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ELECTRON SCATTERING IN THE EXPANDING ATMOSPHERE OF P CYGNI

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High signal-to-noise observations of hydrogen- and helium-line profiles in the spectrum of P Cyg show a new feature—broad weak emission wings extending to ± 1500 km s^{-1} from the line center. The wings are attributed to electron scattering in the extended atmosphere above the line formation region. A simple model calculation shows that an optical depth $\tau_e \sim 0.2$ for the electron scattering layer will fit the Hα observations. The broad wings are stronger for the He I lines and $\tau_e \sim 0.4$ is suggested.

Key words: broad emission lines—stellar atmospheres—P Cygni stars—electron scattering

I. Introduction

Hydrogen and helium lines in the spectrum of P Cygni were observed in 1977 as part of a reinvestigation of line formation in the extended expanding atmosphere of this classic star. The initial inspection of observations of Hα and Hβ showed that the P Cygni profiles were flanked by broad weak emission wings. The central intensity of the broad wings was only 2% of the peak intensity of the P Cygni emission core. The width (FWHM) of the wings to the Hα line was approximately 22 Å. Further observations revealed that broad wings were detectable for all strong lines of hydrogen and helium. A search of the extensive literature on P Cygni appears to show that these broad wings have not been detected in earlier investigations of the line profiles. This is probably not surprising in view of their width and low intensity and the traditional difficulties associated with photographic spectrophotometry. The 1977 detection of the wings is attributable to the high photometric quality of spectra which is routinely attained at the McDonald Observatory with a Reticon detector (Vogt, Tull, and Kelton 1978). The wings are discernible in the interferometric spectra presented by Johnson (1977).

In this paper, the discovery observations of the broad wings are presented and attributed to broadening by electron scattering in the P Cygni atmosphere. Electron scattering has previously been proposed as a contributor of broad wings to the emission lines of Wolf-Rayet stars (Castor, Smith, and Van Blerkom 1970) and Be stars (Marlborough 1969). Broad emission wings were detected by Wilson (1958) in the spectra of O stars and attributed to line formation in an atmosphere expanding at a velocity of about 1000 km s^{-1}.

II. Observations

Observations of P Cygni were obtained between May and December 1977 with the McDonald Observatory's 2.7-m reflector and the Tull (1972) coudé spectrometer equipped with a silicon diode array Reticon detector (Vogt et al. 1978). A single exposure spanned about 90 Å at a resolution of 0.20 Å to 0.25 Å. In average conditions, a ten-minute exposure provided a signal-to-noise ratio of several hundred in the continuum at wavelengths between 3500 Å and 8000 Å. An observation of P Cygni was followed by one of a hollow cathode Fe-Ne lamp which provided reference lines for radial-velocity measurements. The lamp also served to define the instrumental profile (FWHM ~ 0.20 Å to 0.25 Å). Total spectrum coverage was about 1500 Å between 3600 Å and 8900 Å. A majority of the 90 Å exposures are centered on prominent hydrogen and helium lines.

Line profiles of Hα and He I lines at 7065 Å and 6678 Å are shown in Figure 1. The newly discovered shallow broad wings are a striking feature of these profiles. The raw stellar spectrum has been divided by an observation of a standard lamp. This division removes the small variation of spectrometer sensitivity across the bandpass. The result (see Fig. 1) is plot of the relative flux of the star to the lamp. In such a plot, the continuum level is well defined by a straight line. Six H and He I lines (see Table I) show the broad wings sufficiently cleanly that profile definition and measurement was attempted. In other cases, the wings are indisputably present but additional absorption or emission lines preclude a meaningful measurement of the

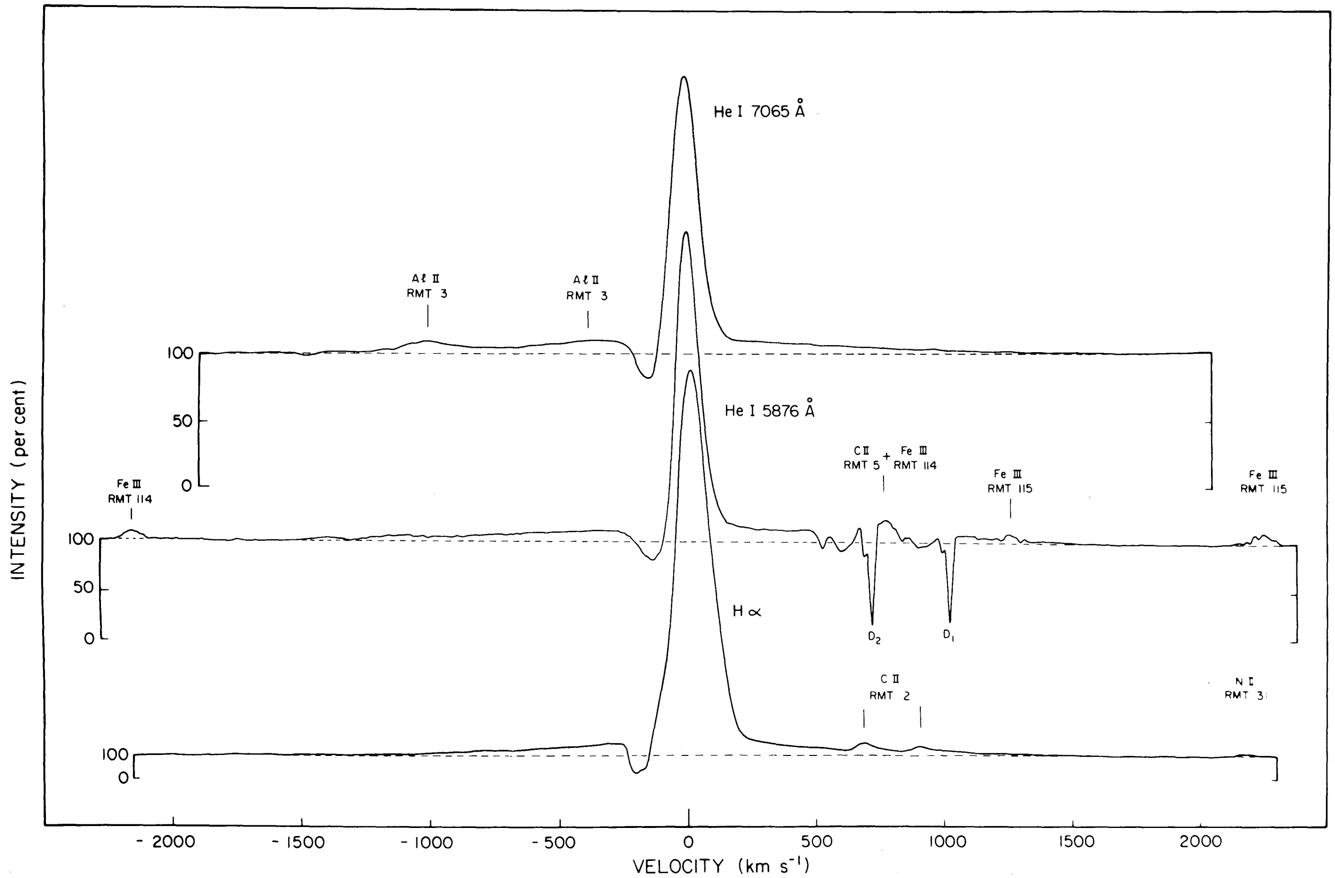

FIG. 1—Profiles of the Hα, He I λ5876 and He I λ7065 line in the spectrum of P Cygni. Note the broad wings extending to ±1500 km s^{-1} from line center.

broad wings.

The equivalent width of the broad wing was measured from a line profile in which the central core is interpolated smoothly from the line wings. The total equivalent width of the shallow wings and the strong emission core refers to the profile drawn across the P Cygni absorption line to meet the emission core near its base. All equivalent widths are given in terms of the local continuum.

Radial velocities were measured for the P Cygni emission and absorption lines. The bisector of the line was determined for several intensity levels and extrapolated to the emission peak or the absorption minimum. This extrapolated velocity appears in Table I. The radial velocity of the broad wings appears to be close to the velocity of the emission core; the bisector of the line drawn between the half-intensity points gives a mean velocity from six lines which differs by only 5 km s^{-1} from the emission core velocity. The bisector of the far wings may be redshifted by a small amount from the velocity defined by the half-intensity points. Additional observations of higher quality are needed to confirm this suggestion.

Hα was observed in each observing run between May and December 1977. Profile changes were observed. The profiles reveal a 30 km s^{-1} shift in the absorption core, a 10 km s^{-1} shift of the strong emission core, and a decrease in the FWHM width by 40 km s^{-1} between May and December. The broad wings were present throughout with a similar profile. Observations of Hδ on August 16 and December 1 show a marked change in the P Cygni absorption line without a detectable change in the emission-line profile; the absorption component was double on 1977 December 1.

III. Electron Scattering in the P Cygni Atmosphere

P Cygni absorption/emission profiles are the characteristic signature of line formation in an optically thick, expanding atmosphere. If the atmosphere above the region of formation for the hydrogen and helium lines has a finite optical depth for electron scattering, some of the emerging photons will be scattered. Since the electrons have high thermal velocities, the scattered photons will provide a broad tail to the P Cygni line profile. The electron-scattering explanation for the shallow emission wings is discussed in this section.

Sample profiles showing the effects of noncoherent

TABLE I

Hydrogen and Helium Emission Lines

Line	Date of Observations (1977)	P Cygni Line: Absorption Core Velocity (km s^{-1})	P Cygni Line: Emission Core Velocity (km s^{-1})	Electron Scattering Wings: FWHM (km s^{-1})	Electron Scattering Wings: W_λ^e (Å)	Electron Scattering Wings: $W_\lambda^e/W_\lambda^{total}$	Notes
Hα λ6563	11 May	-229	+10	1150	13.0	0.19	
	16 Aug	-227	-11	1070	18.0	0.24	
	28 Sep	-220	-13	1020	15.1	0.22	
Hβ λ4861	1 Dec	-198	+15	960	18.9	0.27	
	11 May	-200	-10	1100	3.6	0.25	
	16 Aug	-202	-13	975	2.7	0.21	a
He I λ7065	28 Sep	-159	-21	1100	3.4	0.38	
He I λ6678	20 Oct	-127	+13	1175	2.3	0.40	
He I λ5876	1 Dec	-145	- 8	1200	4.6	0.44	b
He I λ5015	20 Oct	-182	-18	----	1.9	0.53	c

Notes to Table I

a. Profile too noisy to yield a reliable velocity for the electron scattering wings.

b. The red wing (see Fig. 1) is perturbed by several lines.

c. The blue wing is blended with several N II (RMT 19) lines. W_λ^e is obtained by doubling the measured red wing.

scattering by free electrons were calculated following Castor, Smith, and Van Blerkom (1970). In this highly schematic treatment, the free electrons are segregated into a layer external to the line-formation region. The emergent profile from the line-formation region is then the incident boundary condition for the transfer problem in the electron-scattering region. For an electron-scattering optical depth $\tau_e < 1$, the final emergent profile is approximately given by

$$\psi(x) = (1 - \tau_e)\,\phi(x) + \tau_e \int_{-\infty}^{\infty} \phi(x')\, R(x',x)\, dx' \quad ,$$

where x is the frequency displacement from line center in hydrogen Doppler widths, $\phi(x)$ is the incident line profile and $R(x',x)$ is the electron scattering redistribution function (Mihalas 1970). Since our separation of line formation and electron scattering is highly artificial, no attempt has been made to achieve a best fit. The incident profile $\phi(x)$ is taken as a sum of emission and absorption Gaussians. The half-widths, peak values, and location of the absorption minimum were chosen for a reasonable fit. A sample fit for Hα is presented in Figure 2, were $\tau_e = 0.2$, the expansion velocity of the electron shell $v^e_{\text{exp}} = 150$ km s^{-1}, and the electron Doppler width $v_D{}^e = 530$ km s^{-1}, which corresponds to a kinetic temperature of 9200 K. The He I line profiles require a larger optical depth $\tau_e \sim 0.4$. These values are roughly consistent with conditions in the outer layers of the model for P Cygni determined by de Groot (1969).

It is clear that redistribution of line photons by electron scattering provides a reasonable fit to the observations. It is also apparent that the parameters of fit are not unique and depend somewhat on the chosen incident profile $\phi(x)$. However, the combination of v^e_{exp} and $v_D{}^e$ is restricted by the width of the observed profile and τ_e is then determined by the intensity of the broad wings. Figure 2 shows that the value of τ_e appropriate to modeling the wings is larger than the value appropriate to modeling the absorption minimum—an indication of a breakdown of the simple model. The presence of electron scattering insures that the blue-shifted absorption core will not be black.

More accurate calculations of the electron scattering process have been presented by Auer and Van Blerkom (1972) and Mihalas, Kunasz, and Hummer (1976). Auer and Van Blerkom find strong red emission wings in emergent profiles as a consequence of the extension of the atmosphere; Mihalas, Kunasz, and Hummer discuss the modifications of the emergent profiles when continuum absorption and the radial dependence of electron density are included. The observations show a slight effect; for example, the red wing of He I λ6678 is about 25% stronger than the blue wing.

Other facts can be reconciled in a qualitative way with the electron-scattering hypothesis. For example, the ratio of the equivalent width of the shallow emission wing to the total emission line is larger for the he-

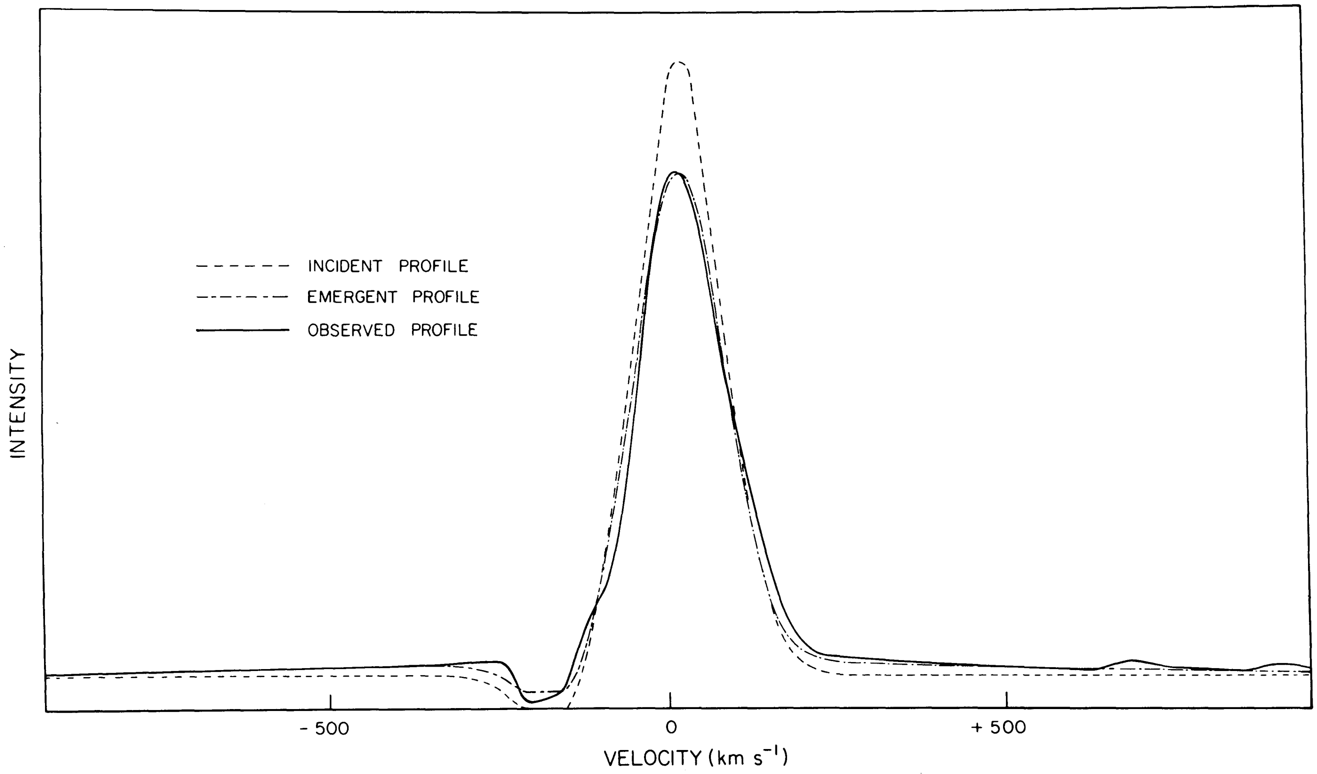

FIG. 2—The observed Hα profile for 1977 December 1 and a sample theoretical fit (see text). Incident and emergent profiles for a layer of optical depth $\tau_e = 0.2$ are shown.

lium lines. The ratio for the He I lines is about a factor of two larger than the H-line ratio. This is readily explained as a result of electron scattering because the higher excitation helium lines are almost certainly formed deeper in the expanding atmosphere and, therefore, they will experience more electron scattering.

Since the electron scattering occurs within and above the hydrogen- and helium-line forming regions, the effective scattering layer must be at least several stellar radii in diameter. In this case, the star occults a minor fraction of the shell and the electron-scattering wings should be centered on the systemic velocity. This appears to be the case for P Cygni. An offset of the shallow wings relative to the systemic velocity would indicate either a failure of the assumption of spherical symmetry or a large optical depth for electron scattering. If the shell is very optically thick, photons scattered in the rear of the shell and directed toward the observer will be rescattered in the front of the shell before escape. In these circumstances, the shallow wings should show a blueshift relative to the systemic velocity. The fact that this is not observed is consistent with the optical depth estimates (e.g., $\tau_e \sim 0.2$ for Hα).

There is a hint of a correlation between the P Cygni profile and the broad wings. A Hβ profile obtained in 1974 (Tull, Choisser, and Snow 1975) shows a black core (residual intensity less than 1% of the continuum) and the broad wings are probably absent. Inspection of a He I λ5876 profile shown by Beals (1951, Fig. 4) shows a much deeper absorption core than the 1977 profiles (Fig. 1). These observations which show reduced wing emission and a deeper absorption core are consistent with a reduction in the electron scattering optical depth above the layers in which the P Cygni profiles are formed. Perhaps, the detection of the broad electron-scattering wings is, in part, attributable to a change in the atmospheric structure. The high photometric precision of the Reticon spectra may have been of secondary importance. P Cygni will be monitored to see if the broad wings change and to define the relation between the wings and the P Cygni absorption/emission profile.

Models of the expanding atmosphere constructed from an analysis of the infrared and radio spectrum of P Cygni predict an adequate column density to account for the observed wings. A recent paper (Barlow and Cohen 1977) presents a model and the authors in their concluding section remark that the electron scattering optical depth down through the atmosphere to the photosphere is $\tau_e = 2.7$ in the preferred model. Lower optical depths are expected to be applicable to the emission lines and the values given in this paper are consistent in a qualitative sense with their model. It would be of special interest to search the spectrum for lines formed very deep in the atmosphere such that the electron-scattering optical depth is large and the profile is dominated by the broadening arising from electron scattering.

Mechanisms other than electron scattering may be invoked to explain the broad wings. Three possibilities are sketched but none appear to be satisfactory. If the emission lines originate in a region of large optical depth, broad wings will be produced. Two difficulties arise with this explanation. First, line-profile calculations (Castor 1970) show that the absorption component of the P Cygni profile extends out to $\tau(x) \sim 1$. However, such an extended absorption component is not seen. Second, neither the equivalent width nor the half-width of the broad wings correlate with the line optical depth; e.g., the wings represent approximately the same fraction of the Hα and Hβ lines even though the total equivalent widths of the lines differ by a factor of about six.

These objections point the search for alternatives to electron scattering in the direction of the optically thin limit. Perhaps, the broad wings are recombination radiation from an optically thin shell with an expansion velocity of about 1000 km s^{-1}. A decisive objection to this model is the gross failure of the Balmer decrement (specifically, the Hα/Hβ flux ratio) to match predictions for the optically thin limit (Osterbrock 1974). Another explanation attributing the wings to strong Stark broadening can also be rejected. High electron densities ($n_e \gtrsim 10^{16}$ cm^{-3}) are required to achieve the observed widths. It is difficult to imagine how such densities can be achieved at the top of an expanding atmosphere. Furthermore, inspection of Stark calculations (Griem 1974) shows that different lines will give different half-widths but the observations show that all lines have a very similar half-width ($\Delta v \sim 1050 \pm 150$ km s^{-1}, see Table I).

In summary, the attribution of the broad wings to electron scattering satisfactorily explains these line-profile observations and is consistent with a published model atmosphere based upon an analysis of the infrared and radio spectrum.

IV. Concluding Remarks

New photoelectric observations of the hydrogen and helium emission lines of P Cygni show extended emission wings superimposed on the classic "P Cygni-type" profiles. Such extended wings are a natural consequence of redistribution of line photons by noncoherent electron scattering. It is clear that past work which relied on line-profile fitting to determine mass-loss rates must be redone to self-consistently include the effects of electron scattering.

Two observational consequences of the electron shell come to mind. The quantitative importance of both effects will depend on the detailed structure of the shell.

Speckle interferometric observations may be able to detect a difference in the angular size of P Cygni as determined from the emission wings and the strong emission cores. Recent speckle measurements (Blazit et al. 1977) resolved P Cygni with a bandpass centered on the Hβ emission but failed to resolve it with a bandpass centered on the adjacent continuum.

Electron scattering will give rise to a variation of polarization across the line profiles. Observations similar to those undertaken for Be stars (Coyne 1976; McLean and Clarke 1976) should be attempted for P Cygni. A more ambitious experiment would be an attempt to measure the polarization across the spatially resolved shell (Cassinelli and Hummer 1971).

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APPENDIX

Na D Emission from P Cygni?

In presenting a thorough description of the P Cygni spectrum, Beals (1951) proposed that the Na D lines could be seen in emission but mutilated by interstellar and stellar absorption lines. This region is shown in Figure 1.

Examination of this spectrum and also the spectrum illustrated by Beals (his Fig. 4) shows that there is no convincing evidence for an emission line at the Na D_1 position. Beals argued that the emission in this weaker line was masked by the overlying strong interstellar line. However, this cannot be the case; the emission near the Na D_2 line extends clear to the red of the interstellar line but there is no corresponding emission near the Na D_1 line.

The C II lines from multiplet RMT 5 (3^2D-4^2P^0) are probably the dominant contributors to the emission near Na D_2. A similar multiplet RMT 2 (3^2S-3^2P^0) is present near Hα (see Fig. 1). Fe III must also contribute because other lines of the same multiplet are present.