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ULTRAVIOLET OBSERVATIONS OF P CYGNI WITH *COPERNICUS*

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ABSTRACT

New *Copernicus* ultraviolet scans of the peculiar mass-losing star P Cyg are described. From the Lα profile and diffuse band strengths reported in the literature, a value of interstellar reddening $E(B - V) \approx 0.35$ mag is derived, leading to the conclusion that the star is intrinsically reddened. This value for the color excess leads to an estimated distance for P Cyg of 0.6–1.8 kpc, on the basis of which a revised visual absolute magnitude $-7.6 \leq M_v \leq -5.2$ is obtained. The wind from P Cyg is quite unlike that for other early B supergiants, displaying a low terminal velocity and low ionization. This difference is connected with great extension of its photosphere and with the fact that the acceleration of the flow begins below the photosphere. It is suggested that the wind in P Cyg results from dynamical instabilities quite distinct from the mechanism which initiates the winds in other OB stars.

Subject headings: stars: emission-line — stars: individual — stars: mass loss — stars: supergiants — ultraviolet: spectra

I. INTRODUCTION

The peculiar variable star P Cyg (HD 193273) has commonly been used as a prototype for understanding mass loss from hot stars and in fact has lent its name to the distinctive spectral line profile which is a manifestation of such mass loss. Reviews of observational data on this star have been presented by Beals (1951), Schneller (1957), and Underhill (1966).

P Cygni was observed in 1600 to have an apparent magnitude of about 3 and in 1655 to have $m_v = 3.5$, whereas at other times it has been fainter than magnitude 6. In recent years the brightness has been relatively steady with $m_v \approx 4.8$ (e.g., Fernie 1969), although small-amplitude variability with a possible periodicity has been reported (Kharadze and Magalashvili 1967). P Cygni was not mentioned in any sources before 1600, probably because it was systematically fainter than it is now.

The spectral type of P Cyg is generally reported as B1 (e.g., Lesh 1968, who lists B1pe), while there are some spectral indicators that later types may be appropriate (e.g., Struve 1935). The visible-wavelength spectrum contains at least 137 lines with the characteristic "P Cygni" profile, that is, profiles consisting of slightly redshifted (in the stellar rest frame) emission with blueshifted absorption at expansion velocities ranging up to ~ 300 km s^{-1} (Struve 1935; Struve and Roach 1939; Beals 1951). Kopylov (1958) and Hutchings (1969, 1976*a*)—using several criteria, primarily empirical correlations of luminosity with equivalent widths of absorption components of spectral lines—found for P Cyg a visual absolute magnitude of $M_v = -8.4$ and a bolometric absolute magnitude of $M_{\text{bol}} = -10.8$, ranking the star as an extremely luminous object more than 2 mag brighter than other B1 supergiants. However, it must be stressed that the equivalent widths of absorption lines in this case are strongly influenced by blending with the emission components, so that the application of existing calibrations based on equivalent widths of absorption lines in normal stars (without emission lines) is risky.

McCrea (1929), in discussing novae, and Beals (1929), referring to Wolf-Rayet stars as well as to P Cyg, recognized that the observed line profiles indicate the existence of outflowing material, with the emission originating throughout an expanding spherical circumstellar shell and the blueshifted superposed absorption forming in the material moving directly toward the observer. Work on P Cyg by Struve (1935), Beals (1935), and Struve and Roach (1939) showed that the outflowing material must be accelerating throughout the observed region, since the lower-excitation lines which presumably form at the highest levels systematically have the highest observed outflow velocities. More detailed analyses of these velocity-excitation relations have been carried out by de Groot (1969) and Hutchings (1969). From the emission-line strengths and the assumption of radiative excitation, Struve and Roach deduced that the

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observed material is within 2.5 R_* of the photosphere (where R_* is the stellar radius).

The question of the dependence of the outflow velocity on height has recently been revived. Kuan and Kuhi (1975), in attempting to fit computed Hα profiles to the observed line, were forced to conclude that the wind from P Cyg has a deceleration zone; otherwise, the computed emission profiles were all much too broad. A decelerating wind is very difficult to reconcile with the observed velocity-excitation correlations and especially with the infrared spectral index (Wright and Barlow 1975; Barlow and Cohen 1977), which is consistent only with an accelerating outflow. In a recent paper, Van Blerkom (1978) has succeeded in fitting computed Balmer line profiles to those observed by means of an accelerating flow. He was able to obtain good fits by adopting a slower acceleration than that found from the studies of Castor, Abbott, and Klein (1975), whose velocity law Kuan and Kuhi had adopted, and by assuming that the emission source function decreases with height rather than being constant. In the velocity law adopted by Van Blerkom, which is a simple linear dependence on height and is probably not the only possible one, the maximum outflow velocity of $\sim 300\ \mathrm{km\ s^{-1}}$ is reached at a height of 10 R_*. Hutchings (1969) had earlier derived a slow-acceleration velocity law on the basis of optical absorption-line data.

The rate of mass loss was deduced by Hutchings (1976*a*), on the basis of an empirical interpolation scheme involving the gradient of the velocity-excitation relation, to be $3.5 \times 10^{-4}\ \mathfrak{M}_\odot\ \mathrm{yr}^{-1}$, slightly lower than an earlier estimate of $5 \times 10^{-4}\ \mathfrak{M}_\odot\ \mathrm{yr}^{-1}$ (Hutchings 1969) based on fitting the visible-wavelength line profiles. Later, Hutchings (1976*b*) used *Copernicus* ultraviolet data on the C III λ1175 line to support this high mass-loss rate, hypothesizing that C III emission is lacking because the wind density is so high that collisional de-excitation dominates over radiative deexcitation from the upper level of the transition. On the basis of this assumption, one derives a mass-loss rate for P Cyg of $\sim 5 \times 10^{-4}\ \mathfrak{M}_\odot\ \mathrm{yr}^{-1}$.

While there is no doubt that the wind density is substantial, forming the large number of visible-wavelength P Cygni profiles, it seems unlikely that it can be as high as Hutchings suggests, since a recent paper by Barlow and Cohen (1977) reports a significantly smaller mass-loss rate of $1.5 \times 10^{-5}\ \mathfrak{M}_\odot\ \mathrm{yr}^{-1}$ based on infrared and radio observations of the outflowing material. The radio data, which directly measure the amount of material beyond the acceleration zone, provide a rather firm estimate of the mass-loss rate, so long as the terminal velocity of the wind is well known.

The present paper reports on more extensive ultraviolet spectrophotometry of P Cyg with *Copernicus.* P Cygni deserves special attention since it differs from other early-B–type supergiants. The presence of P Cygni profiles in visible-wavelength lines indicates that a substantial part of the acceleration takes place in regions of high density. Therefore, the whole spectral picture of P Cyg must be different from that of more normal early-B–type supergiants in which the acceleration takes place in higher layers.

In this paper data are presented on transitions other than the C III λ1175 line, and the UV spectrum of this object is compared with those of more normal mass-losing stars. Section II presents the observations, § III describes the resulting spectra, and § IV discusses the implications of these data for understanding P Cyg.

II. OBSERVATIONS

Because of moderately heavy interstellar reddening, P Cyg is faint in the ultraviolet, and numerous scans were averaged together in order to reduce the photon noise. One result of this was that the spectral coverage was not extensive but instead consisted of a few relatively small wavelength regions. All of the scans described here were obtained with photomultiplier U2 (Rogerson, Spitzer, *et al.* 1973), which has a nominal resolution of 0.2 Å.

The scans covering the C III λ1175 line, which have been described by Hutchings (1976*b*), were carried out on 1975 June 5. The additional scans described here were carried out on 1975 July 10 and on 1976 November 12.

The particle backgrounds were removed following standard Princeton procedures (York and Miller 1974), and the stray light in the nearly continuous portion of the spectrum from 1155 to 1270 Å was removed following the algorithm of Bohlin (1975). For the isolated small pieces of spectrum near 1300 Å for which this procedure could not be used, the stray light was assumed to be 35% of the total signal (after background removal). Since no photometric measurements are attempted here, this estimate of the stray light is quite adequate.

III. RESULTS

a) *Interstellar* H I

Figure 1 shows the spectrum in the vicinity of the Lα line of H I. The line is broad and has the damping wings characteristic of interstellar absorption. Following Bohlin (1975), the H I column density was determined by adopting trial values of N(H I) and multiplying the observed profile by $e^{+\tau}$, where $\tau(\lambda) = N\alpha(\lambda) = 4.26 \times 10^{-20} N(\mathrm{H\ I})/[6.04 \times 10^{-10} + (\lambda - \lambda_0)^2]$, adjusting the trial value of N(H I) until the result matched the expected continuum level. Figure 1 shows the adopted fit, including the smoothed Lα profile used for the fitting. Because of the high noise level, there was some uncertainty in locating this smoothed profile, and this is reflected in a rather large uncertainty in the derived column density. The value $N(\mathrm{H\ I}) = 1.9 \times 10^{21}\ \mathrm{cm^{-2}}$ was adopted, with an uncertainty of ±50%.

b) *Mass-Loss Effects*

The region of the C III (λ1175.7) and N V ($\lambda\lambda$1238.821, 1242.804) lines in the spectrum of P Cyg is also shown in Figure 1. As reported earlier by Hutchings (1976*b*), the C III feature is present and shows no evidence for

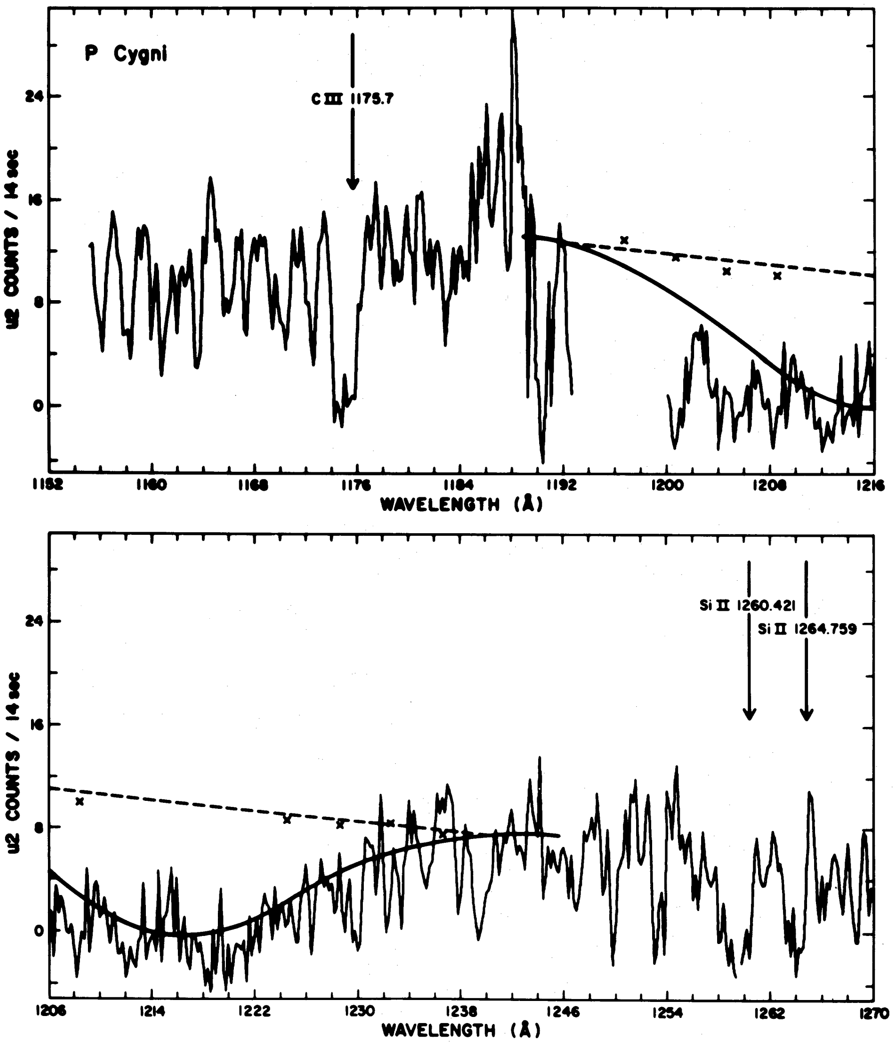

FIG. 1.—The region around Lα in P Cyg. The interval 1155–1184 Å was scanned 11 times, while the interval 1256–1268 Å was scanned 16 times; the remainder, except between 1184 and 1200 Å, was scanned six to eight times. Vertical arrows mark the rest wavelengths of strong lines which appear at shifted positions because of the outflow. The adopted smooth profile of Lα is shown, along with the assumed continuum and points (*crosses*) marking the best fit to this continuum, obtained by multiplying the profile by $e^{+\tau}$, where τ is the optical depth in the line for a pure damping profile.

emission. There is a shift of the absorption, however, with the line center at approximately -190 km s^{-1} in the stellar rest frame. There is no evidence of N v absorption in the 1240 Å doublet, although it is possible that weak N v features could be hidden in the noise. Certainly no strong emission is present.

Figure 1 extends to a wavelength of 1270 Å; at about 1260 and 1264 Å are seen strong absorption lines, which are identified with the Si II lines λλ1260.418 (a resonance line), 1264.730 (a hyperfine excited line with lower-level excitation above the ground state of 287.32 cm^{-1}). The absorption-line centers have velocities of about -200 km s^{-1} for λλ1260, 1264.

It is conceivable that emission is present on the red side of the 1264 Å line, but the high noise makes it impossible to be certain.

Near 1188 Å there is a strong possible emission-like feature with a width of about 4 Å. This falls in a region of the spectrum which was only scanned once and for which the noise is correspondingly greater than in adjacent sections. There is no obvious identification for this feature, if it is real. The S III resonance line at 1190.206 Å might be a candidate, but the emission would have to be shifted substantially toward shorter wavelengths to be responsible for the peak near 1188 Å. There is a strong absorption line at 1190.2 Å which may be S III in absorption, with little or no shift if it is.

Near 1164 Å is a P Cygni–like line, with emission somewhat above any of the adjacent noise. This is in a region which is well scanned; there is a fair likelihood that the feature is real, since its height above the

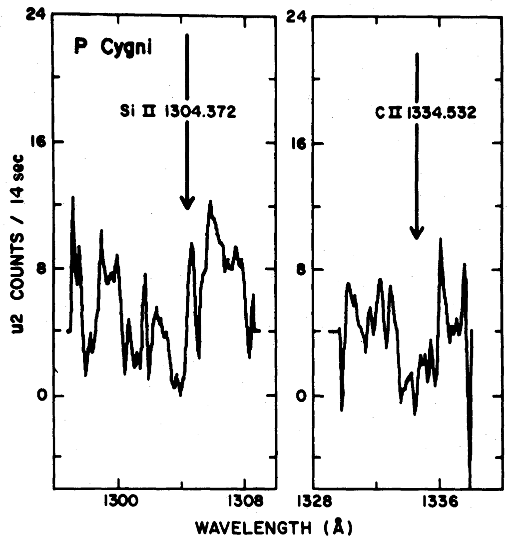

FIG. 2.—The Si II $\lambda1304$ and C II $\lambda1334$ lines. The Si II line shows a small shift toward short wavelengths, whereas the C II line is at the rest position.

continuum corresponds to about 4 times the rms noise due to photon statistics. The identification of this feature with O IV $\lambda1164.545$, a subordinate line requiring high excitation, is hardly conceivable. If the feature is O IV, then the absorption velocity is −200 km s^{-1} and the emission is at the rest wavelength. A strong, unidentified P Cygni profile is seen at this position in the UV spectrum of the Wolf-Rayet star HD 50896 (Johnson 1978).

After the finding that lines such as the Si II features at 1260 and 1264 Å show velocity shifts in P Cyg while high-ionization features like N V are absent, scans were carried out at the wavelengths of other low-ionization resonance lines, including C II $\lambda1334.532$ and Si II $\lambda1304.369$ (see Fig. 2). In both cases, shifted absorption lines were found, with line centers at approximately −80 km s^{-1} for C II and −270 km s^{-1} for Si II (the latter is very uncertain owing to blends on the short-wavelength side). A sharp emission-like spike is seen just to the red of the C II line, with a height above the local continuum corresponding to about 3 times the rms noise. If this is real C II emission, it has a velocity of +350 km s^{-1}.

Table 1 summarizes the data on lines observed for mass-loss effects.

IV. DISCUSSION

a) *Basic Stellar Parameters*

The derived H I column density limits imply, through the correlation published by Bohlin, Savage, and Drake, (1978), a color excess in the range $E(B-V) = 0.30$–0.60, allowing for the full range of uncertainty in N(H I). The specific value $N(\text{H I}) = 1.9 \times 10^{21}$ cm^{-2} yields $E(B-V) = 0.40$. This is substantially below the interstellar reddening derived from the observed $B-V$ color and the assumption that the star has the flux distribution of a B1 supergiant, which yields $E(B-V) = 0.67$.

The strengths of the diffuse interstellar bands toward P Cyg also argue strongly for a low value of $E(B-V)$. Snow, York, and Welty (1977) have compiled all of the published diffuse-band data; the strengths of $\lambda\lambda4430$, 5780 in the spectrum of P Cyg, coupled with the established correlation between band strength and color excess, imply $E(B-V) = 0.30$. There are some known cases of stars with weak diffuse bands for their color excess, but no such regions are known to exist in the vicinity of P Cyg.

It is possible that there is circumstellar reddening of P Cyg which is not accompanied by either H I formation or diffuse-band absorption, so that the star could actually have an extinction color excess of 0.67 notwithstanding the evidence of the other interstellar indicators. This seems unlikely, however, since the infrared data (Barlow and Cohen 1977) show no evidence of silicate emission and can be fitted well with a free-free emission spectrum. Furthermore, if there were substantial circumstellar dust and if the extinction law for this dust bore any resemblance to

TABLE 1

ULTRAVIOLET LINES OBSERVED IN THE SPECTRUM OF P CYGNI

Ion	Laboratory Wavelength (Å)	Ionization Energy Required* (eV)	Excitation (cm^{-1})	Absorption Velocity† (km s^{-1})
C II.........	1334.532	11.260	0.0	−80
C III‡........	1175.7	24.383	52367.0–52447.0	−190
N V.........	1240	77.472	0.0	(absent)
N V.........	1238	77.472	0.0	(absent)
O IV.........	1164.545	54.934	510977.2	(−200)
Si II.........	1304.369	8.151	0.0	−270:
Si II.........	1264.730	8.151	287.32	−200
Si II.........	1260.418	8.151	0.0	−200

* The ionization energy given is for next lower ionization stage.

† The velocity given is the velocity of the absorption-line center in the stellar rest frame.

‡ This feature is a blend of several lines. The given wavelength is a mean, weighted by the f-values, and the range of excitation energies is indicated.

the interstellar extinction law, then the star certainly would not have been detected in the far-ultraviolet by *Copernicus*.

In principle, the color excess could be derived from a comparison of the visual magnitude and the observed UV flux, but this requires the adoption of an intrinsic flux distribution, a risky proposition for a peculiar star. Furthermore, the low count rates for P Cyg combined with the large uncertainty in the absolute calibration of *Copernicus* would make the result of such an analysis extremely inaccurate.

In view of the foregoing, a color excess of $E(B-V)=0.35$ can be adopted as the most reasonable value. The discrepancy between this value and that obtained from the observed $B-V$ color may result from the circumstance that the spectral distribution in a star with an extended photosphere is expected to deviate strongly from that in a blackbody (Kosirev 1933; see also Sobolev 1967). Other factors are the infrared excess of P Cyg, which may contribute to the V magnitude but not to B, enhancing the derived value of $E(B-V)$; or a lower effective temperature for the star than is usually supposed. Possibly a combination of effects is present. Struve (1935) (as noted in § I) found spectral evidence that P Cyg could be cooler than B1; this possibility is supported by spectrophotometric measurements of P Cyg made by Chalonge and Divan (1952).

Regardless of the cause for the discrepant $B-V$ color, the low value of $E(B-V)$ adopted here implies a substantially greater distance for the star than is commonly assumed if the visual absolute magnitude of $M_v=-8.4$ from Kopylov (1958) and Hutchings (1976*a*) is adopted. This yields a distance of $r=2.7$ kpc for $E(B-V)=0.35$, whereas $r=1.7$ kpc for $E(B-V)=0.67$.

An examination of the reddening-distance correlation in the *UBV* catalog of Blanco *et al.* (1968) for normal stars near P Cyg in the sky shows, however, that all stars beyond a distance of about 2.0 kpc have $E(B-V)\geq 1.0$. This implies either that P Cyg is closer than 2 kpc or that its interstellar reddening is actually much larger than that derived either from the observed $B-V$ color or from the arguments presented here. In view of the strong evidence that $E(B-V)\approx 0.35$, it may be concluded that P Cyg is in fact closer to the Sun than 2 kpc. This value for the interstellar reddening gives a distance in the range of about 0.6–1.8 kpc, from the empirical correlation of reddening with distance in this direction. This in turn implies that the visual absolute magnitude of P Cyg is in the range -5.2 to -7.6, somewhat fainter than the value estimated by Hutchings (1976*a*). As mentioned in § I, the value of absolute magnitude obtained by Kopylov (1958) and Hutchings (1976*a*) is very uncertain owing to the many peculiarities of P Cyg. Hence the present evidence that the star is less luminous than expected from standard correlations is not surprising. It is worth noting, however, that the star ζ^1 Sco (HD 152236), which resembles P Cyg spectroscopically, has $M_v=-8$ on the basis of its membership in NGC 6231 (Hutchings 1970).

b) *Stellar Wind*

It is likely that the mass-loss rate is even lower than the value derived by Barlow and Cohen (1977) on the basis of the radio and infrared observations, since the reduced distance adopted here implies a reduction in their rate of about a factor of 3 (Cassinelli 1978); hence the rate is probably not nearly as high as the value derived by Hutchings (1969, 1976*a*). From the velocity law derived by Barlow and Cohen and from their mass-loss rate, a density in the region which forms the UV resonance lines can be derived if the height of this region in the wind is known. Since these lines have shifts (in their centers) corresponding to about 200 km s^{-1}, they must form at a height greater than 1 R_* above the surface, according to the velocity law adopted by Barlow and Cohen. In this region the particle density is less than or equal to 10^{12} cm^{-3}, a factor of at least 10^2 lower than the density required to collisionally de-excite the upper levels of the observed UV transitions. Hence, as noted earlier, the lack of emission is probably not a result of very high density in the wind, as supposed by Hutchings (1976*b*).

The present data show, furthermore, that the lack of strong emission is not confined only to the C III λ1175 transition observed by Hutchings, but is apparent also for the shifted Si II and C II lines.

There are other possible explanations for the lack of strong ultraviolet emission lines. Perhaps the most likely one is that the observed UV lines form in a less extended region than that in which the visible lines with strong P Cygni profiles form, so that the scattering volume for the UV lines is too small to produce strong emission. The fact that the UV absorption lines have a somewhat smaller velocity than the terminal velocity derived from the visible lines supports this suggestion. This is reasonable only if the ionization is decreasing outward, so that the ions observed in the UV do not exist in great quantities in the region where the visible emission lines form. This may be the case, since all of the strongest visible P Cygni profiles are due to neutral species such as H I and He I.

The ionization in the wind from P Cyg is generally anomalous in any case. There is no evidence of highly ionized species such as N V in the wind, unlike any other early-type star with outflow which has been studied so far. In all other cases, ions have been detected in the wind which do not exist in the photosphere (Lamers and Snow 1978), and it is likely that the presence of these ions is linked to the formation of the wind and its acceleration. P Cygni does have shifted lines of Si II and C II, ions which do not exist in the winds of normal early B supergiants. These species do not usually begin to appear as wind indicators until spectral types as late as B8 or so. Thus the ionization balance in the outflowing material from P Cyg is extremely anomalous, bearing in some way a strong resemblance to that of a star some 10,000 K cooler. Quite possibly, the wind from P Cyg is in radiative equilibrium with the photosphere, a clear distinction from other OB stars.

The velocity law which best fits the wind from P Cyg

(Hutchings 1969; Barlow and Cohen 1977; Van Blerkom 1978) is characterized by slower acceleration than the law which evidently governs the outflow from other stars (e.g., Castor, Abbott, and Klein 1975; Lamers and Morton 1976; Lamers and Rogerson 1978). Perhaps the slow acceleration in the case of P Cyg is related to the lack of highly ionized species in the wind. In normal cases, it is likely that species such as O VI in the hottest stars, and N V, Si IV, or C IV in the later types, provide the acceleration to high velocities through their strong UV resonance lines, which are not formed at lower levels (Rogerson and Lamers 1975; Lamers and Snow 1978). In P Cyg, however, where the outer part of the wind is evidently cool, no such transitions exist and the acceleration is slow.

In view of the many ways in which P Cyg differs from other early B supergiants, it seems quite possible that the mechanism driving the mass loss is also different, and may be linked to the fact that P Cyg has a history of major outbursts and bears some similarities to FU Orionis–type variables (Ambartsumian 1971). It may be that processes of internal dynamical instability have to be invoked. Perhaps the star, like the FU Orionis variables, is at a point in its evolution in which rapid changes in the interior conditions cause cataclysmic adjustments in the structure which result in the ejection of some material.

If the mass ejection from P Cyg has dynamical origins, it is still possible that radiation pressure acts on the ejected material once its velocity is great enough to shift the wavelengths of the strong lines away from those of their photospheric counterparts. Abbott (1977) has demonstrated that relatively low ionization in the wind increases the number of strong lines available for radiation pressure to act upon, once overlapping with the photospheric lines is overcome. Furthermore, Abbott (1978) finds that the observed ratio of wind velocity to escape velocity for P Cyg is consistent with those for normal stars with radiatively driven winds.

c) Summary

The principal conclusions regarding P Cyg may be summarized as follows:

1. The true interstellar color excess of P Cyg, derived both from the observed H I column density and from the strengths of the diffuse interstellar bands, is some 0.3 bluer than expected on the basis of the observed $B - V$ color. This is probably due to the peculiar structure of its extended photosphere but may be due partially to an effective temperature which is lower than that usually supposed.
2. The derived color excess, along with the observed correlation of reddening with distance in the direction of P Cyg, places it at a distance between 0.6 and 1.8 kpc, implying that its visual absolute magnitude is in the range $M_v = -5.2$ to -7.6, somewhat fainter than indicated by the standard correlation of emission-line width with M_v.
3. The wind from P Cyg, which has anomalously slow acceleration and low ionization and which produces weak or no emission lines in the UV, much more closely resembles that of a late B than that of an early B supergiant. It may be that the wind has a completely different origin from that in other stars, possibly originating from some kind of dynamical instability, followed by radiative acceleration. The star seems anomalous in many respects, and great care must be exercised in using it as a prototype for understanding other objects.

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