P CYGNI TYPE STARS: EVOLUTION AND PHYSICAL PROCESSES

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ABSTRACT. The class of P Cygni Type (PCT) stars is defined and the brightest members in our galaxy, LMC, M31 and M33 are identified. They are located near the upper luminosity limit in the HRD in the range of $8500 \lesssim T_{eff} \lesssim 27{,}000$ K and $-11.0 \lesssim M_{bol} \lesssim -7.8$. We suggest that all PCT stars are S Dor variables, and that the reverse may also be true. The basic parameters of the PCT stars are derived and compared with those of normal supergiants: the effective gravity is a factor 3 to 10 lower, the mass loss rate is a factor 3 to 10 higher, the terminal velocity is about a factor 10 lower. This results in a wind density which is a factor 30 higher and thus produces the P Cygni lines in the vi*ual spectrum. The history and the physical processes in the star P Cygni are discussed. The photometric variability and the shell ejections on a timescale of about a month are probably due to non-radial pulsations. The acceleration of the wind is due to radiation pressure by numerous ($\sim 10^3$) metal lines in the Balmer continuum. This can also explain the S Dor type of variability. The proposed mechanism will automatically lead to a P Cygni phase in the evolution of the most massive stars and to the existence of an upper limit in the HR diagram. The expected lifetime of the PCT phase is about 10^4 to 10^5 years. Some unresolved problems and recommendations for future research are discussed.

1. THE DEFINITION OF P CYGNI TYPE STARS

P Cygni type stars are stars which, in their visual spectrum, have lines with so-called P Cygni profiles, i.e. an emission component

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which is either undisplaced or slightly red-shifted and a blue-shifted absorption component. They are called after their prototype: P Cygni (HD 193237). This star appeared in the sky in August 1600 as a nova and after a century of irregular brightness variations it has now settled down as a B1 Ia^{+} hypergiant of $V \simeq 4.9$ magnitude.

Although most astronomers seem to agree which stars should be called "P Cygni-stars," there is no clear definition. In his classical study, Beals (1950) called them "stars with P Cygni profiles in the visual spectrum." This definition, however, would also include some Of stars, Be-stars during occasional phases and some B-supergiants which one would normally not call P Cygni stars. Other definitions or descriptions can be found, e.g. in de Jager (1980) and Underhill (1982). A clear but restricted definition is given by Underhill (1960): "Stars with a spectrum similar to P Cygni." This would limit the class to stars with spectral types early-B, whereas there might also be P Cygni type stars of types late-B or A.

The problem of the definition of the P Cygni type stars arises because the P Cygni spectral characteristic, namely the presence of P Cygni profiles in the visual spectrum, is due to a certain astrophysical phenomenon (i.e. a very large mass loss) which may not be restricted to a certain class of objects. For instance, if a Be-star would temporarily develop P Cygni profiles in its visual spectrum, would we call it a P Cygni star? Obviously not. On the other hand, the P Cygni characteristic is usually seen in the spectra of the most luminous B- and A-type supergiants, which do indeed form a certain class of objects. Therefore, I propose that we define the P Cygni type stars as follows:

"P Cygni type stars are luminous supergiants (with $M_V \lesssim -7$) of spectral types O, B and A, which in their visual spectrum show or have shown P Cygni profiles (emission components with blue shifted absorption components) of not only the strongest Balmer and He I lines (Hα, Hβ, He I 6678, He I 5875) but also of other lines, such as lines of higher Balmer numbers and/or lines of other ions."

Since the phenomenon which produces the P Cygni type characteristic (severe mass loss) seems to be variable, a P Cygni type star may not show this characteristic at all times. The star HD 269006 is a good example. It showed the P Cygni type spectrum in 1973 during maximum brightness, but during minimum brightness in 1981 it had an absorption line spectrum in the visual with [Fe II] emission lines (Wolf et al., 1981b).

With the definition given above we have restricted ourselves to a group of stars in a certain part of the HR diagram which have similar characteristics. It is possible, but not proven, that these stars are in the same evolutionary stage. If that is the case, they will really constitute a specific class of stars.

The class of P Cygni stars is not an isolated class. There seems to be a general trend going from A and B supergiants, which may show P Cygni profile in Hα only, through the A and B hypergiants or superluminous supergiants of class Ia^{+} or Ia-0, which show P Cygni profiles in Hα, Hβ, He I 6678 and He I 5875 (Underhill, 1982, p. 131), to the P Cygni stars.

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I propose to indicate the class of P Cygni type stars by: PCT. (Notice that the sympol PC was used by van Genderen et al. (1983) to indicate that the star had P Cygni characteristics in their visual spectrum, irrespective of the number or type of lines. Some of their PC stars may not meet our definition of the PCT stars.)

2. THE RELATION BETWEEN P CYGNI TYPE STARS AND S DOR OR HUBBLE-SANDAGE VARIABLES

Using the definition of the PCT stars in the previous paragraph, we can identify the PCT stars in our galaxy, the LMC, M31 and M33. There are no known PCT stars in the SMC. They are listed in Table I. The PCT stars in the LMC were selected on the basis of the description of their spectru* in the classical paper of the brightest stars in the LMC and SMC by Feast et al. (1960). For several of the stars we listed a range in spectral types because most of them show drastic variations in brightness as well as in color or spectral type.

The reader will notice that several of these P Cygni type stars were also discussed by Wolf in his review of the S Doradus and Hubble-Sandage variables in this symposium. The reason is obvious: The S Dor or HS-variables are identified on the basis of their spectral

Table I. P Cygni type stars in the galaxy, LMC, M31 and M33.

System	HD	Name	Type	Class	Ref.
GAL	193237	P Cyg	B1 Ia^+	PCT	1
	94910	AG Car	B0 I-A1 I	PCT, S Dor	2
	90177	HR Car	B2 eq	PCT, S Dor	3
LMC	268835	R66	B7, Aeq	PCT	4
	269006	R71	B2.5 Iep-A1 Ieq	PCT, S Dor	5
	269128	R81	B2.5 eq	PCT	6
	35343	R88=S Dor	A2-5 eq	PCT, S Dor	7
	269859	R127	0Ia fpe	PCT, S Dor	8
M31		AE And	---	PCT, HS	9
		AF And	---	PCT, HS	9
		Var A-1	---	PCT, HS	9
M33		Var B	---	PCT, HS	9
		Var C	---	PCT, HS	9

References: 1 - de Groot (1969); 2 - Wolf and Stahl (1982); 3 - Bond and Landolt (1970); 4 - Stahl et al. (1983b); 5 - Wolf et al. (1981b); 6 - Wolf et al. (1981a); 7 - Wolf et al. (1980); 8 - Stahl et al. (1983a); 9 - Kenyon and Gallagher (1985).

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type and variability. The PCT stars are identified on the basis of their visual line spectrum. Clearly, many S Dor variables have a PCT spectrum and many PCT stars show S Dor type variations. The interesting question is: are both groups identical?

Consider the stars in Table I. Only three of them, P Cygni, R66 and R81, are not classified as S Dor variables because they have not shown the characteristic brightness variations during the last decades. We know, however, that P Cygni had an outburst in AD 1600 (see Sec. 5.1) and on the basis of this variation P Cygni should be called an S Dor variable. This leaves R66 and R81 as the only PCT stars which are not classified as S Dor variables. We may speculate that these stars are also S Dor variables but that their variations have not been detected yet. This suggests that all P Cygni type stars may be S Dor variables, which are the same as Hubble-Sandage variables (see Wolf's review and Humphreys et al., 1984).

Is the reverse also true? To answer this question we have to look at visual spectra of the S Dor or H-S variables. All the S Dor or H-S variables listed in Table I are PCT stars. I am not aware of other variables of this nature that have been observed at sufficient resolution to check whether they are PCT stars. The only exception is η Car, which has an emission line spectrum in its present phase. We may conclude that all S Dor and Hubble-Sandage variables may show PCT spectra during some phases, and therefore they are PCT stars. So the classes of PCT stars and the S Dor or H-S variables are possibly identical.

3. THE BASIC PARAMETERS OF THE P CYGNI TYPE STARS AND THEIR LOCATION IN THE HR DIAGRAM

The characteristics of the PCT stars are listed in Table II. Since most of the stars are variable, I have selected the data in such a way that they apply as much as possible to the phase when the star showed the PCT characteristics. For instance, for R71 this is at maximum brightness, whereas for R127, I have selected the phase just after the onset of the brightening in Jan 1982. Since the time coverage of the spectra is poor, this selection could not be applied strictly. The phase is given at the end of the table, together with the references. For the stars in M31 and M33 the characteristics were determined at one epoch only. We do know if the stars were at minimum or maximum brightness at that time. The temperatures for these stars were determined by means of a blackbody fit to the UV and visual energy distribution (Humphreys et al., 1984). The temperature of the star AG Car is extremely uncertain. The value of T_{eff} = 9000 K was adopted by Wolf and Stahl (1982) on the basis of the Hβ profile which is formed in the wind and may give rise to a serious underestimate. Therefore, M_{bol} of AG Car should be considered as a lower limit.

I have estimated the masses of the stars on the basis of their luminosity by using the evolutionary tracks of Doom (1982), in which mass loss and convective overshooting were taken into account. An upper limit to the mass, M_u, can be derived from the relation between

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Table II. The characteristics of the P Cygni type stars.

Star	M_V	M_{bol}	T_{eff} (K)	R_* ($R_\odot$)	M_u ($M_\odot$)	M_ℓ ($M_\odot$)	M_* ($M_\odot$)	log g (cm/s^2)	Γ	log g_{eff} (cm/s^2)	V_{esc} (km/s)	Phase	Ref.
P Cygni	-8.3	-9.9	19,300	76	45	35	40	2.29	0.48	2.01	330	quiescent	1,2
AG Car	-7.6	-7.8	9,000	130	--	--	16:	1.50	0.14	1.43	220	max	3
HR Car	-8.0	--	--	--	--	--	--	--	--	--	--		4,5
R66	-8.4	-8.9	12,000	125	23	19	21	1.57	0.37	1.36	200	quiescent	6
R71	-9.4	-10.6	10,000:	390	68	55	61	1.04	0.60	0.64	150	max	7,8
R81	-8.2	-10.0	20,000	75	48	37	42	2.31	0.50	2.01	330	quiescent	9
S Dor	-9.3	-10.6	8,500	540	68	55	61	0.76	0.60	0.36	130	max	10,14
R127	-8.7	-10.6	17,000	135	68	55	61	1.97	0.60	1.57	260	brightening	11
AF And	-8.8	-10.9	25,000:	72	81	67	74	2.60	0.65	2.14	370	unknown	12,13
AE And	-7.0	-8.3	15,000:	60			19:	2.16	0.23	2.05	310	unknown	12,13
Var A-1	-8.8	-11.0	27,000:	65	85	72	78	2.71	0.68	2.22	390	unknown	12,13
Var B	-8.4	-10.3	22,900:	65	57	44	50	2.51	0.56	2.15	360	unknown	12,13
Var C	-7.5	--	--	--	--	--	--	--	--	--	--	unknown	12,13

References: 1 - Lamers et al. (1983); 2 - Cassatella et al. (1979); 3 - Wolf and Stahl (1982); 4 - Bond and Landolt (1970); 5 - Viotti (1971); 6 - Stahl et al. (1983b); 7 - Wolf et al. (1981b). 8 - Thackeray (1974); 9 - Wolf et al. (1981a); 10 - Wolf et al. (1980); 11 - Stahl et al. (1983a); 12 - Humphreys et al. (1984); 13 - Kenyon and Gallagher (1985); 14 - Leitherer et al. (1985).

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L and the mass at the end of the core-H burning. This assumes that the PCT stars are beyond the core-H burning phase. A lower limit to the mass, M_{ℓ}, can be derived by adopting the relation between L and the mass for which the surface composition of H has dropped to X = 0.40. If the mass were lower, X would be smaller and the star would be a WR star. I adopted the mean value M_* between this upper and lower limit. Since the difference between the upper and lower limit is small, this should give a reasonable guess of the actual stellar mass. For the stars AG Car and AE And, which are outside the range of initial masses calculated by Doom, I adopted a mass of 0.75 times the mass that a star with that L would have when it is at the end of main sequence according to the tracks by de Loore et al. (1978). The data in Table II also give the resulting values of log g, log g_{eff} and v_{esc}, where $g_{eff} = g(1-\Gamma)$ and $\Gamma = 2.66 \times 10^{-5}\,(M/M_{\odot})(L/L_{\odot})^{-1}$ is the correction due to radiation pressure by electron scattering. For this I assumed that H is ionized in the atmospheres of the PCT stars.

Figure 1 shows the HR diagram of the stars on the P Cygni phase. Different symbols are used to indicate whether the star is in a

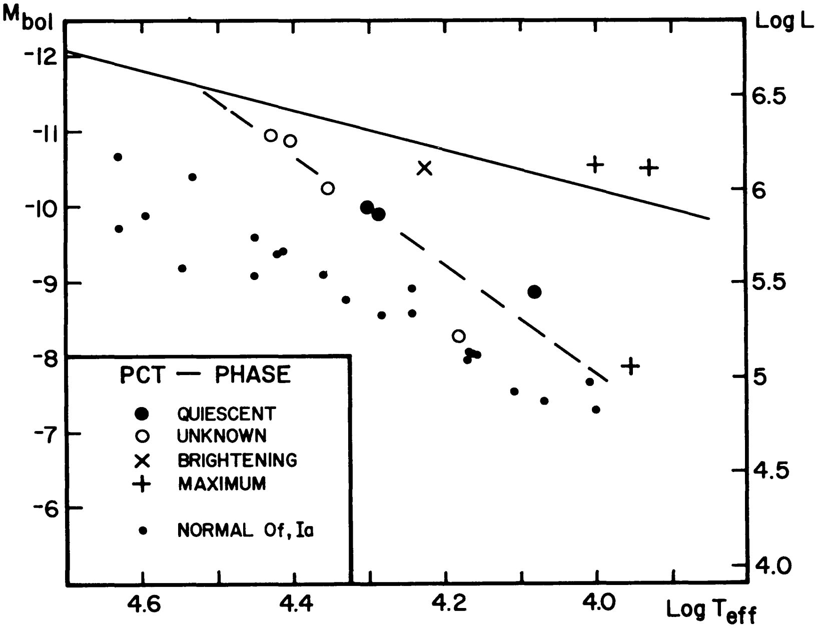

Fig. 1. The HR diagram of the PCT stars. Different symbols are used to indicate the phase in which stars showed their P Cygni type characteristics. The data for normal Ia supergiants are shown for comparison. The full line indicates the location of the Humphreys-Davidson luminosity upper limit. The broken line gives the mean relation for the quiescent phase of the PCT stars.

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quiescent phase or at maximum brightness. For comparison I have also plotted the location of a number of well-studied bright supergiants of class Ia with types between O9 Ia and B9 Ia and the Of stars, from Lamers (1981). If we ignore the stars at maximum brightness, there is a suggestion of a trend between M_{bol} and T_{eff} (dashed line) for the PCT stars which goes approximately as

$$\log L \simeq 5.0 + 3 \log(T_{eff}/10^4) \quad . \tag{1}$$

This relation is very uncertain since it depends on a small sample of stars only, but the trend is suggestive, especially if we take into account the fact that the stars at maximum brightness have moved horizontally to the right in the HRD (see Wolf's review of S Dor variables). It is interesting to notice that this relation is almost parallel to the relation determined by the Of and Ia supergiants, except that it is about 1 to 1.5 magnitudes brighter. The star AE And in M31 is an exception as it is as bright as the normal Ia supergiants. It has the lowest extinction, $A_V = 0.70$, compared to $A_V \simeq 1.1$ to 1.7 for the other stars in M31 studied by Humphreys et al. (1984).

We can compare relation (1) with the one shown by van Genderen et al. (1983) in their Figure 4 for LMC stars with P Cygni profiles (but not necessarily PCT stars!). Their mean relation through 15 stars goes as

$$\log L \simeq 5.6 + 1.7 \log(T_{eff}/10^4) \quad . \tag{2}$$

The difference in the slope between equations (1) and (2) might be due to the fact that our sample is too small or the sample used by van Genderen et al. may contain stars during their maximum.

In Figure 1, I also show the luminosity upper limit from Humphreys and Davidson (1979) (solid line). We see that the PCT stars are below this upper limit, and only those at maximum reach the limit. This suggests that the actual upper limit for stars during their quiescence or minimum (which is the limit to be compared with evolutionary calculations!) is lower and steeper than the one adopted by Humphreys and Davidson.

In Figure 2A I have plotted the adopted masses of the PCT stars and their effective gravities as a function of L. Since the derived masses depend only on the luminosity and not on T_{eff}, the mass is independent of the phase (maximum or minimum brightness) of the star because the light variations occur at almost constant L. The error bars indicate the upper and lower limits of the mass. The mean relation through the data is

$$\log(M/M_\odot) = 1.68 + 0.67 \log(L/10^6) \tag{3}$$

for $L \gtrsim 5.5$. The tightness of the relation shown in Fig. 2A is due to the fact that the masses were derived from evolutionary tracks by assuming a unique relation between M and L. The normal Ia supergiants (not shown in this graph) follow the relation of M_u, i.e. over the top of the error bars. Figure 2B shows the values of g_{eff} as a function

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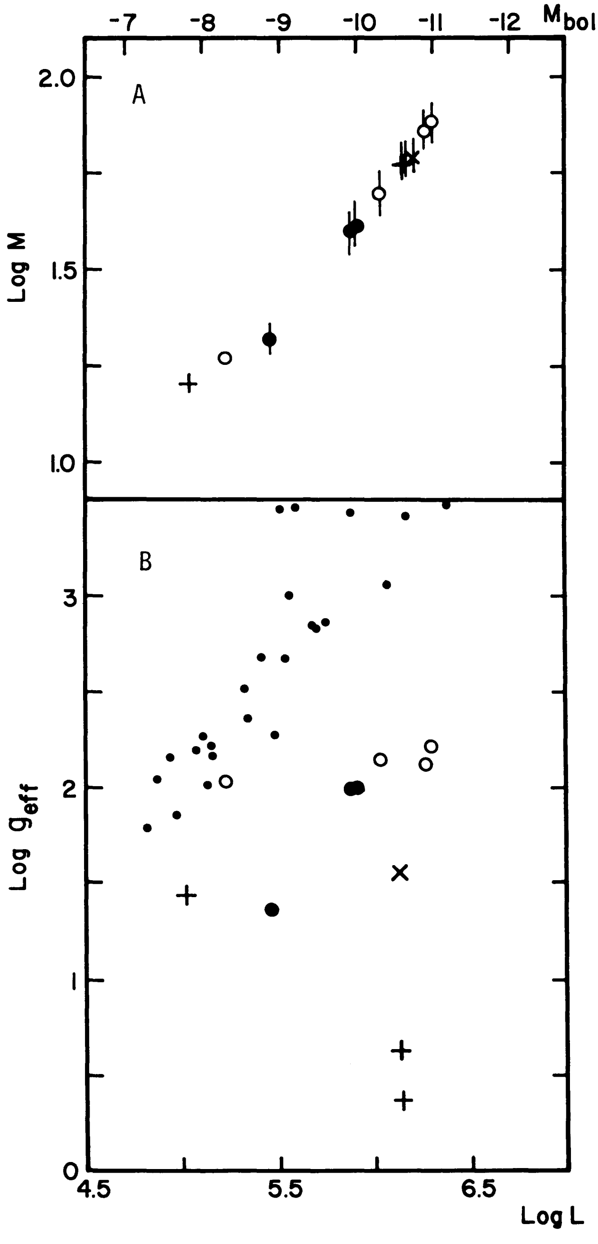

Fig. 2. A: The relation between the mass and the luminosity, derived from the evolutionary calculations. B: The effective gravities of the PCT stars, compared to those of Ia supergiants. The symbols are the same as in Fig. 1. The PCT stars during quiescence have a 5 to 10 times lower gravity than normal supergiants.

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of luminosity for the PCT stars as well as for the Ia and Of supergiants of Figure 1. We see that g_{eff} of the PCT stars is about a factor 5 to 10 smaller than in Ia and Of stars. The two stars R71 and R88 which show a PCT spectrum during maximum have an even lower value of log $g_{eff} \approx 0.5$ during maximum.

It is likely that this low gravity plays an important role in the fact that the stars are PCT stars. One might speculate that the low gravity is in some way responsible for a high mass loss rate which in turn produces the PCT characteristic of the spectrum.

4. MASS LOSS FROM P CYGNI TYPE STARS

The PCT characteristic shows that the stars are suffering a high mass loss rate. The mass loss rates have been estimated for most of the known PCT stars. They are listed in Table III together with some of the relevant basic data. The phase and the references are the same as those of Table II. In Figure 3A the mass loss rate is plotted versus the luminosity and compared with that of the normal Ia and Of stars from Lamers (1981). We see that the mass loss rates of the PCT stars are a factor 3 to 10 higher than those of normal stars, even during the quiescent phase. Var A-1 is an exception, as it has a normal mass loss rate. In Figure 3B I have plotted the terminal velocities v_∞ as a function of T_{eff} for the PCT stars and the normal Ia and Of stars. The values of v_∞ for the normal stars are from the references given by Lamers (1981). We see that the terminal velocity of the PCT stars is

Table III. Mass loss from P Cygni type stars.

Star	log L	log g_{eff}	V_{esc} (km/s)	V_∞ (km/s)	$\dot{M}$ ($M_\odot$/yr)	V_∞/V_{esc}	log n_H (2 R_*)
P Cygni	5.86	2.01	330	300	2×10^{-5}	0.91	10.92
AG Car	5.02	1.43	220	166	3×10^{-5}	0.75	10.88
HR Car	—	—	—	—	—	—	—
R66	5.46	1.36	200	307	3×10^{-5}	1.54	10.65
R71	6.14	0.64	150	127	5×10^{-5}	0.85	10.27
R81	5.90	2.01	330	250	3×10^{-5}	0.76	11.18
S Dor	6.14	0.36	130	130	7×10^{-5}	1.00	10.12
R127	6.14	1.57	260	199	6×10^{-5}	0.77	11.07
AF And	6.26	2.14	370	350	5×10^{-5}	0.95	11.29
AE And	5.22	2.05	310	50	—	0.16	—
Var A-1	6.30	2.22	390	200	1.5×10^{-5}	0.52	11.10
Var B	6.02	2.15	360	350	—	0.97	—
Var C	—	—	—	200	—	—	—

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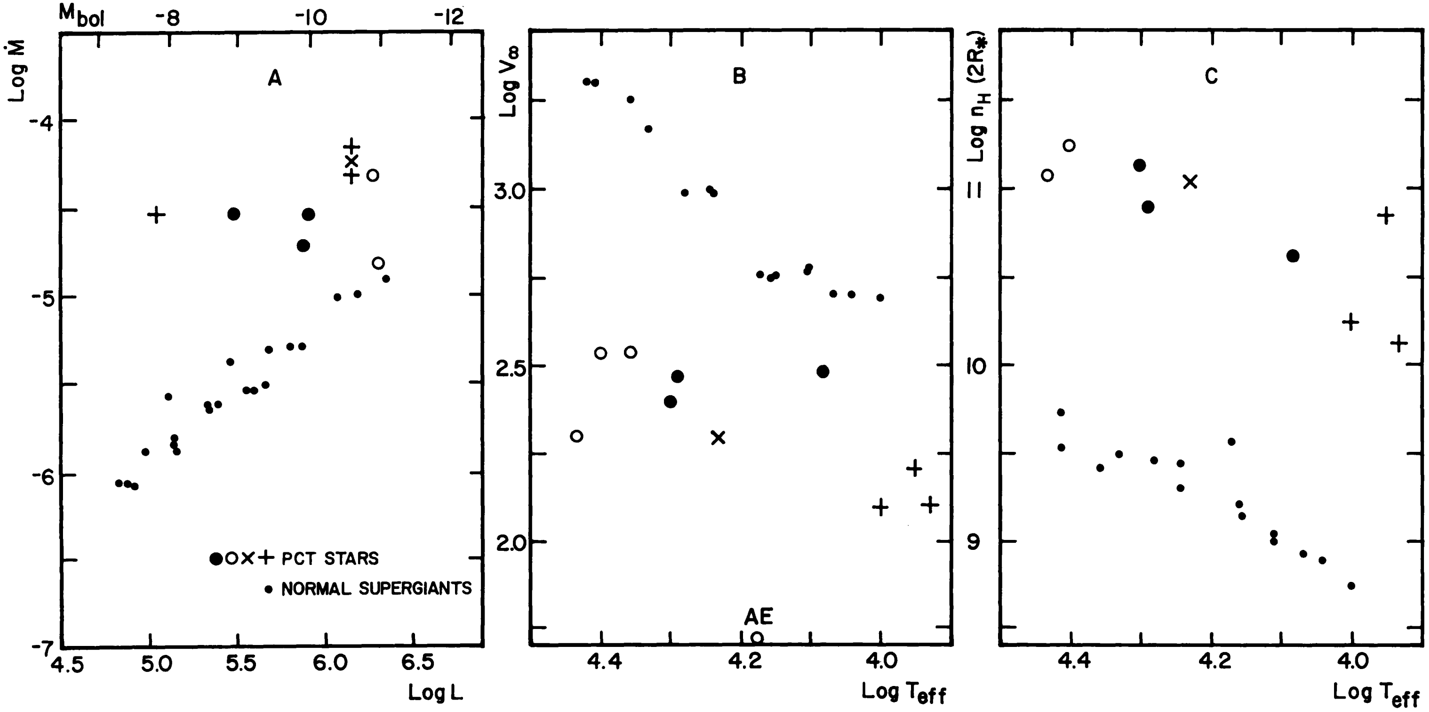

Fig. 3. The mass loss characteristics of the PCT stars are compared with those of normal supergiants. A: The mass loss rate is 3 to 10 times higher than in normal supergiants of the same luminosity. B: The terminal velocity of the winds of PCT stars is of the order of 100 to 300 km/s, and 3 to 10 times lower than in normal supergiants. C: The density of the wind at 2 R_* in PCT stars is 30 times higher than in normal supergiants.

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of the order of 100 to 400 km/s, whereas the normal supergiants have a range of $v_\infty \simeq 500$ km/s for $T_{eff} \simeq 10{,}000$ K to 2000 km/s for 25,000 K. So the values of v_∞ for the PCT stars is about 0.1 to 0.5 times as small as that of normal supergiants. Even if we compare the ratio v_∞/v_{esc} of the PCT stars with those of the normal supergiants we find that the PCT stars have a lower velocity than the normal stars. The PCT stars have $v_\infty/v_{esc} \simeq 0.2$ to 1.5, whereas the supergiants have $v_\infty/v_{esc} \simeq 3.5$ at 25,000 K to 1.5 at 10,000 K. If we concentrate on the PCT stars in Figure 3B and ignore the discrepant value of AE And we find an indication of a trend which shows that v_∞ decreases with decreasing T_{eff}, similar to the case of the normal supergiants but about a factor 0.25 lower. Such a relation implies that the terminal velocity will decrease when the PCT star goes into a brighter state, since the temperature decreases with increasing visual brightness. The stars which are in their maximum/brightness state have indeed the lowest velocity in Figure 3B.

The high mass loss rate and the low velocity of the PCT stars imply that the density in the wind is much higher than in normal supergiants. The density in a stationary spherically symmetric flow is

$$\rho(r) = \dot{M}/4\pi\, r^2 v(r) \quad . \tag{4}$$

Not only is $\dot{M}$ higher and v_∞ smaller in PCT stars than in supergiants, but also the velocity law, i.e. the increase of $v(r)/v_\infty$ with r/R_*, is slower in the PCT stars. The velocity law in the wind of P Cygni was determined from an accurate analysis of the Balmer profiles by Van Blerkom (1978) and from the IR excess by Waters and Wesselius (1985). They found that the velocity increases about linearly with distance from 0.1 v_∞ at the photosphere to v_∞ at 15 R_*. A similar velocity law was derived for S Dor from the IR excess by Leitherer et al. (1985). This implies that at a distance of 2 R_* the velocity is only 0.16 v_∞. In a normal supergiant, the velocity law goes as $v_\infty[1-(R_*/r)]^\beta$ with $\beta \simeq 1$ (Castor and Lamers, 1979), so $v \simeq 0.5\, v_\infty$ at 2 R_*. In Table III I have listed the resulting densities at 2 R_* from the stellar center, assuming that all PCT stars have the same velocity law as P Cygni. The density is expressed in the hydrogen density, for which I assumed a ratio of $n_H/\rho = 4.42 \times 10^{23}$. The densities are plotted versus T_{eff} in Figure 3B. We see that the density in the PCT stars follows about the same trend of decreasing n_H with decreasing T_{eff} as the supergiants, but that the density in the winds of the PCT stars is about a factor 30 higher! <u>It is this high density which is responsible for the PCT spectrum.</u>

We conclude that the presence of the P Cygni profiles in the spectrum of the PCT stars is due to high density in the wind. This high density is a result of three effects:

a. The mass loss rate is about 3 to 10 times higher than in normal supergiants (Fig. 3A).

b. The terminal velocity of the wind is 0.1 to 0.5 times smaller than in normal supergiants (Fig. 3B).

c. The velocity in the wind increases much more slowly than in normal supergiants.

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The key question is: is this only due to high luminosity and the low effective gravity of the PCT stars (Figs. 1 and 2)? In order to answer that question we will consider one star in detail.

5. THE STAR P CYGNI: A CASE STUDY

5.1. The History of P Cygni

The star P Cygni was discovered on August 18 in 1600 by the famous Dutch chartmaker Blaeu when it suddenly brightened as a nova to the third magnitude. Between 1606 and 1626 it faded until it became invisible. Then in 1654 it brightened again to third magnitude and it remained that bright until 1659. From 1660 to 1683 it was faint and strongly variable with occasional drops to invisibility. The observers in the seventeenth century noticed that P Cygni was a "red" star. Between 1683 and 1780 the star gradually brightened to magnitude 5.2. Between 1781 and 1786 P Cygni seems to have been 0.4 magnitude fainter than before, but after that it increased in brightness again between 1786 to 1870 to its present magnitude of 4.9 in the visual. Since that time, the brightness is about constant, apart from some typical irregular variability of about $0^{\mathrm{m}}.2$. (For the light history of P Cygni see Zinner, 1952; de Groot, 1969; van Gent and Lamers, 1985.) The history is sketched schematically in Figure 4.

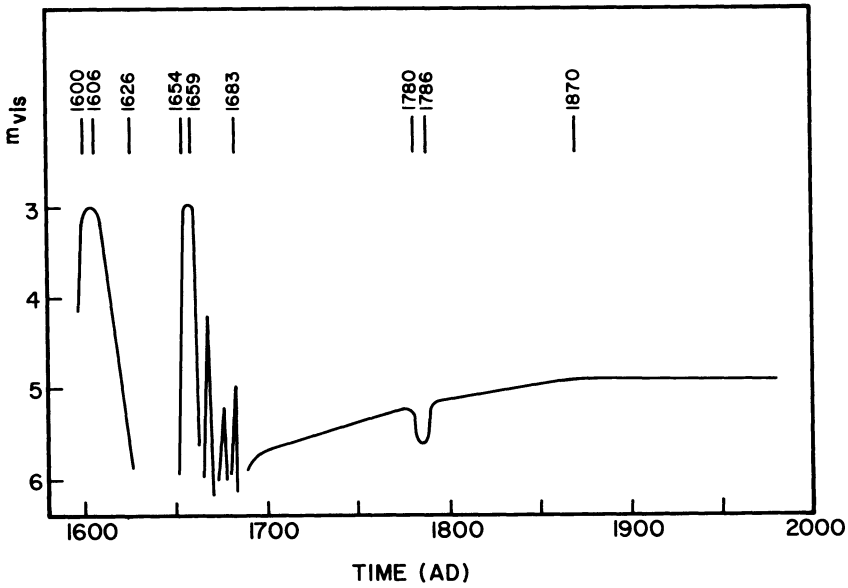

Fig. 4. A sketch of the visual light history of P Cygni.

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It is very likely that the sudden visual brightness changes of P Cygni were due to mass ejection at almost constant luminosity, as is the case for the other S Dor variables. The irregular fadings to below the limit of visibility might be due to the formation of dust during the activity in the seventeenth century. The red color which was observed when the star was bright corroborates this.

Did the outbursts in the seventeenth century leave any remnant? Wendker (1982) has found an arc-like structure around P Cygni at 6 cm with the "head" of the arc pointing in the direction of the proper motion of P Cygni. The diameter of the arc is about 1.2 arc min which corresponds to a diameter of 0.62 pc at $d = 1.8$ kpc. If this is a result of the ejection of AD 1600, the ejection velocity must have been 800 km/s which is very high for the ejection velocity of S Dor outbursts. Their velocities are typically of the order of 50 to 200 km/s. If the ejection velocity is between 50 and 200 km/s, the outburst which might be responsible for the radio arc, should have occurred 1500 to 6000 years ago.

Very recently, van Gent (1985, private communications) has found a letter written by a French astronomer Boulliau to Huygens in 1661 in which he mentions that he has seen P Cygni through the telescope of Hevelius and that P Cygni looks similar to the Orion nebula! If this observation is correct, it might imply that a remnant of the ejection was actually observed about 60 years after the outburst. A drawing of the Orion nebula as seen by Huygens in 1694 through a telescope of 13.4 m focal length (comparable to the one of Hevelius) shows a size of 130" × 230". If a nebulosity around P Cygni had a similar size of, say, 100" in 1661, the expansion velocity would have been 7000 km/s. This velocity is about a factor 10 higher than the one derived from the distance of the present radio arc. This might indicate that the velocity of expansion has slowed down considerably. A historical verification of the observations of P Cygni made in Huygens' time would be extremely interesting!

5.2. Photometric Variations of P Cygni

Apart from the great activity in the seventeenth century, P Cygni is presently an irregular variable with an amplitude of $\Delta V \simeq 0.2$ mag. The photometric periodicities quoted in the literature range from 0.5 days to 18 years! The existence of a true periodicity or the determination of a timescale if the variations are quasi-periodic can give insight into the structure of the star. In a recent paper van Gent and Lamers (1985) have reviewed all the evidence for periodicities in the brightness variations, the radial velocity variations and the polarimetric variations. They conclude that the photometric variations are not periodic but occur on a timescale, τ, between 12 days and 125 days, with a mean characteristic timescale of about 25 days. There is some evidence that the characteristic timescale varies with time; sometimes the Fourier periodograms show peaks near $\tau \simeq 12$ days, at other times the peaks occur near 30 days. The polarimetric observations by Hayes (1985) during 1978/1979 also show evidence of a

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periodicity with $\tau \simeq 12$ days. We can compare this with the expected timescale for non-radial pulsations:

$$P = Q(\bar{\rho}/\bar{\rho}_{\odot})^{-0.5} \quad (5)$$

where the pulsational constant Q is expressed in days. Adopting the parameters of P Cygni from Table II, we find $(\bar{\rho}/\rho_{\odot})^{-0.5} \simeq 105$. The empirical value of Q can be derived from the study of Maeder (1980) who found $Q \simeq 0.16$ for B1 to B3 supergiants. If we take into account the fact that $Q \sim L^{0.27}$ and that P Cygni is about 1.5 mag brighter than normal supergiants, we expect $Q \simeq 0.23$ and $P \simeq 24$ days. The good agreement between the observed characteristic timescale and the one predicted for non-radial pulsations suggests that the photometric variations of P Cygni are due to non-radial pulsations, similar to those in other supergiants.

5.3. Variations in the Mass Loss and Shell Ejections

In addition to the quiescent mass loss rate of $\dot{M} = 2 \times 10^{-5}$ $M_{\odot}$/yr derived from the IR and radio excess and from the Balmer profiles, P Cygni seems to eject shells on timescales of months. This shell-ejection can most easily be observed in the Balmer lines, which show variable absorption components. The first extensive analysis of these shells was made by de Groot (1969) who found three absorption components near -110, -160 and -215 km/s. He suggested that the last component was showing periodic radial velocity variations with a semi-amplitude of 30 km/s and a period of 114 days. Luud et al. (1975) argued that the first component (-110 km/s) was also variable with a period of 57 days, i.e. half the period found by de Groot. A re-analysis of these data by van Gent and Lamers (1985) showed that both periods are spurious.

A very extensive study of the Balmer lines by Markova and Kolka (1984) during 1981 has shown that the absorption components are indeed variable, but not in the way described by de Groot and Luud. They find that at any epoch four absorption components are present in the velocity range of -100 to -250 km/s. (No components are found closer to the line center because of confusion with the core of the photospheric profile.) Each component travels through this velocity range from -100 to about -220 km/s with a mean acceleration of the order of 0.5 km s^{-1}/day or 0.6 cm/s^2. The shells are ejected at a rate of about six shells per year (see Fig. 5).

If we assume that the shells leave the star with an initial velocity of 30 km/s (which is the velocity at the base of the wind of P Cygni) and that the acceleration is constant and 0.6 cm/s^2, we find that they reach their terminal velocity of 220 km/s about 400 days after they were ejected. During that time the shells have reached a distance of $r_{shell} \simeq 90$ R_*. So these shells can be observed in the Balmer components up to a distance of about 10^2 R_*.

Similar shell components have been observed in the UV spectrum of P Cygni by Lamers et al. (1985). They found that the lines of Fe II, Ni II, Cr II etc. have a stationary absorption component at

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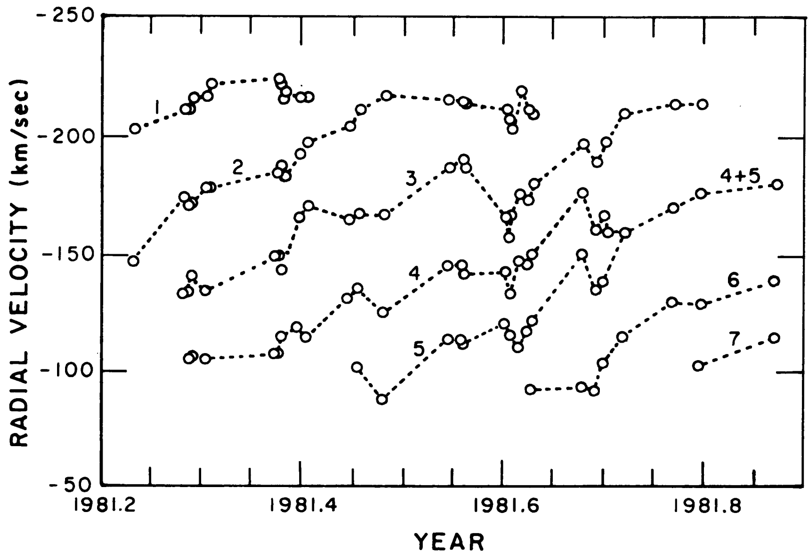

Fig. 5. The velocities of the shell components, observed in the Balmer lines of P Cygni by Markova and Kolka (1984). The average rate of shell ejection is six per year. The mean acceleration of the shells is 0.6 cm/s^2.

v = −206 km/s, which is constant in depth and velocity over a period of at least five years. This component could be due to a massive shell at a distance of at least 1100 R_* with a mass $M_{sh} > 6 \times 10^{-5}$ $M_\odot$. Alternatively, the component at −206 km/s might be due to material in the quiescent wind of P Cygni at a very large distance $r \gtrsim 3000$ R_* which has recombined from Fe III to Fe II. In addition to this stable component, variable components have been observed in the lines of once and twice ionized metals. These variable components increase in radial velocity from −100 to −200 km/s with a mean acceleration of 0.17 cm/s^2. Such variable Fe II and Fe III components are ejected about once per year with a mass of the order of 10^{-5} $M_\odot$.

The shells observed in the UV and in the Balmer lines show the same characteristic of a velocity increase to 200 km/s. The difference is in the recurrence of the shells (about six per year for the Balmer lines and one per year in the metal lines) and the acceleration (0.6 cm/s^2 for the Balmer lines and 0.17 cm/s^2 for the metal lines). I would argue that this is due to the amount of mass in the shell. It is likely that P Cygni ejects shells continuously with different masses. The less massive shells, which can be detected in the Balmer lines only, are accelerated faster than the less frequently ejected, but more massive shells, which can be observed in the metal lines. Until now, no simultaneous study of the shells in Balmer and metal lines has been performed.

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Independent evidence for the ejection of massive shells by P Cygni comes from the variation in the radio flux. Van den Oord et al. (1985) observed a sudden drop in the radio flux of P Cygni by a factor 4 within one month. This timescale is much faster than the timescale in which the extended radio emitting region ($\Delta r \approx 300\ R_*$) can change its density. The timescale for changes in the radio flux due to density changes in the emitting region is $\tau \approx \Delta r/v \approx 300\ R_*/200$ km/s ≈ 2.5 yr. So the observed much faster drop in the radio flux can only be explained by a sudden recombination of the radio emitting region. The recombination timescale in the region where the radio flux is emitted is $\tau_{rec} \approx (\alpha \cdot n_e)^{-1} \approx 1$ month (van den Oord et al., 1985). Why would the wind of P Cygni suddenly recombine? This can only be due to the ejection of a thick shell which temporarily blocks the ionizing flux from the star. I expect that such an ejection would also result in a temporary change in B-V with a duration of about a week.

It is important to monitor photometrically P Cygni with a small telescope with a timescale of days in order to determine the time of the ejections of the shells which are later observed in the Balmer and UV lines or in the radio flux.

The recurrence of the shell ejections observed in the Balmer lines with a characteristic timescale of about 2 months is about twice as long as the timescale of 1 month for the photometric variations. If the star also ejects more shells of lower mass, which may be undetected, the ejection timescale may be shorter and about the same as the photometric timescale, which is probably due to nonradial pulsations. This would suggest that the ejection of shells by P Cygni may be due to nonradial pulsations.

5.4. The Acceleration of the Wind of P Cygni and the Origin of its Mass Loss

The velocity law in the quiescent wind of P Cygni has been determined from Balmer profiles and the IR excess by Van Blerkom (1978) and Waters and Wesselius (1985). They find that the velocity law is linear and goes as

$$v(r) = 0.10\ v_\infty + 0.057\ v_\infty\ \{(r/R_*) - 1\} \quad \text{for} \quad r \lesssim 15\ R_* \qquad (6)$$

with $v_\infty \approx 300$ km/s. From this velocity law we can derive the net outward acceleration which turns out to be only 1 to 3 cm/s^2 at $1 < r < 4\ R_*$. If this is compared with the acceleration due to the gravity, which is $100(R_*/r)^2$ cm/s^2 (Table II), we come to the surprising conclusion that the acceleration in the wind of P Cygni must be due to some force which barely overcomes the gravity and which varies approximately as $(r/R_*)^{-2}$. Lamers (1985) has studied the various processes which might produce such a force. If the force were due to turbulent pressure, which was proposed by de Jager (1984) to explain the mass loss of the hypergiants, the turbulent velocity has to be of the order of 100 km/s. Such a high turbulent velocity is unlikely, as it would exceed the sound velocity by a factor 10. On the other hand, the acceleration can be produced by radiation pressure due to a large

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number (10^3) of weak metal lines in the Balmer continuum. These lines have actually been observed in the IUE spectra of P Cygni (Cassatella et al., 1979; Luud and Sapar, 1980). They produce a blocking of about 40% of the continuum flux in the Balmer continuum.

This strongly suggests that the mass loss from P Cygni is due to radiation pressure by a large number of optically thin lines in the Balmer continuum. Such a mechanism will be effective when a luminous star evolves away from the main sequence and reaches a value of $T_{eff} \lesssim$ 25,000 K, where most of its energy is emitted in the Balmer continuum and the many lines from once or twice ionized metals become effective absorbers. Since the effective gravity decreases with increasing radius as the star evolves away from the main sequence, the mass loss rate is expected to increase very drastically when a very luminous star passes the limit of $T_{eff} \lesssim$ 25,000 K.

5.5. A Summary of the Processes in P Cygni

P Cygni has suffered large outbursts in the seventeenth century. After that time the star has gradually stabilized and is now a B1 Ia^+ PCT star. The star shows irregular brightness variations with $\Delta V \approx$ 0.2 mag. These seem to occur on different timescales between 12 and 125 days with a mean value of about 25 days. This suggests that the star is nonradially pulsating. In addition to the steady mass loss, P Cygni ejects shells at intervals of about 2 months or less. The most massive shells are observed as absorption components in many UV metal lines, the less massive shells are observed in the Balmer lines only. It is possible that the shell ejection is related to the photometric variability and thus to the nonradial pulsations. There is a correlation between the mass of the shells and their acceleration: the most massive shells (observed in the UV) have the lowest acceleration, the less massive shells (observed in the Balmer lines) have a higher acceleration. The quiescent wind is accelerated faster than the shells, but considerably slower than the less dense winds of normal supergiants.

The acceleration of the wind can be explained by radiation pressure due to metal lines in the Balmer continuum. It is likely that this same mechanism is responsible for the high mass loss rate in PCT stars.

6. THE NATURE AND ORIGIN OF THE P CYGNI TYPE PHENOMENON

After having discussed the general properties of the PCT stars and the physical processes in one of them we may combine this information and try to form a coherent picture.

The presence of the P Cygni profiles in the visual spectrum implies that the high mass loss rate and a rather low wind velocity. In comparison with normal supergiants of type Ia the mass loss rate of the PCT stars about 3 to 10 times higher for their luminosity, the wind velocity is about 0.10 times lower, and the density at 2 R_* is 30 times higher (Fig. 3). This high density is responsible for the occurrence of the P Cygni lines in the visual spectrum.

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Which mechanism produces the high mass loss rate and the low velocity, which together give rise to the high density? I suspect that this is due to the combination of two effects: the low gravity and the radiation pressure due to metal lines in the Balmer continuum. If a massive star evolves beyond the hydrogen core-burning phase it will expand. The surface gravity will decrease as R_*^{-2}, but since the luminosity remains about constant, the effective gravity decreases faster than R_*^{-2}. This by itself would produce an extended atmosphere. Other effects, such as turbulent pressure (proposed by de Jager, 1984) or rotation might make the atmosphere even more extended, although this may not be a necessary condition. At the same time the expansion of the star will result in a decrease of T_{eff}. When T_{eff} reaches a value below about 25,000 K, the radiation pressure will increase due to the fact that the many metal lines in the Balmer continuum (where most of the stellar flux is emitted) become efficient absorbers. This will result in an increase in the mass loss rate and a decrease of the wind velocity, since $\dot{M}v_\infty$ is approximately proportional to L/c and L remains constant. The net effect is a drastic increase in the density of the wind. I expect that this will develop into a new equilibrium for a stationary wind, where the mass loss and the acceleration are both due to radiation pressure in the Balmer continuum. The data in Table II suggest that this mechanism will work for stars which have $g_{eff} \lesssim 10^2$ cm/s^2 and $L \gtrsim 10^5\ L_\odot$.

This mechanism will be operating only in the luminous stars. If $L \sim M^2 \sim R^2 T_{eff}^4$ and the stars evolve at about constant L, the gravity of a star will vary as $g \sim T_{eff}^4/M$ and the correction due to the electron scattering will vary as $1-\Gamma$ with $\Gamma \sim L/M \sim M$. So for a given value of T_{eff} the effective gravity decreases faster than M^{-1}.

The mass loss mechanism which I have proposed here will result in a high but steady mass loss, as observed, e.g., in the quiescent phase of P Cygni. However, it cannot be stable over a long timescale. As the star keeps expanding, its g_{eff} will rapidly go to zero and may even become negative. This would result in a sudden ejection of its complete atmosphere. Maeder (1983) and Humphreys and Davidson (1984) have proposed that such a sudden mass loss at the instability limit may result in the ejection of a considerable amount of mass, so that the star "recoils" from this limit and quietly evolves into this limit again. This might explain the multiple outbursts of the PCT stars.

If the recoil interpretation is correct, we would expect that after a more violent outburst (larger amount of mass ejected) the star will remain quiet for a longer time. The long period of quiescence of P Cygni (apart from the recurrent shell ejections) after the violent outbursts in the seventeenth century may be indicative of such a correlation.

It is interesting to realize that the mechanism for the mass loss from P Cygni stars, i.e. radiation pressure due to metal lines, proposed by Lamers (1985), is the same as proposed independently by Appenzeller (these proceedings) to explain the variability in the S Dor stars.

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7. THE EVOLUTION OF THE P CYGNI TYPE STARS

The PCT stars are luminous stars, with $-7.8 \lesssim M_{bol} \lesssim -11.0$. The luminosities of the two faintest stars in Table II are very uncertain and may have been underestimated. For AG Car the temperature was probably underestimated and for AE And the extinction is uncertain and lower than that of the other PCT stars in M31. If we omit these two stars, we find $-8.9 \lesssim M_{bol} \lesssim -11.0$ for the PCT stars. This lower limit agrees very well with the lower limit of $M_{bol} = -8.9$ for the emission line stars in the LMC (van Genderen et al., 1983).

The masses of the PCT stars are estimated to be in the range of $21 < M < 78\ M_\odot$, if we ignore the two lowest luminosity stars. These are present masses. These masses were derived from the evolutionary tracks of Doom (1982). The initial masses of the PCT stars are related to the adopted masses as

$$M_{initial} \simeq 1.32\ M_{adopted}$$

so the initial masses of the PCT stars are $28 \lesssim M_{init} \lesssim 100\ M_\odot$.

The PCT stars are clearly in their post-main-sequence phase. The most compelling evidence of this is the indication that several of these objects have an overabundance of N and an underabundance of C and O. Examples are P Cygni (de Groot, 1969), AG Car (Viotti et al., 1984). S Dor (Leitherer et al., 1985) and R127 which has also been classified at one phase as WN9-10 (Walborn, 1982). Such an abundance pattern is expected to occur when the products of the CNO-cycle of hydrogen burning reach the stellar surface. This implies that the PCT stars are intermediate between the main-sequence and the Wolf-Rayet phase.

Since the PCT stars are near the Humphreys-Davidson upper limit for the luminous stars, they must be located in he HRD at the region where the post-main-sequence evolutionary tracks stop their redward motion and return to the left to become Wolf-Rayet stars (Humphreys and Davidson, 1979; Maeder, 1983). A massive star can become a WR star if it has got rid of 30% of its initial mass (Doom, 1982). During the hydrogen core burning phase the star may lose about 15% cent of its initial mass (Lamers, 1981) so about 15% has to be lost during the PCT phase.

The duration of the PCT phase can be estimated as the time needed to lose 15% of the initial mass

$$\tau_{PCT} \simeq 0.15\ M_{init}/\langle\dot{M}\rangle_{PCT} \quad . \tag{7}$$

What is the average mass loss rate in the PCT phase? Let us take the star P Cygni as an example. It loses mass on three different time-scales, given below.

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Process	Mass Loss ($M_\odot$)	Recurrence (yr)	dM/dt ($M_\odot$/yr)
Violent Outbursts	10^{-3}–10^{-1}	10^2–10^3	10^{-6}–10^{-3}
Shell Ejections	10^{-6}–10^{-5}	0.2	5×10^{-6}– 5×10^{-5}
Quiescent Mass Loss	---	---	2×10^{-5}
			$\langle\dot{M}\rangle = 3 \times 10^{-5}$–$10^{-3}$

These values are very uncertain, especially those of the violent outbursts. Taking a mean of 10^{-3} to 10^{-4} $M_\odot$/yr and $M_{init} = 53$ $M_\odot$ we find $\tau_{PCT} \approx 10^4$–10^5 yr. This is about 0.3 to 3% of the main-sequence lifetime.

8. UNRESOLVED PROBLEMS AND FUTURE WORK

The most important problem to be solved is the exact location of the PCT stars in the HR diagram (accurate T_{eff} and L determinations). The data in Figure 1 and in van Genderen et al. (1983) suggest that they are near the Humphreys-Davidson limit. However, they do not seem to be the only stars in that region (see e.g. the preliminary study by Bohannan in these proceedings). What is the difference between the PCT stars and the more normal super- or hypergiants in the same region of the HR diagram? Are the hypergiants, such as ζ^1Sco and Cyg OB2 Nr. 12 with $M_{bol} \lesssim -10$, also PCT stars which are presently in a long quiescent phase or is there an evolutionary difference, in the sense that the PCT stars are more evolved? Since the luminous stars may spend about 10^4 to 10^5 yr in the vicinity of the instability limit, the region near this limit may contain "freshmen," which are just entering the PCT phase and show little or no PCT characteristics, and "veterans" showing well-developed PCT characteristics (because of their lower g_{eff}) and the scars of their mass loss (increased N-abundance at the surface).

Abundance studies of PCT stars and their ejecta, such as the ring nebula around AG Car (Thackeray, 1974; Viotti et al., 1984), are needed to give critical tests of the evolution theory. Is the CNO abundance in PCT stars different from those of other stars in the same region of the HRD? This would indicate that the PCT stars are more evolved.

How much mass does a PCT star or S Dor star lose during its outbursts? This is important for estimating the lifetimes of the PCT stars. In addition we should estimate the lifetime on the basis of stellar statistics. The LMC seems to be the most suitable system for this.

What is the lower limit for the luminosity or mass of the PCT stars? If the PCT stars occur at $M_{bol} \gtrsim -9.5$ (the upper limit for the

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red supergiants), their outbursts are not sufficient to prevent the star from becoming a red supergiant, unless these PCT stars are different from other stars at that luminosity. Rotation might play an important role in this evolution (Sreenivasan and Wilson, 1982). What is the minimum mass loss rate in the post main-sequence phase which prevents a star from becoming a red supergiant? Are the observed mass loss rates for stars with $M_{init} \gtrsim 50\ M_\odot$ sufficiently large?

What is the reason for the high mass loss rate and the instability near the Humphreys-Davidson limit? Turbulent pressure was suggested by de Jager (1984) and radiation pressure on metal lines in the Balmer continuum was proposed to explain the quiescent high mass loss (Lamers, 1985) and the S Dor type outbursts (Appenzeller, these proceedings). Stothers and Chin (1983) have investigated various other mechanisms.

What is the reason for the shell-ejections in P Cygni and how much mass is ejected? Is this related to nonradial pulsations of the star? To answer these questions a spectroscopic and photometric monitoring of a few bright PCT stars on a timescale of a few days is urgently needed.

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Discussion : LAMERS.

DE JAGER :

In your talk you ascribed the cause of the wind of P Cyg to radiation pressure by the many UV absorption lines. I would rather believe that these lines, visible in the wind spectrum, cause the acceleration, as you actually suggested yourself. I believe there are strong arguments that the cause of the wind is seated in the photosphere and related to shock-driven mass loss initiated by the fact that $g_{eff} < 0$. As shown in Nieuwenhuijzen's and my contribution to these Proceedings : the assumption $g_{eff} = 0$ allows one to calculate the necessary mechanical flux; this appears first to be sufficient to cause photospheric supersonic microturbulence, and secondly, if one assumes that the energy of the mechanical flux is transformed into stellar wind energy one finds the observed rate of mass loss. Radiation acceleration by lines, on the other hand, may not work in the photosphere, which is optically thick in the continuum.

LAMERS :

It is true that my analysis of P Cygni only gives information about the acceleration in the wind. However, if the multitude of faint lines in the Balmer continuum act as a "pseudo-continuum in the wind", they might do the same in the photosphere. In that case the radiation pressure will produce a low effective gravity in the photosphere ($g_{eff} \geq 0$). This, together with the larger radiation pressure in the layers above the photosphere (because the degree of ionization is decreasing outwards) will initiate and accelerate the mass loss.

If the turbulent pressure gradient is large, this may certainly help the initiation of the wind, but whether turbulent pressure alone is responsible for the initiatiion of the wind remains to be seen.

WOLF :

You said P Cygni stars are B or A supergiants. The only "A star" in your list, however, is R66. By fitting the continuum from the satellite UV to the IR, however, we could show that this star is of type B as well. The A type spectrum is the equivalent spectral type of the cooler envelope (see also the contribution by Zickgraf et al., this volume).

LAMERS :

So it may be that the P Cygni stars are always of spectral type B. In that case, most of them, or possibly all of them, are of spectral type early-B. If this is true, it suggests that the mechanism which produces the large mass loss rates, characteristic for the P Cygni stars, is effective in a small temperature regime around T_{eff} - 20,000 K. The proposed mechanism of pseudo-continuum radiation pressure might explain this.

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MELNICK :

Your interpretation of the Humphreys-Davidson-de Jager limit predicts that very low metallicity galaxies should contain no P Cygni S Dor or in general, Hubble Sandage variables. Is that the case for the SMC?

LAMERS :

There are only three known HS variables in the LMC and none in the SMC.

VIOTTI :

FeII is indeed the most important ion for line opacity in the UV of P Cyg and in Hubble-Sandage variables in other galaxies. The contribution is however difficult to evaluate because most lines are saturated and weak. High excitation energy lines might give an important contribution. One should try to compute line formation in stellar winds, and derive synthetic spectra. We indeed find a strong UV opacity from FeII in many galactic and MC stars. Concerning the light history of P Cygni, if you assume for the 1600 maximum a bolometric correction near zero - i.e. a cooler blackbody distribution - you get nearly the same M_{bol} as at the present times. This again pushes in favour of a variability at constant bolometric luminosity over a period of 300 years, without "outburst" events.

LAMERS :

I agree with your suggestion that the luminosity of P Cyg may have been the same during the AD 1600 mass ejection as it is now. The early observers of the seventeenth century call P Cygni a "red" star.

As far as the radiation pressure due to FeII lines is concerned, I have estimated this effect in P Cygni by measuring the observed lines. I agree that a theoretical study of this nature is needed, but difficult.

STALIO :

How reliable is the estimate of g, and what could be that effect of 10 - 20% error in g on your model of the mass loss mechanism?

LAMERS :

The gravity is indeed uncertain, since we have adopted the mass of P Cygni based on evolutionary tracks. This gives an uncertainty of about a factor two in mass and gravity. But even with this uncertainty, the effective gravity of P Cygni is about a factor 10 to 30 smaller than of normal B supergiants. Whether the uncertainty of a factor two will make the proposed origin of the mass ejection impossible is hard to say

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at present. We need better quantitative models to test these suggestions.

KONTIZAS :

How could we explain the high number of narrow UV components in P Cygni stars compared to the Be stars?

LAMERS :

I think that this is due to the small acceleration in the P Cygni stars. If a B supergiant would eject a shell every two months, each one would have become invisible because of its large distance to the star. In a P Cygni star, however, the velocity and the acceleration is so small that the shells travel a much smaller distance in 2 months. So one will be able to see more of the previous shells when new ones are ejected in P Cygni. In addition to this, the shells ejected by P Cygni may be more massive than those in other B supergiants, but this is not very well known at present.

KUDRITZKI :

You know that in my talk I claimed that the improved radiation wind theory can explain the mass loss rate and v_{inf} of P Cygni. What is your opinion of this?

LAMERS :

It is true that a reduction of the gravity increases the mass loss rate and decreases v_{inf} in the framework of the radiation driven wind theory of Castor et al. (1975) and Abbott (1982). However, in P Cygni another effect comes into view : if the mass loss rate is large, the ionization in the wind decreases to FeII, NiII etc, which can absorb very efficiently in the Balmer continuum. For this reason, I think that the effect of lowering the gravity is even more severe than in your calculations. You predicted v_{inf} = 600 km/s, whereas the observed value is between 200 and 300 km/s.

MAEDER :

There is some empirical relation between the characteristic time of supergiant pulsation, luminosity and colour (P-L-C relation). Do you have anything similar for the P Cygni stars? I especially think of the timescale between two successive shell ejections.

DE GROOT :

I want to make two remarks. The first one relates to Maeder's question. Taking a 114-day time scale, I found that this fits the P-L-C

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relation for early-type supergiants quite well. Lamers has just reduced this time scale to 60 days (six shells per year). In view of the uncertainties involved, this is still a reasonable agreement.

My second remark concerns the time scale of the P Cygni phenomenon. The P Cygni phase depends on the presence of hydrogen in the star's atmosphere. For a P Cygni-type star this is between 20 and 60 M_o. Since mass loss, including major outbursts every 100 to 1000 years, is about 10^{-3} M_o/yr, the P Cygni phase lasts between 2×10^4 and 6×10^4 years. Furthermore, in the LMC the P Cygni stars number about 20% of all B-type supergiants. Thus, a B-type supergiant will spend between 10^5 and 3×10^5 years off the main-sequence. This figure agrees reasonably well with Maeder's (1983) evolutionary calculations.

MOFFAT :

Since about half of all stars are in binaries and the fact that no P Cyg star shows strict periodic variations could lead one to conclude that P Cyg stars are preferentially single stars.

LAMERS :

I agree.

APPENZELLER :

I would like to comment on the range of luminosities at which P Cyg stars seems to be observed. Regardless of whether the mass loss is driven by turbulent pressure or radiation pressure, the acceleration will be influenced by the chemical composition. Hence, the mass loss rate should depend on L, Teff, and Z, which perhaps explains the scatter of the location of P Cyg stars in the HR diagram.

LAMERS :

I agree with you. However, what worries me is the fact that Bohannan et al. (these proceedings) from spectroscopic observations find a large scatter in L of the LMC P Cygni stars, whereas van Genderen (1983) from Walraven photometric observations found that the P Cygni stars in the LMC show a clear relation between L and Teff, and follow the Humphreys-Davidson limit quite nicely.

BOHANNAN :

Henny, I would not lose any sleep over the difference between my H-R diagram for the LMC P Cygni-like stars and that of van Genderen . The difference probably lies in making the transformation between the domain of observation and of theory, the calibration of temperature and bolometric correction with spectral type. Until we do profile analyses to measure Teff and log g, there will be significant uncertainty in locating these stars in the M_{bol}-Teff diagram. The uncertainty is much larger if the temperature is derived from photometry.

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