, the modest drop of the accretion rate substantially altered the total central luminosity, and the decreased central luminosity made the dust sublimation radius shrink, i.e. a large amount of dust condensed in the inner disc region during the fading and the subsequent low-brightness state. The bright-state luminosity of $L_{\text{acc}} + L_\text{s} \approx 100 L_\odot$ implies $R_{\text{dust}} \approx 0.7$ au (cf. fig. 7 of Dullemont & Monnier 2010), which might have shrunk to $0.4$ au due to a factor of 2 drop in $L_{\text{acc}}$. The observed drop in the $K_s$-band flux between 2004 and 2007 suggests similar decrease in the dust sublimation radius, if we assume that most of this flux is emitted from the dust sublimation zone. Assuming normal interstellar gas-to-dust ratio, an excess extinction of $A_K \approx 3$ mag requires a gas column density of $\approx 6 \times 10^{22}$ cm$^{-2}$, which, taking into account the size of the dust condensation region, corresponds to a volume density of some $10^9$ cm$^{-3}$. Considering typical mid-plane gas densities and scaleheights at the dust rim (Dullemont & Monnier 2010), the inclination of $62^\circ$ and the fact that the disc of PV Cep is at least 10 times more massive than a typical HAe star disc (Hamidouche 2010), such densities along the line of sight are likely, and thus the newly formed dusty region may account for most of the observed optical and near-infrared fading of the star. The observed drop in the mid- and far-infrared fluxes indicates that parts of the optically thin outer flared disc atmosphere got into shadow.

The transient peak in 2009, according to the colour–magnitude diagrams, resulted from variable obscuration along the line of sight. A very similar transient peak both in amplitude and time-scale appeared in the light curve of PV Cep in 1979, following the end of the outburst (fig. 2 of Cohen et al. 1981), which suggests that the temporary dust clearing might have been related to the end of the outburst. A short-lived outflow, similar to that observed in V1647 Ori after the end of its outburst in 2006, and probably associated with the rearrangement of the stellar magnetic field in response to the dropped accretion rate (Brittain et al. 2010) might have blown out some dust from the line of sight.

The slowly descending light curve accompanied by reddening between 2008 June and 2009 August may result from the dust condensation process. The duration of the low-brightness period suggests that the dust, emerging in the line of sight, was not confined to dense clumps or warps in the disc, but rather it was associated with a restructuring of the inner disc due to the changing central luminosity.

The brightening accompanied by reddening in 2009–2010 may indicate that the dust, condensed during the previous years, started evaporating. The increased Ca II fluxes suggest that invigorated accretion may play role in the processes. The time-scales of the large-amplitude photometric fluctuations suggest that the inner dust rim is involved. Notably, two prominent peaks of the $I_c$ light curve (around JD 245 5103 and JD 245 5143) are separated by 40 d, corresponding to the Kepler period at a radius of 0.4 au. The low $K_s$-band flux, rising fluxes at 3.6 and 4.5 $\mu$m, as well as the reappearance of the nebula suggest that the inner dust rim of the disc became less efficient in shadowing the outer parts of the circumstellar matter.

This scenario can qualitatively explain the fading in the optical, near-, mid- and far-infrared wavelength regions, and the simultaneous variations of the nebula and the Ca II emission line fluxes. Our results suggest that PV Cep differs from both the EXor-, characterized by outbursts driven by strongly enhanced accretion, and UXor-type stars, whose variability is caused by orbiting circumstellar dust structures. The high disc mass and persistent high accretion rate suggest that PV Cep is a protostar-like object: most of its luminosity originates from accretion, and its large-scale photometric variations reflect the changing inner disc structure, resulted from steadiness. Variations in the accretion rate may be triggered by gravitational instabilities in the massive disc of PV Cep.

ACKNOWLEDGMENTS

Our results are partly based on observations obtained at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC). Our observations were supported by the OPTICON. OPTICON has received funding from the European Community’s Sixth Framework Programme under contract number RI3-CT-001566. The 0.82-m IAC-80 Telescope is operated on the island of Tenerife by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Teide. This work makes use of observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. This publication makes use of data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This paper utilized data from the OMC Archive at LAEFF, pre-processed by ISDC. Financial support from the Hungarian OTKA grant K81966 is acknowledged. The research of AK is supported by the Nederlands Organisatie for Scientific Research.

REFERENCES

Acosta-Pulido J. A. et al., 2007, AJ, 133, 2020
Alves J., Hartmann L., Briceño C., Lada C. J., 1997, AJ, 113, 1395
Arce H. G., Goodman A. A., 2002, ApJ, 575, 911
Aspin C., Beck T. L., Reipurth B., 2008, AJ, 135, 423
Bibo E. A., Thé P. S., 1991, A&AS, 89, 319
Briceño C. et al., 2004, ApJ, 606, L123
Brittain S. D., Rettig T. W., Simon Th., Gibb E. L., Liskowsky J., 2010, ApJ, 708, 109
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Cohen M., 1980, AJ, 85, 29
Cohen M., Kuhi L. V., Harlan E. A., Spinrad H., 1981, ApJ, 245, 920
Connelley M. S., Reipurth B., Tokunaga A. T., 2008, AJ, 135, 2346
Curi R. M. et al., 2003, VizieR On-line Data Catalog, IV/246
Dahn S. E., 2008, AJ, 136, 521
Dullemond C. P., Monnier J. D., 2010, ARA&A, 48, 205
Glass I. S., 1999, Handbook of Infrared Astronomy. Cambridge Univ. Press, Cambridge, p. 63
Gómez M., Whitney B. A., Kenyon S. J., 1997, AJ, 114, 1138
Grinin V. P., Arkarshorov A. V., Barsunova O. Yu., Sergeev S. G., Tambovtseva L. V., 2009, Astron. Lett., 35, 114
Gullbring E., Hartmann L., Briceño C., Calvet N., 1998, ApJ, 492, 323
Gyulbudaghian A. L., Magakian T. Y., 1977, Pis’ma Astron. Zh., 3, 113
Hamidouche M., 2010, ApJ, 722, 204
Hartigan P., Strom K. M., Strom S. E., 1994, ApJ, 427, 961
Herbig G. H., 1989, in Reipurth B., ed., ESO Workshop on Low Mass Star Formation and Pre-Main Sequence Objects. ESO, Garching, p. 233
Ishihara D. et al., 2010, A&A, 514, A1
Kenyon S. J., Hartmann L., 1995, ApJS, 101, 117
Kun M., Balog Z., Kenyon S. J., Mannajek E. E., Gutermuth R. A., 2009, ApJS, 185, 451

© 2011 The Authors, MNRAS 413, 2689–2695
Monthly Notices of the Royal Astronomical Society © 2011 RAS
Levreault R. M., 1984, ApJ, 277, 634
Lorenzetti D., Larionov V. M., Giannini T., Arkharov A. A., Antonucci S., Nisini B., Di Paola A., 2009, ApJ, 693, 1056
Magakian T. Y., Movsessian T. A., 2001, Astrophysics, 44, 419
Meyer M. R., Calvet N., Hillenbrand L. A., 1997, AJ, 114, 288
Movsessian T. A., Magakian T. Yu., Sargsyan D. M., Nikogossian E. H., 2008, Astrophysics, 51, 387
Mazzerolle J., Hartmann L., Calvet N., 1998, AJ, 116, 2965
Neckel T., Staudt H. J., Sarcander M., Birkle K., 1987, A&A, 175, 231
Pál A., 2009, PhD thesis, Eötvös Loránd University, Budapest (arXiv:0906.3486)
Palla F., Stahler S. W., 1999, ApJ, 525, 772
Reipurth B., Bally J., Devine D., 1997, AJ, 114, 2708
Stetson P. B., 2000, PASP, 112, 925
Straižys V., Cernis K., Kazlauskas A., Meistas E., 1992, Baltic Astron., 1, 149
Thé P. S., de Winter D., Pérez M. R., 1994, A&AS, 104, 315
Welin G., 1971, A&A, 12, 312
Yamamura I., Makijian S., Ikeda N., Fukuda Y., Oyabu S., Koga T., White G. J., 2010, AKARI-FIS BSC Release Note, version 1.0. ISAS/JAXA

Zhu Z., Hartmann L., Gammie C., McKinney J. C., 2009, ApJ, 701, 620

SUPPORTING INFORMATION
Additional Supporting Information may be found in the online version of this article:
Table 1. Comparison stars.
Table 2. Results of the photometry of PV Cep.
Table 4. Spitzer photometry for PV Cep.
Appendix A. Spitzer data reduction

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TeX/\LaTeX file prepared by the author.