CHARACTERISTICS OF THE VARIABLE STAR P CYGNI DETERMINED FROM CLUSTER MEMBERSHIP

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Abstract

Empirical information on the luminosity, reddening, age, and mass of the variable B2 Oe supergiant P Cygni is derived from its assumed membership in the sparse anonymous cluster on which it is projected, as well as its association with the spatially adjacent cluster IC 4996, which forms a double cluster with the P Cyg cluster. Evidence for the high luminosity of P Cyg is confirmed by its derived absolute magnitude of $M_V = -8.46 \pm 0.03$, which translates to $\log (L/L_{\odot}) = 5.54 \pm 0.02$ for an effective temperature consistent with the star's derived space reddening ($E_{B-V} = 0.53 \pm 0.02$). More surprising is an age for the associated clusters of 6 $(\pm 1.5) \times 10^6$ years, corresponding to a turnoff point mass of 25.1 $(\pm 5.5)\ M_{\odot}$. By inference, P Cygni, as a post main-sequence object, should have a mass of no more than ~23-35 $M_{\odot}$.

1. Introduction

P Cygni stars are those whose spectra exhibit the diagnostic signature of outward-flowing stellar winds, as evidenced by emission lines with characteristic absorption features on their short wavelength wings. P Cygni itself is one of a handful of hypergiant stars in the Galaxy (*e.g.,* de Groot *et al.* 1986), sometimes designated as S Doradus variables. All are extremely luminous, high mass, early-type, post-main-sequence stars that are also light-variable. Spectroscopically the star is mostly characteristic of spectral type B2 Oe (Turner 1985).

It is possible to learn a great deal about any star if it is a member of an open cluster, since direct information on age, reddening, and distance can be obtained from other cluster stars. In the case of P Cyg, the field of the variable is rich in early-type stars, and it has always been assumed that a star as massive as P Cyg should have many massive companions in its general vicinity. The variable does lie within the extensive boundaries of the association Cyg OB1, which has stars dispersed over several degrees of sky around P Cyg, and is also located 27 arcminutes northeast of the young cluster IC 4996, which may be associated with Cyg OB1. Both stellar groups have been used extensively in the past as a means of establishing the distance and reddening of P Cyg (see Table 1). Less well known is the anonymous cluster surrounding P Cyg itself. As we demonstrate here, information on P Cyg that is inferred from its cluster membership can address many of the questions about the star that have been raised in the literature.

Table 1. Estimates for the distance and reddening of P Cygni.

V-M_V	d (kpc)	E_{B-V}	*Object Used*	*Source*
10.4 ±1.1	1.2 ±0.6	——	IC 4996/Cyg OB1	Beals (1950)
11.11 ±0.2	1.67 ±0.15	0.62	IC 4996	Purgathofer (1961)
11.14 ±0.2	1.69 ±0.16	0.62	IC 4996	van Schewick (1967)
12.24 ±0.46	2.81 ±0.59	0.58 ±0.06	Stellar Ring 274	Isserstedt (1970)
10.4 ±1.1	1.2 ±0.6	0.35	——	Ambartsumian *et al.* (1979)
10.4 ±1.1	1.2 ±0.6	0.4	——	Hutchings (1979)
10.4 ±1.1	1.2 ±0.6	0.35	——	Underhill (1979)
11.14 ±0.2	1.69 ±0.16	0.35	IC 4996	Underhill (1982)
11.28 ±0.12	1.80 ±0.10	0.63 ±0.05	IC 4996	Lamers *et al.* (1983)
>11.63 ±0.25	2.12 ±0.24	0.53 ±0.02	P Cyg companion	Turner (1985)
11.42 ±2.09	1.92 ±1.85	——	P Cyg parallax	Perryman *et al.* (1997)
11.82 ±0.03	2.31 ±0.03	0.53 ±0.02	IC 4996/P Cyg Cluster	This Paper

By way of historical background, P Cygni was discovered in 1600 near the end of the pre-telescopic era by the Dutch chart maker Blaeu after it suddenly brightened to about third magnitude (de Groot *et al.* 1986). It gradually faded below sixth magnitude over the next half-century, when a second brightening to about third magnitude occurred in 1655, followed by another decrease in brightness below sixth magnitude. The star was characterized by irregular brightness changes for about 30 years, following which it gradually stabilized towards its present brightness of $V \approx 4.81$. The star is recognized to undergo small-scale irregular variability on time scales of a few days to several months, and possibly on a time scale of a decade or more (*cf.* Percy *et al.* 1988, 1996), but is otherwise fairly stable in brightness. Archival visual and photoelectric (V) AAVSO observations of the star (Figure 1) from Mattei (2000) suggest a possible long-term trend towards increasing brightness, and that has already been incorporated into the schematic light curve for the star published by de Groot *et al.* (1986). One must be careful, however, about interpreting other trends in the older visual observations in the AAVSO database. For example, the unusual dip in the star's brightness in 1953 (~JD 2434500) can be attributed almost exclusively to one observer who continued to observe P Cygni frequently during an extended interval in which it was not being observed by many others.

The cluster that surrounds P Cygni (see Figure 2) has never been included in any catalogues of open clusters, and even today is not well recognized or well studied. Its discovery can be attributed to independent investigations by George Herbig

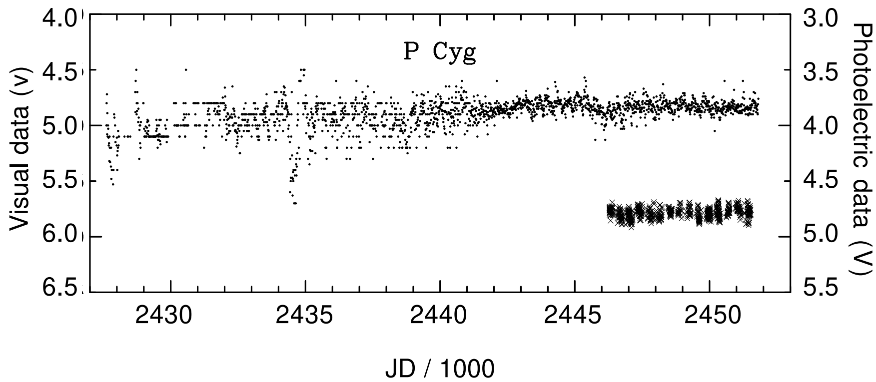

Figure 1. Long-term visual-band observations of P Cygni from the AAVSO International Database. Upper plot refers to 10-day means of visual observations made between 1934 and 2000. Lower plot refers to individual photoelectric (*V*) observations obtained between 1985 and 1999. [The figure includes data based on observations submitted to the AAVSO by variable star observers world wide, and is published, with thanks, by permission of the American Association of Variable Star Observers.]

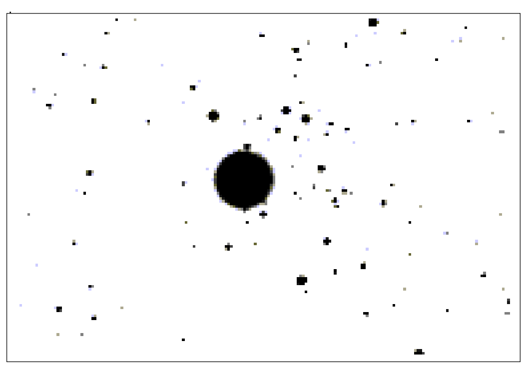

Figure 2. An enlargement of the 6.3 × 4.4 arcminute field immediately surrounding P Cyg (the bright star at center) obtained with a special camera that suppressed the light of P Cyg itself. The brightness of P Cyg is roughly two orders of magnitude fainter than it normally appears. North is up, east to the left.

(unpublished), Walter Feibelman (Feibelman 1995), and David Turner (Turner 1985), in which only limited photometric data were generated for cluster stars. The cluster is reasonably rich, and is centered just west of P Cyg, as revealed by photographs taken with the light of P Cyg suppressed (see Feibelman 1995). As we argue here, the stellar grouping appears to form a double cluster with IC 4996, which is the next closest open cluster to P Cyg. Both clusters can be used to establish important empirical information regarding the nature of P Cyg itself.

2. IC 4996 and the P Cygni Cluster

We have collected photometric *UBV* data for stars in both clusters as well as spectroscopic observations for the brightest companions to P Cyg. Our *UBV* photometry is a mix of photoelectric, CCD, and photographic data for the P Cyg cluster. That for IC 4996 represents photographic photometry that has been combined with the photoelectric observations of Hoag *et al.* (1961) and the CCD *BV* data of Vansevicius *et al.* (1996) and Delgado *et al.* (1998) for stars in the cluster core. Delgado *et al.* published *U-B* data as well, but we found the values to be affected by systematic errors (a common problem with CCD photometry in the ultraviolet), and omitted them entirely. Owing to the brightness of P Cyg, background contamination is a serious problem for CCD and photographic photometry of its surrounding cluster. We made a special effort to eliminate that problem in compiling our collection of best data for the cluster. Full details will be presented elsewhere.

From the photometric observations it is clear that the reddening in both the P Cyg cluster and IC 4996 is very similar (Figure 3). There is some evidence for a small amount of differential reddening in both clusters, with that in IC 4996 being slightly greater. The reddening near P Cyg itself is fairly uniform, however, and averages $\langle E_{B-V} \rangle = 0.53 \pm 0.02$ for the surrounding stars, in agreement with what was found previously by Turner (1985). (Readers are referred to the 1985 paper for details on the manner in which reddening was analyzed.) The derived color excess confirms the star's spectral class as B2, which is also the spectral type of stars lying at the main sequence turnoff points for both clusters.

Since the extinction properties of dust in the field of P Cyg are reasonably well established (Turner 1985), it is a simple matter to correct the colors of all stars belonging to the P Cyg and IC 4996 clusters for the effects of interstellar reddening. The procedure generates intrinsic $(B-V)_0$ colors for each star, from which one can derive estimates of absolute magnitude that correspond to those of zero-age main sequence (ZAMS) stars (see Turner 1976). The procedure underestimates the luminosities of stars that do not fall on the ZAMS (Turner 1976), but that complication can be eliminated through a variable extinction analysis of the data.

Figure 4 presents a variable-extinction diagram for inferred B-type members of the two clusters, namely a plot of the estimated distance moduli $V\text{-}M_V$ (ZAMS) for each cluster star as a function of its observed color excess E_{B-V}. In such a diagram the scatter is both random and systematic. Random scatter exists for true ZAMS stars, which scatter about a linear relation with slope $R = A_V/E_{B-V}$ corresponding to the ratio of total-to-selective extinction in the field—typically a value near ~3. Systematic scatter arises because many stars, namely evolved stars, unresolved binaries, and rapidly-rotating stars, are more luminous than ZAMS objects (likely foreground stars have already been omitted from Figure 4). Such systematic scatter is typical of variable-extinction diagrams (Turner 1976), but the lower envelope of the data should be dominated by random scatter and should have a slope representative of the value of *R* appropriate for the dust extinction in the field. A subgroup of 33 stars that appear to define best the lower envelope of the data was analyzed by means of least squares and non-parametric techniques (see Guetter and Turner 1997), and yielded a value

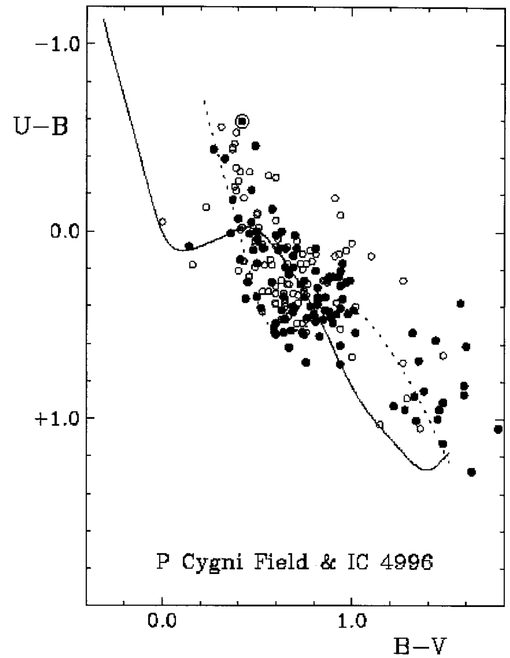

Figure 3. The observed colors (*U-B* and *B-V*) of stars in the P Cyg cluster (filled circles) and in IC 4996 (open circles) are shown relative to the intrinsic relation for main-sequence stars (solid curve). The dashed curve represents the intrinsic relation reddened by $E_{B-V} = 0.53$, which is typical of most stars near P Cyg that lie at roughly the same distance. The colors of P Cyg are represented by the circled point.

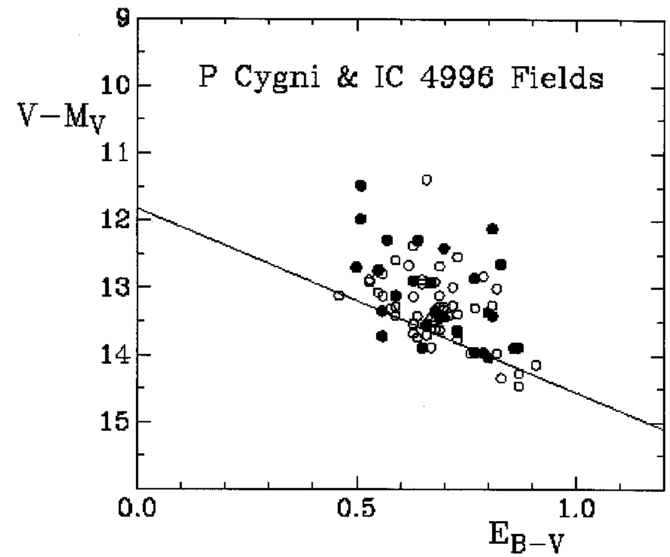

Figure 4. A variable-extinction diagram for stars in the P Cyg cluster (filled circles) and IC 4996 (open circles), with apparent distance moduli based upon zero-age main sequence estimates of M_V. The line represents a fit to the 33 stars selected to define the lower envelope of the data, and has a slope given by $R = A_V / E_{B-V} = 2.73$.

of $R = A_V/E_{B-V}$ = 2.73 ±0.23, which has been adopted in what follows. Such a value is smaller than values near R = 3.0 adopted by most previous researchers studying P Cyg, but is justified by the corresponding steep slope of the reddening relation for the field (see Turner 1996).

Since lower envelope stars in Figure 4 contain members of both IC 4996 and the P Cyg cluster, it can be concluded that the distances to both clusters are identical to within our ability to distinguish by ZAMS fitting. For 33 members of both clusters firmly established to be ZAMS stars, the mean intrinsic distance modulus is $\langle V\text{-}M_V \rangle$ = 11.82 ±0.03, where the uncertainty represents the standard error of the mean for the vertical scatter of lower envelope data points in Figure 4. The corresponding standard deviation of the same data about the fitted line is ±0.16. In cluster studies involving proper reddening analyses there is no need to perform sliding fits in a color-magnitude diagram to obtain the cluster distance. That value is already established from the variable-extinction analysis, as in Figure 4.

The corresponding distance to both clusters is 2.31 ±0.03 kpc, which corresponds to a parallax of 0.43 ±0.01 milliarcsecond. By way of comparison, the Hipparcos value for the trigonometric parallax of P Cyg is 0.52 ±0.50 milliarcsecond (Perryman *et al.* 1997), which is clearly much less precise. The distance estimated here for P Cygni is larger than most results obtained previously (Table 1), primarily as a consequence of the smaller value we find for R. The derived luminosity of the star is affected to a lesser extent, yet is slightly larger than the values obtained in previous studies.

A combined color-magnitude diagram for both IC 4996 and the P Cyg cluster is presented in Figure 5, where it can be noted that both clusters are of similar age according to their main sequence turnoff points. A fairly accurate age estimate is possible, since there are pre-main-sequence stars detectable as well as evolved upper main-sequence stars. For comparison we use evolutionary isochrones for solar metallicity stars taken from Meynet *et al.* (1993) for upper main-sequence stars, and similar isochrones for pre-main-sequence objects interpolated from theoretical tracks published by Palla and Stahler (1993)—see Guetter and Turner (1997). Both turn-off point stars and pre-main-sequence stars are consistent with cluster ages of 6 (±1.5) $\times 10^6$ years ($\log t$ = 6.8 ±0.1), which presumably also applies to P Cyg. The membership of P Cyg in the complex is argued by the coincidence in its radial velocity with that of cluster stars (Table 2), although it must be admitted that the radial velocity of P Cyg itself is not very well established because of the nature of its spectrum. Absorption-line velocities are difficult to establish for stars that exhibit strong redward emission on their line profiles, as is the case for all "P Cygni" stars.

Table 2. Radial Velocity Data.

Star	Spectral Type	$\langle V_R \rangle$	Comments
P Cyg Cluster:			
+37° 47	B2.5 IVe	-15 ±3 km s^{-1}	
+37° 49	B2.5 Vn	-18 ±4 km s^{-1}	
+37° 51	B2 Vn	-15 ±3 km s^{-1}	
+37° 54	B2 V	-11 ±2 km s^{-1}	
Star 26	B5: Vp(Si)	-17 ±2 km s^{-1}	
Cluster Mean		-15 km s^{-1}	
IC 4996:			
HD 193076	B0.7 II	-11 km s^{-1}	Value from Abt and Biggs (1972)
P Cyg	B2 Oe	-18 ±2 km s^{-1}	Value from Markova and de Groot (1997)

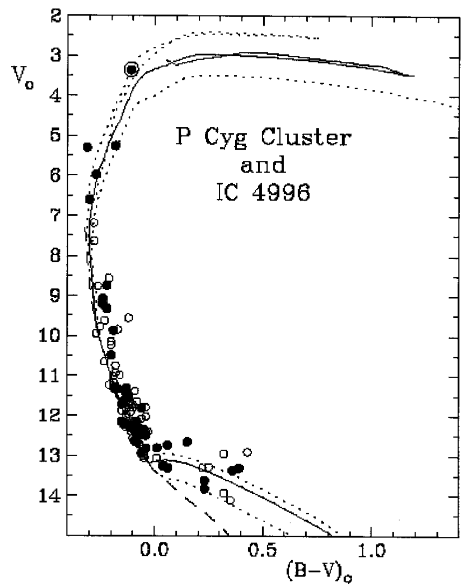

Figure 5. The unreddened magnitudes and colors for stars in the P Cyg cluster (filled circles) and IC 4996 (open circles) are plotted relative to the zero-age main sequence (ZAMS) relation (dashed line) corresponding to a distance of 2.31 kpc. The solid line is a theoretical isochrone for post-main-sequence and pre-main-sequence stars at an age of 6 million years (log $t = 6.8$). Similar isochrones for log $t = 6.7$ and 6.9 are plotted using dotted lines. The data for P Cyg are represented by the circled point.

3. Inferences about P Cygni

The ages of both clusters correlate with a mass of 25.1 ±5.5 $M_{\odot}$ for stars that are just reaching the end of their main-sequence lifetimes, according to the relations of Meynet *et al.* (1993) that are tied to stellar evolutionary models. At masses of ~30 $M_{\odot}$ the various stages of post-main-sequence helium burning have a duration that is ~11% of the hydrogen-burning lifetime of the star. The location of P Cyg in Figure 5 suggests that it likely to be near the end of, or past, the various stages of helium burning. If that is the case, one can establish its evolutionary mass by finding the mass corresponding to stars with ages that are ~11% smaller than the cluster age of 6 (±1.5) × 10^6 years. Such an analysis places the mass of P Cyg at no more than ~23–35 $M_{\odot}$ as a member of the double cluster system. Lamers *et al.* (1983) estimated the star's mass to be ~30 ±10 $M_{\odot}$ from a comparison of its overall energy distribution with models, and those authors consider P Cyg to be an enigmatic object that is evolving blueward from the red supergiant stage to eventually become a Wolf-Rayet star (Lamers *et al.* 1984; de Groot *et al.* 1986). The agreement in the two mass estimates is reasonably good, although the present result is on somewhat firmer footing.

P Cyg has been the subject of numerous studies aimed at establishing its effective temperature, radius, and luminosity. The absolute magnitude of P Cyg as a cluster member is $M_V = -8.46 \pm 0.03$, and its luminosity and distance established here are larger —particularly the distance—than all previous estimates (Beals 1950; Ambartsumian *et al.* 1979; Underhill 1979; Hutchings 1979; Lamers *et al.* 1983) except that of

Isserstedt (1970). Estimates of its bolometric luminosity require an accurate knowledge of its effective temperature. That is difficult to establish because of the star's extreme luminosity. Based solely upon the star's intrinsic color of $(B\text{-}V)_0 = -0.11 \pm 0.02$, we obtain $T_{eff} = 13{,}100 \pm 850$ K ($\log T_{eff} = 4.12 \pm 0.03$) with the scale of Böhm-Vitense (1981). That corresponds to $M_{bol} = -9.06 \pm 0.06$, or $\log (L/L_\odot) = 5.54 \pm 0.02$, and leads to an estimated radius for P Cyg of $115 \pm 18\ R_\odot$. Most estimates for the last parameter in the literature are smaller—$\sim 75\ R_\odot \pm 15\ R_\odot$ (de Groot *et al.* 1986; Kudritzki *et al.* 1992), a consequence of the higher effective temperatures adopted for P Cyg in those studies.

4. Discussion

The constraint placed upon the mass of P Cyg from its cluster membership is tied directly to its likely evolutionary status. The location of the star in the cluster color-magnitude diagram (Figure 5) implies that the progenitor was at one time a main sequence O-type star of spectral type O7–O8. At present it appears to be nearing the end of its helium burning lifetime, its location in the H-R diagram being consistent with late stages of core helium burning or shell helium burning, or perhaps of other advanced burning states. Its derived luminosity lies close to the upper limit for single star evolution for an age of 6 million years, and it may be necessary to invoke a scenario in which P Cyg is a merged binary system in order to reconcile its current parameters with the age of the cluster(s) with which it is associated.

It is of some interest to speculate that P Cygni originally consisted of two stars of smaller mass in close orbit about one another that merged into the present single system towards the end of the main-sequence lifetime of the more massive star. The presence of a moderately rich cluster of lower-mass stars surrounding P Cyg is consistent with such a scenario, since it is necessary to have numerous close encounters with other stars during its lifetime for a close binary system to lose enough potential energy to merge into one star.

As an alternate scenario, the data are also consistent with single star evolution, provided that P Cyg has previously completed all stages of both hydrogen and helium burning in its core. In that event, the star may be close to its natural lifetime as a star, since it must lose a sizeable proportion of its present mass during the next stage of evolution. Its six-fold greater brightness four centuries ago may have marked the end stages of shell helium burning in P Cyg. In that event, its next stages of evolution may make it an object well worthy of future observation.

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