CCD OBSERVATIONS OF THE COUNTERFAN IN PV CEPHEI

RUSSELL M. LEVREAULT AND CHET B. OPAL
Department of Astronomy, University of Texas at Austin, Austin, Texas 78712
Received 23 September 1986; revised 21 November 1986

ABSTRACT

Deep CCD images of PV Cephei reveal a faint, red "counterfan," opposite the star from the optically prominent fan previously known. This counterfan is clearly associated with the redshifted lobe of the PV Cephei molecular outflow, and its detection supports the contention that cometary nebulae are the optical counterparts of bipolar molecular outflows. The relative colors of the two halves of the optical nebulosity can be explained by differential reddening between the two lobes. Photometry of the gap between the stellar image and the bright optical fan is consistent with this gap being totally "black," indicating either high (~ 4) values of A_V due to a circumstellar disk or a total lack of material within the gap.

I. INTRODUCTION

Cometary nebulae are a class of fan or cone-shaped reflection nebulae with the illuminating star occupying the very tip of the fan or cone. The most prominent example of such a nebula is NGC 2261 (Hubble's Variable Nebula), which has the peculiar pre-main-sequence star R Monocerotis at its tip. The Parsamian and Petrosian (1979) catalog lists over one hundred cometary nebulae. While not all of these objects meet the fairly narrow definition quoted above, it is clear that the optical morphology of these nebulae cannot be ascribed to chance, and must indicate some underlying physical structure. Suggestions on the nature of this structure revolve around disks (Cohen *et al.* 1981), wind-blown cavities (Arny and Bechis 1978), and combinations of the two (Canto *et al.* 1981; Levreault 1984).

PV Cephei was "discovered" by Cohen, Kuhi, and Harlan (1977) and Gyul'budagyan, Magakyan, and Amirkhanyan (1977). It is visible on the POSS plates as a faint, red star associated with a distinctive linear streak of nebulosity. By 1976, this streak had vanished, to be replaced by a cometary nebula with PV Cephei at its tip. The star then went through some extravagant photometric behavior (see Cohen *et al.* 1981). PV Cephei was later found to be the source of a bipolar molecular outflow (Levreault 1984). The blueshifted lobe of this outflow lies to the north and northwest of PV Cephei, in essentially the same direction defined by the optical nebulosity. This suggested a model in which the observed optical nebula was due to the illumination of the cavity evacuated by the stellar wind in the process of creating the molecular outflow. This model has two main implications. The first is that cometary nebulae are the optical counterparts of bipolar molecular outflows. Second, it predicts that a highly reddened counterfan should be associated with the redshifted lobe, and appear on the opposite side of the star from the cometary nebula. This paper describes the search for this counterfan in the PV Cephei system.

II. OBSERVATIONS

The observations were obtained using the 0.76 m reflector at McDonald Observatory. During August and December of 1984, VR_cI_c observations were obtained using an unthinned, front-illuminated RCA SID53601 CCD, which has higher quantum efficiencies in the red and is less troubled by interference fringes due to night-sky lines than the usual thinned, back-illuminated CCDs. However, it is more susceptible to cosmic-ray events. During August 1985, we obtained better-quality V band observations using a thinned, back-illuminated RCA SID53612 CCD. For all observations the plate scale was 20″/mm or 0.6″/pixel, and the total field of view was $5.1' \times 3.8'$. A series of modest exposures (20 min for R_c and I_c, 10 min for V) was obtained, moving the object around on the CCD between exposures to improve flat-field reliability. The exposures were aligned and stacked digitally, and cosmic-ray events were eliminated by discarding aberrant pixel values. The total integration times were 100 min for R_c and I_c and 50 min for V. No obvious changes in the morphology of the nebula occurred over the duration of the observing program.

Calibrations were obtained for stars in the PV Cep field by normalization to stars in NGC 7006 and M92 as measured by Christian *et al.* (1985). The R filter used did not quite match the Cousins system, and we found the following color transformations: $(V - R_c) = 0.88\ (v - r)$ and $(R - I)_c = 1.14\ (r - i)$, where v, r, and i refer to instrumental magnitudes. The V and I_c filters were well matched to the system. We note that very few standard stars showing the extremely red colors we report here were observed. Such stars would be very cool and would have a spectral-energy distribution radically different from that of a highly reddened warm star, as would be expected for PV Cep and its nebula, so any required color transformations would be unreliable anyway.

Diffuse source magnitudes were determined by integrating all of the light in the standard-star images and converting the result to diffuse source sensitivity using the known plate scale. This is a somewhat shaky procedure because of potential scattered-light losses, and we estimate the absolute accuracy of the results as only 0.15 mag.

III. RESULTS

Figure 1 [Plate 42] shows a montage of images of PV Cephei. On the left is the deep R_c band image; the center shows the deep I_c band image; on the right we present the I_c band image with a different contrast stretch to show details of the bright portions of the nebula. The stellar image is at the tip of the fan, which opens to the north with an opening angle of about 60°. Lying to the south of the star, in the direction of the redshifted lobe of the molecular outflow (see Levreault 1984), is a faint smudge of nebulosity. This smudge is distinctly more visible in the I_c frame than in the R_c, indicating that it is quite red. By comparing the two

 0004-6256/87/030669-03$00.90

TABLE I. Photometry results.

Location	V	R_c	I_c	$(V-R_c)$	$(R-I)_c$
+ 13″	18.10	16.90	15.58	1.20	1.32
0″ (PV Cep)	17.76	16.44	14.73	1.32	1.71
− 13″	(22.6)	20.52	18.31	(2.08)	2.21

Notes to TABLE I

Values at ± 13″ are in magnitudes per square arcsecond averaged over a 5″ × 5″ square aperture. Values for PV Cep are integrated magnitudes. Parentheses indicate values with poor signal-to-noise.

different I_c band images, it can be seen that the correspondence between the brighter parts of the fan and the nebulous smudge is quite good, allowing for a mirror reversal. This even extends to the peculiar "gap" between the stellar image and the nebulosity itself. Such a gap is seen in other cometary nebulae (see Gething *et al.* 1982). It seems quite clear that this smudge of nebulosity is the expected counterfan.

Table I shows the results of surface photometry of comparable areas of the fan and counterfan, as well as results for PV Cephei itself. The numbers in Table I simply confirm what is obvious from Fig. 1, that the counterfan is much fainter ($\Delta R_c \sim 3.6$) and redder ($\Delta(R-I)_c \sim 1$) than the fan. In the picture of Levreault (1984), this is due to differential extinction between the two lobes. The counterfan is associated with the redshifted lobe of the bipolar outflow, which is directed away from the observer. This will place it deeper within the ambient molecular cloud, and thus subject to greater extinction. For instance, assuming an observed physical extent of 0.2 pc, an inclination angle of 45°, an ambient cloud density of 10^3 cm^{-3}, and the standard interstellar dust-to-gas ratio, the additional extinction expected toward the counterfan would be of order 1 mag. We can define $R' = A_{R_c}/\mathrm{E}(R-I)_c$, which is analogous to the familiar ratio of total to selective extinction $R = A_V/\mathrm{E}(B-V)$. If we assume that the fan and counterfan have the same intrinsic surface brightness and colors, and that the difference between the fan and counterfan is the result of differential extinction, we derive a value of $R' \sim 4$ for this extinction. This compares favorably to the nominal value of 3.9 for a normal extinction curve. We do note that the assumption of equal surface brightnesses for the two lobes does depend on the grain-scattering phase function and the inclination of the

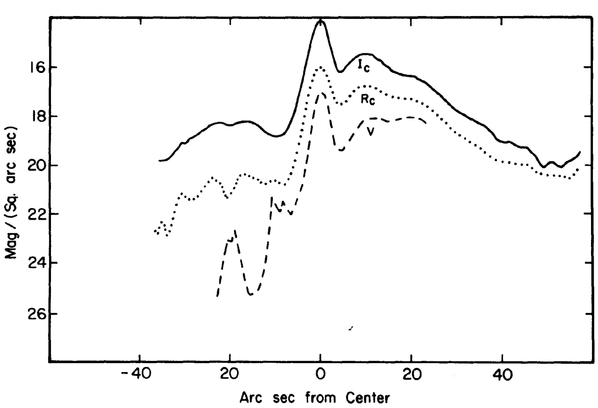

FIG. 2. Plot of the observed azimuthally averaged brightness distribution as a function of distance from PV Cephei (north is positive).

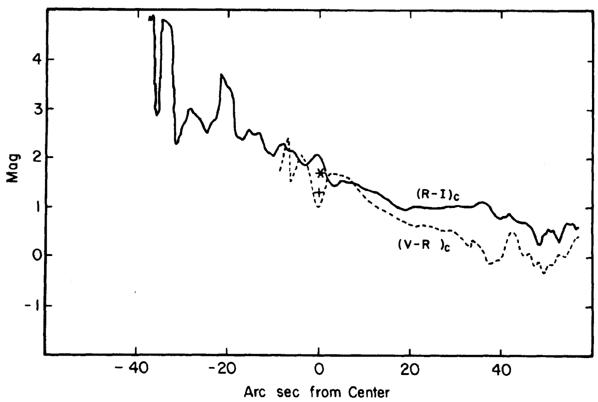

FIG. 3. $(V-R_c)$ and $(R-I)_c$ colors as a function of distance from PV Cephei. The colors of the star itself are plotted as a " + " for $(V-R_c)$ and a "*" for $(R-I)_c$.

PV Cephei system, neither of which is well established.

Figure 2 shows the azimuthally averaged surface brightness at V, R_c, and I_c plotted as a function of distance from PV Cep. Although there is some detectable emission in V to the south of the star, it is too noisy to be useful. The features in the R_c and I_c data reproduce very well; note in particular the deep notches on either side of the central star. These correspond to the gaps visible between the star and both lobes of the nebula (see Fig. 1).

Figure 3 plots the $(R-I)_c$ and $(V-R_c)$ colors on the same spatial scale as Fig. 2. Regions with poor signal-to-noise have not been plotted, and the colors of PV Cephei itself are indicated by symbols. A roughly linear increase in the $(R-I)_c$ color can be traced from about 40″ north of the stellar image straight through the star and well into the counterfan. That is what would be expected for an object embedded near the front surface of a molecular cloud and inclined to the line of sight. The molecular cloud material forms a smooth screen of extinction that increases in thickness as the outflow retreats into the cloud.

Less expected is the lack of significant color variations across the gap between the stellar image and the nebulosity itself. The model of Levreault (1984; see also Cohen *et al.* 1981) suggests that this gap is due to extinction by the outer portions of the disk (or flattened density distribution) that is responsible for the collimation of the outflow. Only the stellar image is of sufficient brightness to punch through this obscuration. If this is true, then one would expect to see very red colors within the gap. Instead, very little variation is noted.

It is possible that the gap is entirely black, and the light that is observed there is simply due to smearing by atmospheric seeing or instrumental scattering of light from the stellar image and the nearby bright nebulosity. The brightness distribution on the bright side of the nebula can be approximated by a straight line (on a magnitude scale) over a large range beginning about 15 arcsec away from the central star. We have made an *ad hoc* model for the nebula by linearly extrapolating this brightness distribution to 10″ from the central star, truncating it abruptly at this point. A convolution of this model with the point-source response function determined from one of the field stars is shown in Fig. 4. The agreement with the observed I_c band brightness distribution

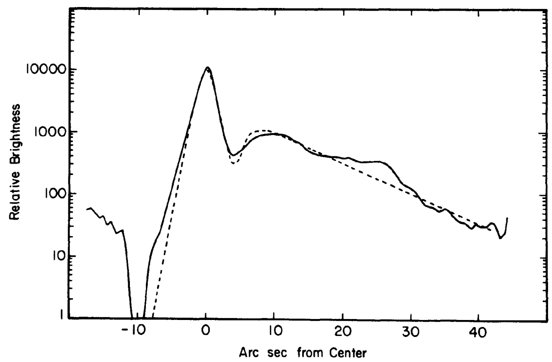

FIG. 4. Predicted I_c band surface brightness for a simple model (see the text) convolved with the point-spread function (dotted line) versus the observed distribution (solid line).

is quite good, and could be improved by making the inner edge of the nebula somewhat less sharp. Thus, we conclude that the observations are consistent with the lack of emission in the gap; in any case the extra I_c band extinction must be at least 2.5 mag, corresponding to an A_V of ~ 4 mag.

IV. CONCLUSIONS

Deep CCD imagery reveals the cometary nebula associated with PV Cephei to be bipolar in nature, as predicted by Levreault (1984). The colors of the two lobes can be understood purely in terms of differential reddening. The peculiar gap between the stellar image and the nebula proper is due either to a true absence of material within the gap or at least 4 mag of additional extinction. These findings help to confirm a model where cometary nebulae are the optical counterparts of bipolar molecular outflows.

One of the authors (R.M.L.) wishes to acknowledge the support of NSF grant AST-8116403.

REFERENCES

Arny, T. T., and Bechis, K. P. (1978). Astrophys. J. **226**, 455.

Canto, J., Rodriguez, L. F., Barral, J. F., and Carral, P. (1981). Astrophys. J. **244**, 102.

Christian, C. A., Adams, M., Barnes, J. V., Butcher, H., Hayes, D. S., Mould, J. R., and Siegel, M. (1985). Publ. Astron. Soc. Pac. **97**, 363.

Cohen, M., Kuhi, L. V., and Harlan, E. A. (1977). Astrophys. J. Lett. **215**, L127.

Cohen, M., Kuhi, L. V., Harlan, E. A., and Spinrad, H. (1981). Astrophys. J. **245**, 920.

Gething, M. R., Warren-Smith, R. F., Scarrott, S. M., and Bingham, R. G. (1982). Mon. Not. R. Astron. Soc. **198**, 881.

Gyul'budagyan, A. L., Magakyan, T. Yu., and Amirkhanyan, A. S. (1977). Pis'ma Astron. Zh. **3**, 162.

Levreault, R. M. (1984). Astrophys. J. **277**, 634.

Parsamian, E. S., and Petrosian, V. M. (1979). Soobsh. Byur. Obs. No. 51.

1987AJ.....93..669L

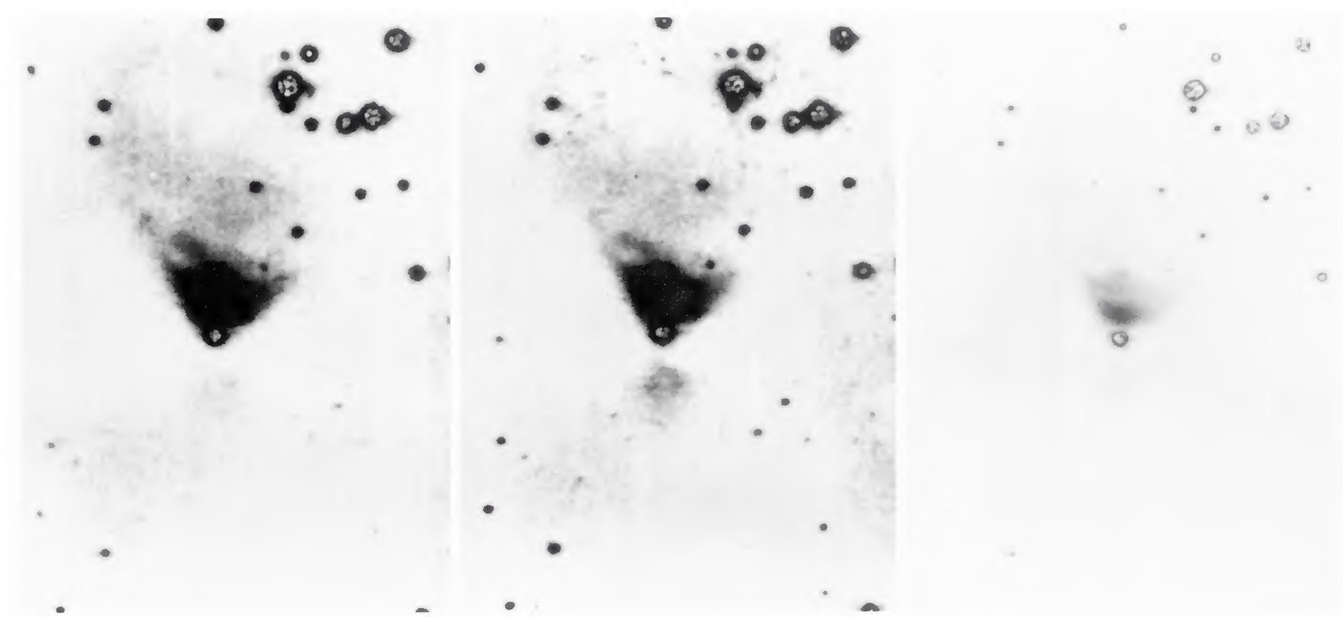

FIG. 1. Montage of images of PV Cephei. From left to right the images are a deep R_c band image, a deep I_c band image, and the same I_c band image printed so as to show details from the brighter portion of the nebula. North is up, east is to the left. The field shown is 3.85′ high.

R. Levreault and C. Opal (see page 669)