H. Acknowledgments

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V. INTRINSIC VARIABILITY IN ULTRAVIOLET SPECTRA OF EARLY-TYPE STARS: THE DISCRETE ABSORPTION LINES*

A. Introduction

The long missions of the Copernicus and IUE satellites made it possible to monitor ultraviolet spectra of early-type stars on time scales from less than 1 hour to many years. Intrinsic variability (i.e., not due to binary effects) is frequently found in the resonance lines of O VI (1032, 1038 Å), Si III (1207 Å), N V (1239, 1243 Å), Si IV (1394, 1403 Å), C IV (1548, 1551 Å), A1 III (1855, 1863 Å), the nonresonance line of C III (1176 Å), etc. (i.e., spectral lines that indicate the presence of a stellar wind). Like most stars across the HR diagram, early-type stars are thought to lose mass in the form of a stellar wind. Determining mass loss on the basis of spectral line shapes is therefore one of the main tasks of the ultraviolet spectroscopists. (Of course, other methods are also available.)

To assist in this task, theoreticians have been developing models for stellar winds and their structure. This enables a prediction to be made for a specific spectral line shape, depending on the stellar-wind structure parameters such as mass-loss rate, velocity, density and ionization structure, presence of X rays, etc. A comparison of predicted and observed line profiles then gives numerical values for the desired parameters.

In theoretical models, however, the basic assumption is usually made that the stellar-wind structure is time-independent. (For a recent review, see, for example, Abbott, 1985.) On the other hand, it has become obvious from the steadily accumulating UV data that the majority of spectral lines that are stellar-wind indicators are, to some level, variable on all time scales—in some cases even as short as ½ hour (i.e., comparable to a typical flow time scale of a stellar wind (defined as the stellar radius divided by the observed radial velocity)). Of particular concern is the interpretation of the (generally) blue-shifted "discrete absorption components." These are also frequently called narrow components, narrow lines, shifted narrow components, etc. (narrow to emphasize the contrast to the often-observed broad underlying P Cygni profile). In fact, the best description is "unexpected" absorption. In most cases, the components are narrow and/or shifted, but not always. This is why we refer to the phenomenon in general as "discrete" absorption components. These spectral features are beyond any doubt identified as mostly resonance transitions of abundant ions that are indicators of mass outflow. The most well-known example is given by Morton (1976), who observed the N V doublet in ζ Oph, O9.5 V(e), with the Copernicus satellite (Figure 4-30). Both members of this doublet are found at their correct relative position, as well as relative strength, but are observed to be blue-shifted corresponding to 1400 km/s, whereas the width is only 200 km/s. The earliest UV spectrum of ζ Oph (recorded around 1968 by Smith, 1972) shows essentially the same features. Other early examples may be found in Underhill (1975).
In a survey to detect mass outflow, Snow and Morton (1976) discovered discrete absorptions in many other stars (ς Pup, O4 I(n)f; 15 Mon, O7 V((f)); λ Ori, O8 III((f)); ρ Leo, B1 Iab; ξ Per, O7.5 III(n)((f)); etc.). These stars appear to be superimposed on the blue absorption wing of a P Cygni profile. The first systematic investigation of their presence (i.e., without studying variability) was presented by Lamers et al. (1982), who found 17 stars with high-velocity discrete absorptions in a sample of 26 OB (non-Be) stars, which indicated that this phenomenon is rather common in such stars. Lamers et al. noticed an important property in their sample: if the discrete components in a given spectrum are found in different ions, they always show the same velocity, and this velocity is in all cases less than the terminal velocity of the wind (being identified with the steep blue edge of saturated profiles of other P Cygni lines when available). (See Figure 4-34c for a clear example.)

The discrete absorption lines have also been discovered in a number of Be stars (γ Cas, B0.5 IVe (Hammerschlag-Hensberge, 1979); 59 Cyg, B1 Ve (Doazan et al., 1980); ω Ori, B2 IIIe (Peters, 1982b); etc.) as well as in some sub-dwarfs (e.g., HD 128220B sdO (Hamann et al., 1981; Bruhweller and Dean, 1983). In the case of Be stars, it is well known that the P Cygni lines are not well developed (in the sense that the emission is absent), and the discrete components are superposed on the asymmetric absorption wings. Multiple absorption components are frequently found with different velocity and strength (e.g., 59 Cyg, γ Cas, ω Ori, 66 Oph, and HD 128220B). A detailed summary of observed properties is given in Section C.

Connected with the presence of the discrete components is the issue of their variability. Typical examples are collected in Figure 4-34. (See also Figure 4-44.) As mentioned previously, the observed time scales can be as short as a 1/2 hour. In some cases, particularly the less luminous Be stars (i.e., with later spectral type), the entire absorption profile is variable and may sometimes disappear (e.g., θ CrB, B6 IIIe (Doazan et al., 1984)). (See also Figure 4-34g.) In this case, we need two time scales to describe the variability: (1) the short time scale which characterizes the variations in a given discrete component, and (2) a much longer time scale which characterizes the activity level, where
"active" indicates the presence of the (variable) discrete components.

Quite a few explanations for the origin of these lines, which are definitively formed somewhere in the expanding stellar wind, have been proposed during the past 10 years. None of these explanations appears to be accepted by the different investigators. The main concern is to explain the observed variability of the discrete absorptions. The pioneering work by Snow (1977) contains the first systematic study of the variable character of UV spectra of early-type stars. Snow found in many of his 17 stars conspicuous changes over a few years, mostly in strength of the high-velocity components, although some changes in velocity were also observed. His sample contained O I-V stars and a few B supergiants. Many reports on variable UV lines in OB stars have appeared. (See for example, Snow (1979), Underhill and Doazan (1982), Marlborough (1982), and Henrichs (1984).) A more recent compilation appears in Section D.

The first systematic investigation of the discrete high-velocity absorption lines in one particular star was made by Henrichs et al. (1980, 1982, 1983) for γ Cas, B0.5 I Ve. Drastic changes both in strength (Figure 4-31) and in velocity of narrow features were observed in the majority of 28 high-resolution IUE spectra. The time scales involved varied between 1 week and 1 month. A remarkable "memory" in the star, γ Cas, has been found in the sense that, when the discrete absorption lines were strong, they were found at a systematically lower velocity than when they were weak, even though they sometimes completely disappeared between such different episodes. (This "memory" of this star did not appear to hold over more than 5 years (Doazan, private communication).) Henrichs et al. (1983) proposed that the time scale involved for the appearance of the narrow absorption lines might, in fact, be of the order of hours. In addition, they gave arguments that this behavior might not be unique for this single Be star, but in fact, would be representative for all early-type stars. An actual recording of such an "appearance" event has been looked for and observed in ξ Per, O7.5 III(n)((f)). (See Section D.) Since then, more systematic surveys concentrating on multiple spectra of a number of stars have been carried out. The most important survey study is the paper by Prinja and Howarth (1986), which contains a detailed analysis of available ultraviolet IUE spectra of more than 20 OB stars and draws systematic conclusions. (See Section C.)

Although this review is supposed to be concerned mainly with O stars, it will be obvious to the reader that the nature of the UV variability is such that we must inevitably include information about B and Be stars.

Motivated by these considerations, we devote the present review to the following topics:

(a) Statistics: In what fraction of early-type stars are discrete UV absorptions found
and is their occurrence possibly related to spectral type, luminosity, rotation, Be characteristics, etc.? It will appear that, generally speaking, more than 60 percent of all OB stars show discrete absorptions at high velocity, whereas there is strong evidence that the discrete absorptions are, in fact, always variable. The fraction must be considered as a conservative lower limit. Another major conclusion is that, among the less luminous B stars, only Be stars show discrete components, in contrast to "normal" B stars, in which not much (if any) variability has been seen.

(b) **Variability:** A wide range in time scales of observed variations in both velocity and strength has been observed. We shall present significant examples of such variability on time scales as short as 1/2 hour, comparable to a typical flow time scale of stellar winds. A second, much longer, time scale is needed to describe the presence of discrete components in Be stars.

(c) **Models:** A short description of current models will be given. At present, none of them is capable of explaining all the observed properties of the variable discrete absorption components. However, some models explain reasonably well the general behavior of these lines in a few particular stars. No clear conclusion can be drawn about the origin of this phenomenon, although interesting suggestions have been made.

(d) **Related Observations of Interest:** High signal-to-noise optical spectroscopy has revealed that many early-type stars are in fact nonradial pulsators with varying amplitude and/or, to a lesser extent, modes. In a few cases, a correlation between variability in pulsation behavior and UV line profiles has been observed. This is a new and promising area in which only a first step has been made.

In summary, at present, it is at least the author's belief that the understanding of the line-profile variability is crucial for understanding the structure of the stellar winds of early-type stars generally, as well as for comprehending the unexplained Be phenomenon, a viewpoint which was a few years ago perhaps not as widely shared. The reader is referred to the book on B and Be stars (Underhill and Doazan, 1982) for earlier views regarding this matter.

Any realistic model describing stellar-wind structure must account for the observed time-dependent character. It is well recognized that stability analyses of stellar winds driven by radiation pressure, which is generally accepted to be the major driving mechanism in early-type stars, have shown that such flows are unstable against several kinds of perturbations. (See also Section E.) None of these models, however, can predict or even describe the behavior of the discrete absorptions as a function of time. For this reason, the major emphasis of this review is on the observational facts.

**B. Statistics**

The first question which must be addressed is: How common is the presence of discrete absorption components in the UV spectra of early-type stars? We shall see that they occur in all kinds of early-type stars, not specifically in "peculiar" stars, and that the observational evidence indicates that in fact encountering discrete absorption components is the rule rather than the exception. Another evident question is whether known physical properties of stars might be related to the occurrence of discrete absorptions.

Profiles of resonance lines in the UV spectra of many early-type stars can be found in the literature, much of which was published for the purpose of determining mass-loss rates and for showing variability. Major systematic surveys for the presence of narrow absorption lines are presented by Snow and Morton (1976, 47 stars),
Snow (1977, 17 stars), Lamers et al. (1982, 26 stars) and Abbott et al. (1982, 53 stars), all of which are based on Copernicus spectra. Lamers et al. (1982) found discrete absorptions in 17 of 26 OB (non-Be) stars. Garmay (1982) collected data on 45 luminous spectra. The most detailed analysis has been made by Prinja and Howarth (1986) on 21 stars (again, no Be stars).

Recently Henrichs and Wakker (1987) analyzed published data of both the Copernicus and the IUE satellites (including many spectra from the IUE data bank). The resulting sample of 241 stars was examined for the presence of discrete absorption lines, and possible ways that properties of these lines might depend on a number of stellar parameters were investigated. Grady et al. (1987b) studied 62 Be stars and 45 normal B stars. Results of these studies will be summarized later. It should be stressed that detailed studies of individual stars indicate that the features are always variable.

1. Distribution in the HR Diagram. We summarize here the main results of Henrichs and Wakker (1987), whose work incorporates earlier results. Their sample consists of stars of spectral type O3 to B7 with luminosity class I to V, including Oe, Be, and a few subdwarf stars. Most of the information exists on the N V, Si IV, and C IV doublets. A star was adopted in the survey only when at least two of these doublets had been inspected. In view of the transient character of the discrete absorption lines, all available spectra were scanned for their presence. A common property of occurring at the same velocity in different ions aided the identification. If the presence of discrete absorptions could be established with confidence in at least one spectrum, the star was classified as "yes," otherwise as "no"; 16 stars (of 241) were discarded because their resonance lines were heavily saturated P Cygni profiles, making identification impossible. Table 4-6 gives a number of representative examples of stars in which (variable) discrete absorptions have been encountered, together with information on velocity and occurrence.

The results are summarized in a theoretical HR diagram with $M_{bol}$ against log $T_{eff}$ (Figure 4-32).

Special emphasis is given to Be stars. Some Be stars are classified as "yes" only because of their strong transient character (mainly in C IV). Comparison of detailed studies of individual stars, however, strongly suggests that we are dealing with the same phenomenon. For example, in spite of the many UV spectra of 59 Cyg, which show high-velocity absorptions with very irregular shapes (e.g., Doazan in Underhill and Doazan, 1982, p. 397), some of the spectra of this star strongly resemble the regular shapes of those in $\gamma$ Cas as in Figure 4-31 (e.g., Figure 8b in Doazan et al. (1985)). Of the 225 stars without saturated lines, positive evidence for discrete absorption features has been found in 118 stars. We must bear in mind, however, that this number must be regarded as a lower limit because of the transient nature of the lines, especially in the Be stars. For example, at least 50 IUE spectra of $\gamma$ Cas give no indication of narrow absorptions!

From the distribution in the HR diagram, a number of very significant quantitative results can be concluded:

(a) Among stars brighter than about $M_{bol} = -7$, discrete absorptions are observed at least once in 65 percent of the sample of about 150 stars, counting only those with unsaturated P Cygni profiles, regardless of their effective temperature. There is strong evidence that essentially all supergiants (luminosity class Ia, Iab, and Ib) earlier than B1 show discrete absorption components. In the sample of these bright stars, the occurrence of discrete absorption lines is not correlated with Walborn's "f" or "n" classification, stellar radius, $V$ sin $i$, rotation period, or binarity, nor is it correlated with a reported presence or absence of H\alpha or X-ray emission for a given star (i.e., the same ratio yes to no is found among the known H\alpha or X-ray emitters). However, these two types of
Table 4-6
Well-Known Examples of O, sdO, B, and Be Stars Showing Variable Discrete Absorptions*

<table>
<thead>
<tr>
<th>Name</th>
<th>HD</th>
<th>Spectral Type</th>
<th>Lines Showing Discrete Components</th>
<th>Typical Velocity (km/s)</th>
<th>References on Variability**</th>
</tr>
</thead>
<tbody>
<tr>
<td>ξ Pup</td>
<td>66811</td>
<td>O4 I1nI1f</td>
<td>Si IV</td>
<td>-2200</td>
<td>8,20,21,22,24,29,30</td>
</tr>
<tr>
<td></td>
<td>199579</td>
<td>O6 V(iff)</td>
<td>N V</td>
<td>-2300</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>167771</td>
<td>O7 III(Iv)(ifl)</td>
<td>N V, Si IV</td>
<td>-2400</td>
<td>21</td>
</tr>
<tr>
<td>15 Mon</td>
<td>47839</td>
<td>O7 V(iff)</td>
<td>N V, C IV</td>
<td>-1900</td>
<td>10,21,22</td>
</tr>
<tr>
<td></td>
<td>48099</td>
<td>O7 V</td>
<td>N V, C IV</td>
<td>-2800</td>
<td>21</td>
</tr>
<tr>
<td>ξ Per</td>
<td>24912</td>
<td>O7.5 III(n)(ifl)</td>
<td>Si IV</td>
<td>-2200</td>
<td>19,21,22</td>
</tr>
<tr>
<td>δ Cir</td>
<td>135240</td>
<td>O7.5 III(iff)</td>
<td>N V, C IV</td>
<td>-2200</td>
<td>21</td>
</tr>
<tr>
<td>λ Ori A</td>
<td>36861</td>
<td>O8 III(f1)</td>
<td>N V, C IV</td>
<td>-2000</td>
<td>7,21,22</td>
</tr>
<tr>
<td></td>
<td>47129</td>
<td>O8p</td>
<td>N V, C IV</td>
<td>-2200</td>
<td>21</td>
</tr>
<tr>
<td>τ CMa</td>
<td>57061</td>
<td>O9 II</td>
<td>N V, Si IV</td>
<td>-2000</td>
<td>21</td>
</tr>
<tr>
<td>ε Ori</td>
<td>37043</td>
<td>O9 III</td>
<td>N V, C IV</td>
<td>-2000</td>
<td>10,21,22,30</td>
</tr>
<tr>
<td>10 Lac</td>
<td>93521</td>
<td>O9 Vp</td>
<td>N V, Si IV</td>
<td>-150</td>
<td>21</td>
</tr>
<tr>
<td>α Cam</td>
<td>30614</td>
<td>O9.5 Ia</td>
<td>N V</td>
<td>-1100</td>
<td>21</td>
</tr>
<tr>
<td>δ Ori A</td>
<td>36486</td>
<td>O9.5 II</td>
<td>N V, Si IV, C IV</td>
<td>-1800</td>
<td>10,21,22,23,30</td>
</tr>
<tr>
<td>ζ Oph</td>
<td>149757</td>
<td>O9.5 Ve</td>
<td>N V, C IV</td>
<td>-1400</td>
<td>14,21,22</td>
</tr>
<tr>
<td>µ Nor</td>
<td>149038</td>
<td>O9.7 Iab</td>
<td>N V, Si IV</td>
<td>-1700</td>
<td>21</td>
</tr>
<tr>
<td>α Ori</td>
<td>37742</td>
<td>O9.7 Iab</td>
<td>NV</td>
<td>-1600</td>
<td>21,22</td>
</tr>
<tr>
<td>128220</td>
<td>sd09</td>
<td>O9 V</td>
<td>N V, Si IV</td>
<td>-600</td>
<td>2</td>
</tr>
<tr>
<td>V851 Sco</td>
<td>37128</td>
<td>B0 la</td>
<td>N V, Si IV</td>
<td>-1700</td>
<td>3,21</td>
</tr>
<tr>
<td>x Ori</td>
<td>152667</td>
<td>B0 la(II)</td>
<td>N V, C I, Si IV, Al III, Fe III</td>
<td>-600</td>
<td>13</td>
</tr>
<tr>
<td>γ Cas</td>
<td>5394</td>
<td>B0.5 Ia</td>
<td>N V, Si IV, C IV</td>
<td>-1400</td>
<td>3,21,22,27</td>
</tr>
<tr>
<td>HR 285</td>
<td>58978</td>
<td>B0.5 IVe</td>
<td>N V, C IV</td>
<td>-1400</td>
<td>12</td>
</tr>
<tr>
<td>ρ Leo</td>
<td>91316</td>
<td>B1 Iab</td>
<td>N V, Si IV, C IV</td>
<td>-200</td>
<td>18</td>
</tr>
<tr>
<td>ρ Ara</td>
<td>157246</td>
<td>B1 Ia</td>
<td>N V, Si IV</td>
<td>-500</td>
<td>21,22</td>
</tr>
<tr>
<td>59 Cyg</td>
<td>200120</td>
<td>B1 Ve</td>
<td>N V, Cl V</td>
<td>-750</td>
<td>4,6,9,15</td>
</tr>
<tr>
<td>ω Ori</td>
<td>37490</td>
<td>B2 Ille</td>
<td>Si III, Si IV, C IV</td>
<td>-850</td>
<td>16,17,26</td>
</tr>
<tr>
<td>λ Eri</td>
<td>33328</td>
<td>B2 III(e)p</td>
<td>C IV</td>
<td>-1000</td>
<td>1</td>
</tr>
<tr>
<td>δ Cen</td>
<td>105435</td>
<td>B2 IVe</td>
<td>Si III</td>
<td>-700</td>
<td>25</td>
</tr>
<tr>
<td>66 Oph</td>
<td>164284</td>
<td>N2 IV-Ve</td>
<td>Si III, Si, C IV, C IV, Al III</td>
<td>-500</td>
<td>1,11,17,18</td>
</tr>
<tr>
<td>6 Cep</td>
<td>203467</td>
<td>B2.5 Ve</td>
<td>C IV</td>
<td>-400</td>
<td>1</td>
</tr>
<tr>
<td>105 Tau</td>
<td>32991</td>
<td>B3 Ve</td>
<td>C IV</td>
<td>-500</td>
<td>1</td>
</tr>
<tr>
<td>192685</td>
<td>B3 Ve</td>
<td>C IV</td>
<td>-500</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HR 7739</td>
<td>138749</td>
<td>B6 III</td>
<td>Si IV, C IV, Al III</td>
<td>-100</td>
<td>5,7,28</td>
</tr>
</tbody>
</table>

Figure 4-32. A theoretical HR diagram with the position of 241 stars searched for the presence of high-velocity discrete components in C IV, Si IV, and N V (Henrichs and Wakker, 1986): • denotes a positive identification, o means that no spectrum with discrete absorptions has been found with certainty, s denotes saturated P Cygni profiles, making identification impossible, and Δ denotes Be stars. Note that, below $M_{bol} \approx -7$, Be stars are the only nonsupergiant stars which show discrete absorptions.
emission are known to be varying with time (for example, Ebbets, 1982, and Snow et al., 1981), and almost no simultaneous UV observations exist, which makes this absence of correlation probably insignificant.

(b) For nonsupergiant stars fainter than about $M_{bol} = -7$, only a fraction of the Be stars shows discrete absorption features. In none of the normal B (i.e., non-Be) stars less luminous than $M_{bol} = -7$ has positive evidence for discrete absorptions been found. This result has been confirmed by Grady et al. (1987b).

(c) In about 50 percent of the Be star sample studied (i.e., 17 of 33), the discrete components are sometimes found. This quoted fraction may not be as reliable because, in Be stars, the absorption features tend to disappear completely from time to time. A similar conclusion was reached in a recent study by Grady et al. (1987b).

(d) Of the limited sample of four subdwarfs, two clearly showed evidence of multiple narrow absorption lines. In HD 228220B, the lines are strongly variable. (See Figure 4-36.)

2. Be Stars. The remarkable conclusion that discrete absorptions appear in stars less luminous than $M_{bol} \approx -7$ (corresponding to spectral type around O9 near the main sequence) only if the star is known to be a Be star is probably one of the most pronounced spectral properties of Be stars in the ultraviolet. (Refer to Underhill and Doazan (1982) for a review of general Be star properties.) The C IV doublet appears to be the most clear indicator of this variability (see for example, Barker and Marlborough, 1985). In other words, C IV variability in the UV for stars less luminous than $M_{bol} \approx -7$ means that the star is a Be star. Note that the reverse is not necessarily true because many Be stars have not yet shown C IV activity. Some Be stars appear to have very complicated UV spectra, making identification of discrete components uncertain. These stars were listed by Slettebak (1982) as showing a shell spectrum in the visible region at the epoch of his observation(s). It would be of interest to see whether the discrete component behavior changes during B–Be–Bshell transitions in the visible.

A search among Be stars for a possible correlation with $V\sin i$ is presented in Figure 4-33. In this figure, the distribution in $V\sin i$ of all Be stars with corresponding spectral type (Slettebak, 1982) is also shown. The great similarity between this distribution and that of the sample shows that the statistics are more or less complete. The conclusion is that the fraction of Be stars which show discrete absorption features is probably not correlated with $V\sin i$. Grady et al. (1987b) essentially confirmed this result on the basis of a larger sample of stars.

![Figure 4-33](image.png)

Figure 4-33. The distribution of $V\sin i$ of Be stars in the sample searched for high-velocity discrete absorption components (Henrichs and Wakker, 1986): the hatched area denotes positive identification; the dashed line denotes the (scaled) distribution of 136 Be stars (Slettebak, 1982), indicating that the sample is reasonably complete. No correlation with $V\sin i$ can be concluded.
and stressed the paucity of discrete components in Be stars with $V \sin i < 150 \text{ km/s}$. The meaning of such a threshold is not established. A closer investigation is worthwhile as to what extent latitudinal effects are important.

3. Discussion. The apparent division between stars brighter and fainter than $M_{bol} \simeq -7$ must tell us something about the physical origin of the phenomenon of discrete UV absorptions, assuming one common origin (which seems likely but is still to be shown). This division apparently does not coincide with the boundary which separates stars with and without detectable mass outflow ($M_{bol} \simeq -6$, Snow and Morton, 1976) because many stars below this line clearly exhibit asymmetric absorption profiles (e.g., $\tau$ Sco, $\mu$ Col, $\delta$ Sco, and X Per) but have never shown indications of discrete absorption components. A systematic study of stars occupying this part of the HR diagram might be worthwhile, especially in view of the well-known uncertainties in $M_{bol}$ ($\pm 0.5 \text{ mag}$ is no exception). We must conclude that the presence or absence of a stellar wind as observable from (steady) asymmetric absorption profiles is apparently not related to the occurrence of discrete components.

It is important to realize how the reported variability might influence the foregoing statistics and what its outcome actually implies. For instance, one might wonder if the quoted fraction of 50 percent among the Be stars actually means that all Be stars have discrete components in their spectra during 50 percent of the time. Long-term studies of a few stars (e.g., $\gamma$ Cas (Henrichs et al., 1983), 59 Cyg (Doazan et al., 1985), and $\xi$ Oph (Howarth et al., 1984)) have taught us that this is not the case over a 5-year period. For example, $\gamma$ Cas was very “active” over a period of 2 years, but during the following 4 years, hardly any discrete absorption feature was found. In 59 Cyg, there are only a few known spectra without the features, whereas in $\xi$ Oph, they vary but never disappear like almost all stars from the study by Prinja and Howarth (1984), which contains only stars more luminous than $M_{bol} = -7$. In summary, it appears that, in Be stars, the features come and go, whereas among the O stars and other B stars, the features are either always present but variable or always absent.

That the occurrence of discrete absorptions depends strongly on the Be character of the stars might, in our opinion, be fundamental for the understanding of the Be phenomenon. Many of the luminous (non-Be) stars which exhibit discrete absorptions also have emission lines in the visual spectrum (at least on some occasions because there are numerous examples of varying emission (e.g., Ebbets, 1982)). It is therefore suggestive to conjecture that the same underlying mechanism that is responsible in some way for the variable optical emission in both Be stars and luminous stars also causes the discrete absorption lines in the UV. It has been suggested that the changing behavior of nonradial pulsations might play a significant role in producing discrete absorptions in the stellar-wind profiles (Henrichs, 1984), analogous to the suggestion by Vogt and Penrod (1983) that nonradial pulsation behavior might be responsible for Be outbursts. (See Section F for possible evidence and further discussion.) Whatever the physical difference between Be and other stars might be, the explanation of the phenomenon of discrete absorption components should, of course, account for the fact that occurrence of the components is not restricted to Be stars.

C. Summary of Properties

This section summarizes the main characteristic features of the discrete absorptions. Significant examples of variabilities in stellar-wind lines in OB stars are given in Figure 4-34 (a-g). Tickmarks on vertical axis indicate zero flux level. The scale is similar to that of Figure 4-32. This summary is based on the work of Lamers et al. (1982), Henrichs (1984), and Prinja and Howarth (1986).

(a) The features are often found in resonance lines of abundant ions (C IV, Si IV, N V, Si III, O VI, and Al III and
hundred to 3000 km/s, depending on the star and is typically between 0.5 and 0.9 times the terminal velocity ($v_\infty$) of the stellar wind, if the latter can be observed (as a steep edge of a saturated P Cygni profile). There is no correlation between this fraction and the actual value of the terminal velocity. In general, the later the spectral type, the lower the velocities involved. In the star, θ Crb, B6 IIIe, the central velocity can be as low as around zero (Doazan et al., 1984).

(d) When the features are observed at high velocity and are found in lines of different ions, they occur at the same velocity within the observational error

Figure 4-34a. Two spectra in the C IV region of HD 93250, O3 V((f)), taken 4 months apart. Note the sharp additional doublet near ~3000 km/s in the lower spectrum.

(b) They are sometimes multiple. (Four components or more have been observed.)

(c) The range of the velocity of the center of the feature(s) is usually from a few

Figure 4-34b. Significant variability within 2 days in N V and C IV lines in 15 Mon, O7 V((f)).
(f) A typical observed value for the column density (not corrected for abundance or ionization fraction) is $2 \times 10^{14}$ cm$^{-2}$ with a range of a factor of 5 on both sides (Figure 4-35). Interestingly enough, the column densities of the discrete components do not depend on those of the underlying P Cygni profile (Figure 4-35). In other words, the column density of a discrete component in an early O star is often comparable to that of a B or Be star. One must bear in mind that a specific model has been used to derive the quoted column densities. However, different methods have thus far given similar results, and the

Figure 4-34c. Resonance lines in $\xi$ Per, O7.5 III(3n)(1f): dashed line denotes the terminal velocity derived from the C IV and N V profiles. The discrete components in the Si IV doublet are found at significantly lower velocity. See Figure 4-44 for the time series of this star.

(about 20 km/s). In particular, the velocity does not correlate with ionization potential.

(e) The width is typically 30 to 300 km/s, or in other words, between 0.03 and 0.14 $v_{\infty}$ (Prinja and Howarth, 1986), again without depending on the value of $v_{\infty}$ itself. Although differences in width between lines of different ions have been found, there is no substantial evidence that a systematic difference exists. The width is not correlated with the central depth of the feature.

Figure 4-34d. Two spectra of $\delta$ Ori, O9.5 II, taken 5 days apart, which is approximately the binary period, illustrating that the variability is not binary-phase-dependent.
range quoted is therefore considered to be fairly representative.

(g) The degree of ionization in the discrete components is somewhat complicated. Lamers et al. (1982) found that the degree of ionization is higher than that of ordinary wind lines. This conclusion has been supported by the study of Prinja and Howarth (1986). However, these authors realized that, if one considers the effects of Auger ionization, the simplest explanation of the data is, in fact, that the level of ionization in the discrete components, as measured by the dominant ions, is lower than in the ambient wind. The efficiency, however, with which superions (N⁴⁺, O⁴⁺) are produced in the discrete components is enhanced. (More study is obviously required, particularly in the form of simultaneous X-ray and ultraviolet observations.) Regarding the time-dependence of the ionization conditions in discrete components, Prinja and Howarth found that, for most of the stars in their sample, the column density ratio of the components of different ions did not change significantly as a function of time. This led them to conclude that the variability observed in the strength of the discrete absorptions is more likely attributable to fluctuations in the total (hydrogen) column density than to changes in the local ionization balance.

(h) Some stars display a correlation between velocity and column density: the higher the velocity, the weaker the discrete component. This correlation was called a "memory" by Henrichs (1984) in order to acknowledge the fact that, for a given star at a given episode, the discrete absorptions might completely disappear but that, when they come back, the relation between the new velocity and column density tends to be the same as before. The range is about 10 percent in velocity and a factor of 5 to 10 in column density. It should be emphasized that there are many more stars without such a memory. Prinja and Howarth (1986) found that, in HD 199579, O6 V((f)), the correlation is also present, but instead, a lower column density is related to a lower velocity.

(i) The strength and velocity are often variable on time scales of hours, days, and weeks. However, not many detailed observations with high time resolution...
(i.e., hours) exist. No periodicity in the variability has ever been found. In the detailed study of 21 stars by Prinja and Howarth (1986), it was found that, for a given star, the column density can vary by at least a factor of 2 and at most by a factor of 10, with an average of 3. The typical time scales are days and are comparable to the dynamical time scales of variations in Hα emission as discussed by Ebbets (1982). In γ Cas, B0.5 IVe, time-resolved observations covering a couple of days have shown that the velocity of a high-velocity feature does not change but that its strength decreases. In ξ Per, O7.5 III(n)((f)), however, the features are found to accelerate, "settle" at high velocity, and consequently become fainter. (See Figure 4-44b and Section D for more details.) Two time scales are needed to describe the variability: (1) a short time scale (hours) identified with the flow time scale, and (2) a longer time scale (weeks, months) to characterize the strength of each episode, varying from completely absent to permanently present.

(j) In a few well-studied cases (O stars ξ Per and δ Ori and most of the Be stars), low-velocity absorption is sometimes associated with the high-velocity component(s). (See for example, Figures 4-34 and 4-44.) The best-studied star thus far, ξ Per, showed that the low-velocity features evolved into high-velocity absorption within 1 day (Figure 4-44). It remains to be shown, however, whether the behavior of ξ Per is representative or not. The low-velocity features can be asymmetric or have irregular shape and are clearly much more variable than the high-velocity features. There appears to be a general trend that the later the spectral type, the more pronounced the low-velocity features. When observed simultaneously in different ions, the shapes may differ for the individual ions, which therefore results in different average velocities. In contrast to the case of ξ Per, in θ CrB, B6 IIIe, the star with the latest spectral type in which the variable absorption features are reported, the averaged central velocity is found to be slowly increasing from around 0 to -140 km/s over a period of
Figure 4.34g. Variability in the resonance lines of C IV and Al III in 66 Oph, B2 IV–Ve (Grady et al., 1987a). Note that the character of the profiles is very different in the two ions and that the absorptions disappeared in 1985.

5 years (Doazan et al., 1984). However, the behavior on a daily time scale (or shorter) of the absorptions in this star is not known. Again, whether such behavior is typical for a Be star or not is an open question. Obviously, such observations are extremely important because they might reveal how the features are actually formed and/or whether the characteristics are epoch-dependent.

D. Variability

Numerous examples exist of varying high-velocity absorption in UV line profiles of many stars on time scales down to 30 minutes. Typical examples are listed in Table 4-6. The list is not
Figure 4.35. Observed range in column density of discrete components in C IV, Si IV, and N V as a function of column density of the underlying P Cygni profile (based on Prinja and Howarth, 1986): dots denote average values, bars indicate highest and lowest measured value (no error bars!), and arrows up and down indicate saturated discrete components or no components at all had been detected, respectively. Star 17 (ε Ori) has two distinct sets of discrete components, indicated by a and b, respectively. From this graph, one can conclude that the column density of discrete components is not related to the column density of the P Cygni profile or the spectral type.
exhaustive, but rather illustrative. Earlier examples can be found in Snow (1979), Underhill and Doazan (1982), Marlborough (1982), and Henrichs (1984). It is important to notice that not only the high-velocity absorption part is variable, but that changes are also observed at lower velocities. Most of the papers report only qualitatively on variable absorption. Some of the papers cited in Table 4-6 contain quantitative measurements of column density and velocity of especially the discrete components, based on many of high-resolution IUE spectra of these stars, notably the paper by Prinja and Howarth (1986). The main conclusion is that variability in strength and velocity is most likely a property of all discrete absorptions.

1. Quantitative Measurements. Results of quantitative measurements of properties of discrete absorptions depend on the model and method used. Therefore, we summarize briefly the different techniques and their underlying assumptions before quoting results. The technique for deriving the column density of narrow absorption lines, including the case of multiple components, is described in detail in Henrichs et al. (1983). The basic assumptions are that the absorption line is formed in a homogeneous plane parallel slab of gas between the star and observer, that forward scattering and emission are negligible, and that no radiative coupling occurs between the line and the (often present) underlying P Cygni profile. (The latter assumption was not made by the analysis of Lamers et al. (1982), but we note that the resulting column densities are similar.) Such an analysis is basically similar to interstellar work. The farther the gas layer is from the star, the more reasonable the assumptions are likely to become appropriate. These assumptions imply that the intensity of the radiation emerging from the star, including stellar wind \( I_0 \), is modified according to:

\[
I(v) = I_o \exp \left\{ -\tau_c \exp \left[ -\left( \frac{v - v_c}{v \_i} \right)^2 \right] \right\},
\]

where \( v \) is the velocity with respect to the stellar rest frame, \( \tau_c \) is the optical depth at the center of the line which has a radial velocity \( v_c \), and \( v \_i \) is the broadening parameter \( (v \_i = 0.601 \text{ FWHM}) \) characterizing the Gaussian velocity dispersion. A least-square fit of such a profile (corrected for the instrumental profile of the spectrograph used) returns the values of \( \tau_c, v_c, \) and \( v \_i \). Such a prescription gives for the column density:

\[
N = \frac{\nu \pi}{\pi e^2/mc} \frac{1}{\lambda_o f} \frac{\tau_c v \_i}{1 + v_c/c}, \tag{4-40}
\]

where \( \pi e^2/mc = 0.02654 \text{ cm}^2 \text{ s}^{-1}, \lambda_o \) is the laboratory wavelength of the line which has oscillator strength \( f \), and \( c \) is the velocity of light. In the case of doublets, it is assumed that the value for the broadening parameter \( v \_i \) is the same for both members. This implies that

\[
\frac{\tau_1}{\tau_2} = \frac{\lambda_1 f_1}{\lambda_2 f_2}, \tag{4-41}
\]

for both optical thick and thin lines. The use of this well-known doublet ratio greatly improves the reliability of a fit. (Note that the question of optical thickness arises only when equivalent width measurements are to be converted into column densities, which is avoided by the present method.) When a doublet is being fit and the velocity scale used is relative to one of the doublet lines, the velocity of the second doublet line must be modified accordingly. (See Henrichs et al., 1983, Equation (3.3).) When multiple (overlapping) discrete components are present, profiles of the first type can be combined where the same set of assumptions apply.

In practice, a basic difficulty of this method is to separate contributions from the "persistent" part of the P Cygni profile, including the photospheric lines, and the superimposed discrete absorption(s). In the case of \( \gamma \) Cas (Henrichs et al., 1983) and \( \xi \) Pup (Prinja, 1984), spectra without components (e.g., Figure
4-31) of the same star were used as a reference spectrum relative to which the measurements were done. In most stars, however, no such spectra are available. Therefore, in V 861 Sco (Howarth, 1984), ξ Oph (Howarth et al., 1984), and ω Ori (Wakker and Henrichs, 1987), a "theoretical" P Cygni profile (e.g., as described by Castor and Lamers, 1979) was fitted to the part of the resonance lines outside the discrete absorption region, and the column densities were derived with respect to this local background. The complicated structure of the Si IV doublet in ξ Per (see Figure 4-44), classified as O7.5 III(n)((f)) by Walborn (1972) and as O7.5 I by Conti and Leep (1974), was analyzed by Prinja et al. (1984) by using a spectrum of λ Ori. This star has a spectral type comparable to that of ξ Per, but it often shows only photospheric Si IV absorption lines and rotates much more slowly. After the convolution of such a λ Ori spectrum with a proper rotational broadening profile, the constructed spectrum (containing many photospheric lines mainly due to Fe IV and V) appeared to be very similar to that of ξ Per, except near the Si IV doublet, and was used as a photospheric input spectrum in constructing the template used to separate the persisting and varying part in ξ Per. In a similar way, Prinja and Howarth (1986) used the C IV part of the spectrum of the O7 V((f)) star, 15 Mon (V sin i = 63 km/s), as a photospheric standard for the analysis of the O7 V star, HD 48099. They also used the Si IV region of λ Ori, O8 III((f)); μ Col, O9.5 V (V sin i = 97 km/s); and τ Sco, B0.2 V (V sin i ≤10 km/s) for analyzing other stars. Figure 4-35 gives an impression of values of column densities thus obtained.

It is appropriate to stress that many ad hoc assumptions were made in the foregoing analyses, most of which were made only because one did not know how to do better. The justification of this kind of analysis is found in the many cases in which the obtained fits represent the observed profiles remarkably well. In other cases, especially in the later Be stars, the irregularity of the observed profiles clearly indicates the inadequacy of the described method.

Figure 4-36. Two IUE spectra in the C IV range of the O subdwarf, HD 128220B (after Bruevich and Dean, 1983; graph courtesy of Giddings et al., 1986). Note the striking variability in strength, velocity, and multiplicity.

We present here some remarkable properties of the narrow lines which emerged from the few existing detailed studies of individual stars. We review, in turn, the "memory" found in some stars and the time scales involved.

2. The Memory. Figure 4-37 displays the memory of γ Cas, B0.5 IVe, regarding the high-velocity narrow absorptions found by Henrichs et al. (1983): a higher velocity is clearly correlated with a smaller column density in spite of the fact that, between the different episodes, the narrow absorptions sometimes disappeared completely. This is valid for all three ions in which they have been observed. However, Doazan (private communication) reports that spectra of γ Cas in 1986 indicate that the described memory does not hold when the new epoch is included, possibly implying that the phenomenon might be time-dependent.

A good example of a memory was found in ω Ori, B2 IIIe, by Sonneborn et al. (1987) and Wakker and Henrichs (1987). Figure 4-38 is an example of the Si IV doublet in ω Ori. The four
spectra shown in this figure are arbitrarily chosen and have no particular time sequence. The range in velocity is again rather small but very significant and occurs simultaneously in the Si IV, C IV, and Si III (λ1206) lines. Figure 4-39 shows this memory of the discrete absorption component of the Si IV and C IV lines in a quantitative way. Note that these narrow lines are present in all spectra of ω Ori (also in the Si III λ1206 line) and that sometimes the (broader) low-velocity absorption part of the profile is also variable.

A third example of a similar memory is found in ξ Per, O7.5 III(n)(f), by Prinja et al. (1984, 1987). (See Figure 4-40.) Note that, in this case, the velocity (in the stellar rest frame) is in the range of 2000 km/s, much higher than in the previous two stars.

A different kind of memory, found in ζ Pup, O4 I(n)f, by Prinja (1984), is illustrated in Figure 4-41. In this case, there are often two absorption components at different velocities, but when the first is strong, the second is weak and vice versa. Two more examples, 10 Lac, O9 V, and, HD 199579, O6 V((f)), are shown in Figure 4-42 (after Prinja and Howarth, 1986). Remarkable is the thus far unique case of HD 199579, which also seems to have a significant correlation, but with a positive slope (i.e., a higher (negative) velocity is related to larger column density), as opposed to the “memories” of the stars previously mentioned.

It is important to mention that there are many more well-studied stars for which no memory of any kind has been established (e.g., ζ Oph, O9.5 V(e) (Howarth et al., 1984), and 66 Oph, B2 IV–Ve (Barker and Marlborough, 1985), and most of the stars from Prinja and Howarth’s study. There exists a very long record of the BI Ve star, 59 Cyg (e.g., Doazan et al., 1985, and references therein). Because of the complexity of the structure of the absorption features in this star, only equivalent width measurements have been made, so that no conclusion about a memory can be made.

We should mention that there is no clear explanation for the existence of the described behavior. An obvious difficulty is that, in some stars, the significance of the phenomenon is very high, whereas in other stars, no trace of such behavior can be found. More discussion of this remarkable phenomenon will appear in Section E after the available detailed time-sequence studies of these stars have been described.

Figure 4-37. The memory in γ Cas (Henrichs et al., 1983). A higher column density is clearly correlated with a lower velocity in spite of the fact that, between different episodes, the discrete components might completely disappear. Open circles denote uncertain points due to instrumental effects. The vertical dashed lines are the ranges observed in six spectra taken within 15 days (see also Figure 4-43).

3. Time Scales. In IUE spectra of γ Cas taken in May 1978, Henrichs et al. (1980) noticed that discrete absorptions were clearly present in a spectrum taken 7 days after a spectrum without
any trace of them. This observation led these authors to suggest that the appearance of discrete components might be caused by ejected material that has a higher density than the ordinary stellar wind. This material would be accelerated (by radiation pressure) during a short time (typically less than 1 day) up to its (own) terminal velocity, causing a narrow absorption line at high velocity. This short acceleration time would make it rather unlikely to find the lines at low velocities, which would explain the frequent absence at low velocity. Subsequent expansion of this dense layer (with a constant velocity) would then cause the column density of the narrow lines to decrease as a function of time proportional to \((t_0 + t)^{-2}\) where \(t_0\) is a constant. (See Section E.3 for a detailed description of this model.) With these time scales in mind, new observations of \(\gamma\) Cas were made in the hope of recording the appearance and acceleration of the narrow absorptions and its decay. Figure 4-43 (from Henrichs et al., 1983) displays the result: a clearly decaying narrow absorption line on a time scale of 1 week with hardly any change in velocity, in accordance with the expectation. The range in column density is indicated in Figure 4-37. The appearance of the discrete absorptions, however, has never been found in this star, except that in one spectrum of \(\gamma\) Cas (March 25, 1980), there is a very broad and strong absorption component at low velocity (−650 km/s as opposed to the narrow lines at −1400 km/s a few days later). A 48-hour continuous observation run in January 1982 of both \(\gamma\) Cas and 59 Cyg (Grady et al., 1982) showed, unfortunately, only very weak narrow absorptions at high velocity in these two stars. Since then, \(\gamma\) Cas seemed to have been inactive.
Figure 4-39. The memory in the C IV and Si IV lines in 28 spectra of ω Ori (Wakker and Henrichs, 1987) taken over a 3-month interval. Formal error bars, obtained from least-squares fits, are indicated. A graph for the Si III λ1206 line looks very similar.

Figure 4-40. The memory of the discrete high-velocity absorptions in ξ Per (Prinja and Howarth, 1986). The ranges in column density of the three time series (Figures 4-44, 4-45, and 4-46) are indicated. The dashed line of the October 1984 data above the solid line (eyeball fit) represents 6 hours of data; below the line it pictures the next 24 hours.

Figure 4-41. A different memory in ζ Pup (Prinja, 1984). Often two separated components are present, but if the high-velocity component is strong, the low-velocity component is weak and vice versa. Here the persistent part of the SI IV line is removed.
and there were, with two exceptions, no spectra with narrow absorptions until the summer of 1986, when strong absorption around \(-1400 \text{ km/s}\) reoccurred (Doazan, 1986). This star is a very good example of the two time scales involved: a long time scale (months) characterizing the presence of the discrete components and the short time scale characterizing the variability of the features when they are present.

Much more fortunate were the observations of \(\xi\) Per, O7.5 III(n(f)), reported by Prinja et al. (1984). An extended paper was given by Prinja et al. (1987). In September 1983, a broad low-velocity feature seemed to have almost disappeared in 7 hours, while at the same time, the narrow feature at high velocity had become considerably stronger. (See Figure 6 in Henrichs (1984).) A second successful attempt to pin down the short time scale was made in February 1984. (See Figure 4-44.) Four spectra taken within 2 hours showed a gradual increase in strength of an appearing and accelerating broad low-velocity feature, whereas the high-velocity narrow absorption continued to decrease in strength. An exact pattern was found in spectra of \(\xi\) Per taken in October 1978 (available through the IUE data bank). Encouraged by these results, Prinja et al. (1987) monitored the star over several days (Figure 4-44) with varying time resolution down to 0.5 hour. These observations showed, for the first time, a complete cycle of the formation and development of a high-velocity narrow component in \(\xi\) Per, beginning with a broad low-velocity feature. The general picture emerging from these observations is that, first, a rather broad absorption feature centered around \(-1300 \text{ km s}^{-1}\) begins to develop (superposed on the P Cygni doublet). Figure 4-44b shows the velocity measurements. At the beginning of such an episode, the red emission of the P Cygni profile is somewhat enhanced. The broad absorption feature first grows in strength and, consequently, strongly narrows during its acceleration, which takes about 0.5 day. After becoming a narrow feature, it remains almost stationary in velocity at about \(-2150 \text{ km s}^{-1}\). From this point, the strength (column density) of the discrete absorption line decays rapidly with time proportional to \((t_0 + t)^{-2}\), where \(t_0\) is a constant (Figure 4-45). One can see that another episode begins to develop around October 20 at 8:37 UT. On two previous occasions, similar behavior was observed (Figure 4-46), but with

![Figure 4-42. The memories (?) of HD 199759 and 10 Lac (Prinja and Howarth, 1986). In the first star (the only one known), the correlation has an opposite sign. Such an apparent correlation appears to be present only rarely.](image)

![Figure 4-43. A time sequence of \(\gamma\) Cas spectra in 1980 (Henrichs et al., 1983). A time axis is added. Notice the strong decay of the narrow absorptions without significant change in velocity.](image)
Figure 4-44a. A complete cycle of the formation, development, and decay of discrete components in ξ Per, O7.5 III(n)((f)) (Prinja et al., 1987). The first time sequence was obtained within 1 hour in February 1984 (Prinja et al., 1984); the second within 2.5 days in October 1984 with a time resolution of 0.5 hour over two blocks of 12 hours. The rest wavelengths of the Si IV doublet are marked. A template spectrum used to separate varying and persistent parts of the spectrum (see text) is superposed on each spectrum as a reference. Note the gradual increase of additional broad absorption near λ1388 in the first three spectra. This also happened between October 18 and 19—a very broad low-velocity feature (present in both doublet members) appeared subsequently narrowed when it accelerated during the next 12 hours (October 19 from 6:11 to 18:59). The final velocity was about −2150 km/s, significantly less than the edge velocity of the completely saturated C IV and N V profiles. Note that, in the first October 20 spectrum, the emission is strongest and is decreasing thereafter. This emission phase signals the beginning of a new cycle, visible as new broad absorption around 1388 Å. The column densities are displayed in Figure 4-45.
different central velocities, different values of \( v_0 \), and different proportionality factors. It is interesting to note that the latter contains information on how much matter is involved with such an event. A preliminary conclusion is that the more matter is involved, the lower the central velocity of the discrete absorption line is at its maximum velocity. Assuming a spherical shell (for simplicity), Prinja et al. (1987) derive a typical mass of \( 6 \times 10^{-8} M_\odot \) for the October 1984 event. Before firm conclusions can be drawn from these exciting results, however, it needs to be established that this star is indeed representative of how discrete absorption components are formed, at least in some O stars. In other words, is \( \xi \) Per unique?

Finally, the decay observed in both \( \gamma \) Cas and \( \xi \) Per seems to suggest that the scatter in the “memories” of these two stars is real and

---

*Figure 4.44b. Central radial velocity of the discrete absorption components in \( \xi \) Per as a function of time corresponding to Figure 4.44a (Prinja et al., 1987). The velocities were measured on spectra which are rectified using the procedure described in the text. The dashed lines are suggested connections between the different points. There are not enough data available to conclude a possible periodicity. The acceleration of the feature is pronounced.*
The important issue of uniqueness of discrete component behavior is ξ Per can be settled only when more such studies are made. The fact that ξ Per showed a memory similar to γ Cas, ω Ori, and 10 Lac is suggestive of a common origin in both O and Be stars. Presently available data in IUE archives are not of a sufficiently high time resolution to answer this in the affirmative.

A third important point is concerned with the uniqueness of the line-fitting method. The rapidly changing complex Si IV profiles in ξ Per (Figure 4-44) can be fitted equally well with a continuously changing “underlying” P Cygni profile with additional absorption (see Prinja et al., 1987). It is not clear, however, how to interpret such a fit because the method used to calculate P Cygni profiles assumes a steady-state (time-independent) configuration, which is obviously not the case. It is clear that many more model calculations are necessary before we may conclude what information about the geometrical structure the observed profiles actually reflect. (See also Section E.4 for a further discussion of model calculations.)

depends on the particular epoch during an episode in which the spectrum is taken.

4. Discussion. Detailed studies of a few stars (γ Cas, ξ Per, 59 Cyg, and ω Ori) have shown that, in our opinion, the appearance of discrete components occurs on a short time scale (hours) and that the subsequent decay takes much longer (days or weeks). If this were the case for all stars with discrete absorptions, the fact that, in some stars, the features appear to be more or less permanently present (but variable) can be explained by assuming a rather frequent production of “new” narrow lines superimposed on the “old” ones, as occasionally observed in ξ Per. Detailed studies of more stars are clearly needed to verify or deny this extrapolation. The study of 66 Oph by Barker and Marlborough (1985) probably did not have high enough time resolution to establish the short time scales.

Figure 4-45. Column-density measurements of the October 1984 spectra of ξ Per. The lower left group of points corresponds to the high-velocity component visible in the first few spectra of October 19. The central group pictures the column density of the broad, and, later, narrow absorption components, initially accelerating with about 35 km/s per hour. A $(t_o + 1)^{-2}$ fit is superposed. The lower right group (shown with different formal error-bar shapes) is the beginning of the new cycle.

Figure 4-46. Decaying column density of Si IV narrow absorptions on two earlier occasions observed in ξ Per (Prinja et al., 1984). The velocities at which they occurred remained the same during the decay, but were significantly different.
Finally, in our opinion, the longer time scale mentioned previously reflects changes in the star itself, rather than a time scale determined by the flow properties of a stellar wind. Growth of instabilities, for instance, takes place on a time scale much shorter than the flow time scale.

E. Models

In a spectral line indicating mass outflow, there are several ways to form a discrete high-velocity absorption component:

(a) The presence of a velocity plateau (or a decrease in velocity gradient) which will increase the path length of absorbing ions at a given velocity.

(b) The existence of an ion density that is higher at a specific velocity than at neighboring velocities. This might be caused either by an overall enhancement of the density at that velocity or by ionization effects which favor the observed ionization fraction at that velocity.

(c) As described in terms of the model by Lucy and White (1980) and Lucy (1982a, 1982b, 1983), an increase of either the number of scattering surfaces or the shock amplitudes in a flow with a nonmonotonic velocity law will increase the number of resonances of a photon and, hence, the optical depth at a given velocity.

All of the proposed models for the formation of a discrete absorption feature fall in one of these categories. A basic unresolved question about their origin is: Given the ubiquity of the absorption features, do they reflect the intrinsic behavior of any stellar-wind flow or are they caused by the underlying star in a way that we observe the resulting interaction with the stellar wind? We shall see that, from the observational side, the major constraint imposed on a model does not come from the formation of discrete components, but from the predicted time variability. Earlier reviews and discussions of current models are given by Lamers et al. (1982), Howarth (1984), Henrichs (1984), and Prinja and Howarth (1986). In the following, we summarize and briefly comment on the different models which can be considered for explaining the behavior and origin of narrow absorptions. Many of these models were proposed without the present knowledge of the time variability.

(a) Peaks in the radial ionization structure in the stellar wind: Excluded by the lack of correlation of velocity with ionization potential. In addition, a plausible mechanism for changing the ionization balance appropriately does not exist, especially regarding the high-velocity features which cannot be formed close to the photosphere.

(b) A stationary shell in the wind: Excluded by the observed variability.

(c) Velocity plateau(s) in the stellar-wind flow (e.g., Hamann, 1980): Doubtful in view of the frequent occurrence of multiple components and variability. Detailed model calculations by Prinja and Howarth (1984) of the effects of a velocity plateau on theoretical P Cygni profiles also showed that velocity plateaus, given the assumed properties, are unlikely to provide the correct explanation.

(d) Postcoronal decelerated region of low temperature (Doazan in Underhill and Doazan, 1982, p. 394) explaining the absence of absorption at intermediate velocities by the existence of a steep gradient in the ionization balance. The deceleration comes from two interacting mass flows. Difficulties similar to those in (a), (b), and (c) apply.

(e) A stellar wind decelerated by the gravity of the star or by running into the interstellar medium: Found unlikely by Lamers et al. (1982).
(f) A two-component stellar wind (high and low density) caused by the inherent instabilities of a radiation pressure driven flow (Lamers et al., 1982). (Various instabilities have been discussed by Lucy and White (1980), Carlberg (1980), Kahn (1981), Lucy (1982a, 1982b, 1983, 1984), Owocki and Rybicki (1984, 1985), and Krolik and Raymond (1985).) A model like this (based on time-averaged flow properties) is intrinsically unable to describe the coherent time behavior of discrete absorptions as observed in some stars (γ Cas and ξ Per), although, of course, the predicted effects of clumpiness, the production of X rays, etc. in a flow with a nonmonotonic velocity law remain unaltered. At present, this possibility has not been applied to the aspect of time-dependence. In general, such analyses can predict a time scale for the development of an instability, which turns out to always be much shorter than the flow time scale, the latter apparently being the characteristic observed time scale of variability. Therefore, the flow instabilities might be related to the narrow absorption components, but an additional ingredient is needed to explain the observed time scales. Lucy (1983) mentioned the formation of an additional high-velocity absorption component in a stellar wind as a result of a shadowing effect caused by multiple shocks. This remark, however, is primarily concerned with the origin of the high-velocity layer(s) and not as much with its precise location or time behavior. Further investigation is worthwhile.

(g) Temporary release of parcels of matter from “open” magnetic loops which are attached to, but above, the stellar surface, and consequently coupled with rotation (Underhill and Fahey, 1984): Difficulties in explaining the absence of predicted strong, low-velocity, suddenly disappearing absorption components in addition to ad hoc assumptions about geometry and time of ejection of parcels. (See Section E.1 for a more detailed discussion.)

(h) Corotating interacting regions (CIR’s) arising from (assumedly) coexisting high- and low-velocity regions in the stellar wind which, at their interface, may produce a velocity plateau, analogous to that observed in the solar wind. In this model, proposed by Mullan (1984), rotation is also an essential ingredient. In the way CIR’s are formed in the description given by Mullan, however, the fast streams are identified with the terminal velocity of the wind, which presumably carries the bulk of the matter, opposite to the solar case. Such an assumption makes it difficult to explain the often encountered saturated P Cygni profiles in O stars, but cannot be excluded in Be stars. In addition, an expected correlation between the ratio $v_{\text{rot}}/v_{\infty}$ and the column density of discrete components can not be found, with the present data, among O stars and B supergiants, but could not be tested for Be stars. For these reasons, apart from the necessary (but probably not unreasonable) ad hoc assumptions about the existence of coexisting high- and low-velocity material, we consider it unlikely that the concept of CIR’s in its present form can be applied to explain the occurrence of discrete absorptions in the O and luminous B stars, but might find some application in Be stars. (See Section E.2 for a more detailed discussion.)

(i) Expansion of a high-density layer in the stellar wind, proposed by Henrichs et al. (1980), elaborated in Henrichs et al. (1983) and Henrichs (1984): This descriptive model is probably the most simple one for explaining or predicting the time-dependent behavior of the discrete components as observed in some stars, but it gives no clue of the cause of the origin of the high-density
layer. (Episodic mass loss has been proposed.) This model was rejected by Lamers et al. (1982) because, at that time, no substantial short time variations had been observed.

In the following, we give more detailed discussions of the three last-mentioned models, as they enable specific predictions regarding the occurrence and time behavior of a discrete absorption component which can be compared with observational data. It should be made very clear in advance, however, that by no means does a "final" picture exist or that the correct model is even included in any of them; these models hopefully provide a good starting point for future research. Considering the wide variety of behavior of discrete absorptions, it is more likely that ingredients of more than one of the foregoing models might apply. For instance, the assumption of spherical symmetry in some of these models is certainly not correct in the case of the rapidly rotating stars, but it is unknown how large the deviations are.

1. The Model of Underhill and Fahey. To explain the existence and behavior of discrete components, Underhill and Fahey (1984) envisage that early-type stars have localized spots above (but not on) the stellar surface from which parcels of gas are released in addition to a uniformly emitted steady stellar wind. They argue that such local spots can arise only from magnetic field configurations on the surface of a star and therefore postulate the existence of "closed" and "open" magnetic loops, the latter being regions in which the magnetic field lines extend far into space and from which the parcels are released. The configuration resembles that of solar corona models. It is beyond our scope to discuss those assumptions concerning the magnetic field configurations associated with early-type stars, but we will consider the predictions for the behavior of discrete absorptions implied by this model. Figure 4-47 illustrates the model. A star with radius $R$, rotating with angular velocity $\omega$, emits a parcel

![Figure 4-47. Stellar-wind trajectories (dashed lines) and "parcel" trajectories (heavy solid lines) in an inertial frame illustrating the model of Underhill and Fahey (1984). Angle $\phi'$ represents $360^\circ - \phi_0$ in the terminology of Underhill and Fahey. The figure is drawn to scale for the equatorial plane of a star with $v_0/v_{\infty} = 360/1700$ (resembling $\xi$ Oph) and a velocity law with steepness $\beta = 1/2$. An observer will never see an absorption component from parcel A, but will from parcels B, C, D, and E. Parcel B will cause a relatively long-lived absorption feature. Parcels C, D, and E will each produce shorter living low-velocity features. The model predicts an equal likelihood for production of parcels A, B, C, and D. The observational absence of strong, suddenly disappearing absorption features might lead to the conclusion that this model cannot represent the behavior of the discrete components.](image)
of gas from location \( \vec{r}_0, \vec{\theta}_0, \vec{\phi}_0 \), which will subsequently follow a trajectory \( r, \theta, \phi \), in a plane containing \( r_0 \) and \( \omega_0 \times r_0 \), thereby conserving its angular momentum. Underhill and Fahey present expressions for the trajectories of both wind particles (originating at \( R_e \)) and parcels (originating at \( r_0 \) in an inertial frame).

To facilitate the discussion, we consider only parcels in the stellar equatorial plane (i.e., \( \theta = \theta_0 = 90^\circ \), as drawn in Figure 4-47), where we note that, for different colatitudes, the \( \theta \) dependence will be reduced by a projection factor. (See Underhill and Fahey, 1984.) We will discuss the velocities, lifetimes, and column-density behavior, respectively.

The velocity of a parcel \( v_\phi(r) \) can be readily calculated from the wind velocity \( v_w(r) \) by making the (reasonable) assumptions that the parcel acceleration is the same as that of the wind and that the rotational energy can be neglected (as \( v_\phi^2 << v_w^2(\infty) \)). This implies that

\[
v_p^2(r) - v_p^2(r_0) = v_w^2(r) - v_w^2(r_0) \quad (4-42)
\]

It is obvious that the terminal velocity of a parcel will always be less than the terminal velocity of the wind if the initial velocity of the parcel is smaller than the wind velocity at the location where the parcel was emitted. By identifying the observed radial velocity of a discrete component with the approximate terminal velocity of a parcel, Underhill and Fahey (1984) infer that “average” parcels must be emitted from about \( r_0 = 2 R_e \), depending on what velocity law is assumed. The closer the point of release is to the star, the less the difference between \( v_p(\infty) \) and \( v_w(\infty) \). We conclude that the predicted velocity range is in agreement with the observations.

However, the observability of a parcel as an absorption component strongly depends on the point of origin of the parcel. This can be readily seen from Figure 4-47, which is drawn to scale for a star with \( v_\phi/v_w(\infty) = 360/1700 \) (it is this ratio that determines the pattern of wind and parcel trajectories), representative of a star like \( \xi \) Oph, O9.5 V(e). (For stars with a smaller ratio, \( v_\phi/v_w(\infty) \), the pattern would deviate less from purely radial motion than in Figure 4-47, but the following reasoning would remain unchanged.) A parcel following trajectory A has no chance to cross the line of sight to produce an observable absorption component. A similar parcel emitted at the same distance from the star but a little later (B) is obviously capable of causing an observable absorption feature. A parcel (C) emitted still later crosses the column of sight only for a while, causing a strong absorption feature at low velocity which will accelerate and suddenly disappear when the parcel trajectory leaves the line of sight. Parcels following trajectory D will cause strong, very short-lived absorption features at low velocity. If emitted at the appropriate time in the stellar rotation cycle, a parcel emitted from a larger distance from the star (e.g., E) may stay in the line of sight, but will enter it with a higher fraction of its (lower) terminal velocity. From this geometry, it is clear that an observable absorption component can be produced only by a parcel which has the correct initial location and which is launched within a time window that is rather small with respect to the stellar rotation period.

To be compatible with the observational fact that, for the majority of the stars, the discrete absorptions appear to be present for most of the time (if not always) and are variable in both strength and velocity (the latter to a lesser extent), the Underhill and Fahey (1984) model requires that, for a given star, parcels are allowed to be released only from approximately the same spot relative to the observer (i.e., only at the same phase in the stellar rotation cycle). This is because, if they were emitted from other longitudes as well, one would expect cases C and D (stronger, suddenly disappearing lines) to prevail over the longer living lines (case B), in strong disagreement with the observations. However, if we accept the existence of such a preferred spot above the stellar surface (we cannot exclude, however, parcels being released from different colatitudes because they will not be observable), we find it unlikely that so many stars show discrete components. On the other hand, a continuous stream of matter with a
higher density than the ambient wind being released from a single spot can immediately be excluded because, in such a "lawn-sprinkler" model, multiple absorption components will always be present, each of which arises from the different gas layers crossing the line of sight at equidistant radial intervals, causing a new component to appear during each rotation cycle. Such a strictly periodic behavior has not been observed. We can also exclude intermediate cases, in which only a small fraction of a sprinkler pattern exists because of a stream of matter released from one point for a time period shorter than the stellar rotation period. We would expect to see as many trailing as leading edges. In conclusion, it is the absence of suddenly disappearing strong absorption components that presents a major difficulty in the Underhill and Fahey model.

Another concern in this model is the size of a parcel at its release and consequent expansion due to geometric and pressure effects. The fact that there are many reported cases of essentially saturated discrete absorption lines (see for example, Prinja and Howarth, 1986, and Figure 4-35) means that the material must cover most if not all of the stellar disk as seen by the observer. This also seems to be implied by the observed enhanced emission. (See Figure 4-44.) In such cases, relatively small areas, as pictured by Underhill and Fahey (1984), are not appropriate.

A final point we want to mention is the time dependence of the column density as predicted by the Underhill and Fahey model. After a parcel has expanded to cover the full stellar disk, its column density will rapidly decrease according to \( (t_0 + t)^{-2} \), where \( t_0 \) is a constant. To account for the observed, rather constant range in column density (Figure 4-35), new parcels have to be released rather frequently to replenish the absorption. As stated previously, the only way to accomplish such a replenishment is to repeat the release of parcels at instants which are separated in time by an integer multiple of the stellar rotation period, which required an unusual ejection mechanism. We conclude that the Underhill and Fahey model is unlikely to be compatible with the behavior of discrete absorption components as observed in most stars. However, it might have its application in some Be stars, among which such a wide variety of different behavior has been observed. (See for instance, the examples in Figure 4-34.) On the other hand, the high flexibility of the Underhill and Fahey model makes it difficult to make specific predictions as to precisely what to expect in such cases. See Bates and Halliwell (1986) for additional discussion and extended application of this model.

2. Corotating Interacting Regions. Mullan (1984) proposed that, if fast and slow streams coexist in a stellar wind arising from different longitudes on the stellar surface, the fast stream will catch up with the slow stream when the stellar rotation is taken into account. The strongly shocked interaction region between the two streams might cause a velocity plateau and an enhanced density region (called a CIR), which would then be responsible for a high-velocity discrete absorption component. The picture closely resembles the behavior of the solar wind as observed near the ecliptic plane by means of space probes.

A first point of objection is related to the proposed applicability of the analogy between the Sun and hot stars. Mullan (1984) identifies the velocity of fast streams in OB stars with the terminal velocity of the wind. In many O stars, \( v_w(\infty) \) is derived for a given star from saturated P Cygni profiles, whereas the discrete components are observed in unsaturated lines. This makes one think that the terminal velocity of the wind is reached over most of a \( 4\pi \) solid angle seen from the star and will carry the bulk of the outflowing matter. This is in contrast to the solar case, in which the fast streams are believed to originate in the much smaller coronal holes.

A second point is concerned with the rotation rate of the stars. In Mullan's (1984) description, the wind speed is a function of longitude at the stellar surface. Of course, this function is unknown, but would probably show
up as a rotationally modulated stellar wind. No clear indications for such an effect have been found thus far. On the other hand, when, in terms of this model, the assumption is made that the wind speed becomes different beyond a given distance from the stellar surface, the model resembles more and more the model of Underhill and Fahey (1984) (see the previous section) with similar implications.

Another point is that the CIR model predicts that the ratio $v_{\text{rot}} / v_w(\infty)$ controls the radial distance at which the discrete components begin to form. Because one might reasonably assume that the associated column density will decrease as a function of distance, a correlation between the ratio previously mentioned and the column density is expected for a randomly chosen collection of stars. When we use the sample of Prinja and Howarth (1986), we find that a possible trend (if significant) for the N V data appears to be opposite to that of C IV, when $V \sin i / v_w(\infty)$ is plotted against the column density of the discrete components. This is difficult to explain.

At the moment, it appears unlikely that the CIR model in its present form is capable of explaining the observed properties of discrete components in O stars and B supergiants. Like the model of Underhill and Fahey (1984), it might find its application in some Be stars, where we do not directly observe the high-speed wind in the asymmetric line profiles and where spherical symmetry is absent. At present, not enough data exist to support such a hypothesis. Additional discussion on this model (from a different point of view) appears in Prinja and Howarth (1986).

3. Expansion of a High-Density Layer. This descriptive model was originally called the “UV-shell model” because it considers the ultraviolet discrete absorption lines which are observable only in lines of ions which are stellar-wind indicators; these are situated mostly in the UV. Figure 4-48 (from Henrichs, 1984) displays the characteristics of the model. At a certain epoch, the star produces a high-density layer in its wind. The origin of this behavior is not specified; it might be caused either indirectly by enhanced mass loss during a short time (hours), spherical (shells) or nonspherical (puffs), as proposed by Henrichs et al. (1983), alternatively by instabilities in the flow as

![Figure 4-48. Schematic representation of the time history of a high-density layer (causing discrete absorption components), spherically expanding in a stellar wind (Henrichs, 1984). (a) A typical velocity profile of an accelerating wind (dashed line). $v_w(\infty)$ denotes the terminal velocity of the wind, which is always observed. (b) When a high-density layer (caused by enhanced mass loss, by instabilities in the flow, a combination thereof, or by some other process) begins at some epoch $t$ at low velocity, a broad absorption feature will be observed. The acceleration of this layer is slower than that of the continuous stellar wind (dashed line) because the density is higher. (c) The time scale for acceleration is of the order of hours. (d) Within 12 hours, a narrow high-velocity feature will be observed. Its strength will decay simply because the layer geometrically expands. (e) A possible explanation for a memory as observed in some stars: when the layer contains much material, it might undergo less acceleration than when there is little material. Multiple structure will be observed when more layers coexist.](image-url)
discussed in model (f), by a combination of the two (e.g., an instability triggered by enhanced mass loss), or by some other (unknown) process. The rapid expansion of this high-density region is presumably due to the same acceleration mechanism that accelerates the stellar wind: radiation pressure (Lucy and Solomon, 1970; Castor et al., 1975a; Abbott 1980, 1982a). Because of the higher density of this layer, its "terminal" velocity is expected to be equal to or smaller than the terminal velocity of the continuous wind. How much smaller will depend on how effectively saturation reduces the radiative acceleration. This might be a very qualitative explanation for the "memory" of some stars; when the layer contains much material, its terminal velocity will be less than when the layer contains less material. A quantitative comparison with model calculations and observations has yet to be carried out. As mentioned previously, the short acceleration time (likely to be different for different stars) explains why the discrete absorption lines are observed mainly at high velocity. The faster the acceleration, the smaller the probability of finding them at low velocity. In conclusion, the overall picture in terms of this model is that, when only one high-density layer is involved, one expects to see the well-known \( (t_g + t)^{-2} \) behavior of the column density as soon as the velocity is at its maximum value (assuming constant ionization fractions). The associated lifetime is of the order of days to weeks. (γ Cas might be such a case.) When more layers, which are unlikely to have exactly the same properties, are involved, they will cause overlapping absorption features, each with its own time constant, giving the impression of a more or less constant, but variable, feature at high velocity. This picture might be applicable to many O and B stars. When the time resolution of the observations is short compared to the replenishing time scale, one might see the acceleration, as seen for instance in ξ Per, Figure 4-44.

We note that, in this model, as in almost any model of a high-density layer that has a significantly lower velocity than the terminal velocity of the ambient stellar wind, this layer must be strongly shocked toward the star, where the (less dense) wind runs into the backside of the layer. This might be the reason for the observed ionization differences between the P Cygni profile and the discrete components as found by Lamers et al. (1982) and Prinja and Howarth (1986).

Arguments against this model for stars other than those mentioned previously are the absence of low-velocity material in some of the best monitored cases, like ζ Oph, and the sometimes very irregular behavior in some Be stars, like 66 Oph. (See for example, Figure 4-34g, based on Grady et al. (1984a).)

Finally, it should be emphasized that, in this model, the predicted time behavior follows directly from simple geometric effects in which the expansion speed dictates the observed time dependence. In other words, no physical effects such as ionization, etc. are taken into account.

4. Discussion. Simple model calculations by Prinja and Howarth (1985) showed that a high-density layer caused by episodic mass loss, and accelerating at the same rate as the ambient wind, would not cause an absorption feature until it reached a substantial fraction of its terminal velocity, making the probability of finding low-velocity absorption even smaller (Figure 4-49a). The same spherical model calculations fit reasonably well with the few existing observations of the narrowing during the acceleration phase. Prinja and Howarth's model calculations also showed that rather frequent ejections of "shells" are necessary to maintain a "long-lived" more or less stationary absorption feature (Figure 4-49b). On the other hand, those calculations are based on a simple enhancement of the mass-flux parameter, keeping all other flow properties unchanged. This is certainly not a realistic assumption because it neglects the interaction of the stellar radiation with the matter in the layer and, hence, ignores a probably different acceleration. In addition, the ionization structure is imposed in those models, whereas in reality, it is actually a function of the radiation field and shock
properties. For instance, the positive slope in the memory (Section D.2) as found in HD 199579 (Figure 4.42), if significant, cannot be explained by this model without invoking a change in the run of the ionization balance with distance. Such a change would also alter the expected statistics of occurrence of low- and high-velocity material. A detailed model which considers those effects has not been constructed. Nevertheless, it is encouraging to see that at least some of the observed properties of the discrete components as observed in some stars can be fairly represented.

Another issue is the question of spherical symmetry. Within the scope of current theoretical considerations, expanding spherical shells are expected to give rise to decaying emission (at the red side), eventually disappearing beyond detectability. The emission phase is expected to be much shorter than the absorption phase, but should nevertheless be observable. Because there are only a few reports about enhanced emission, a tentative conclusion is that the line-forming regions are probably not spherically symmetric. However, the fact that a large fraction of stars show discrete absorptions suggests that the material subtends a significant solid angle as seen from the star.

In the model described above, the intriguing question remains: What causes the high-density region(s) in the wind? Is it a basic property caused by the star itself or does it find its origin in the flow? Many model calculations must be carried out before we can answer those questions. Note that multiple shocks in a stellar wind, as proposed by Lucy (1982a) are believed to be primarily responsible for the production of X rays throughout the wind. X-ray emission from early-type stars, however, appears to be always present (e.g., Cassinelli et al., 1981; Seward and Chlebowski, 1982) and sometimes variable (e.g., Snow et al., 1981), but the variability does not seem to be as dramatic as in the discrete components. Hence, if multiple shocks are indeed the cause of most of the observed X-ray emission, they seem unlikely at first, to be the cause of the much more variable discrete absorption lines. One might argue, however, that we are dealing with X-ray emission integrated over a volume and, in the case of discrete absorptions, only with line-of-sight effects.

Simultaneous observations in other wavelength bands are also helpful. We give a short account of a few of them which are, in our opinion, significant.

F. Related Observations

If a high-density region in a stellar wind would originate in the flow, there would be a minimum velocity at which a discrete absorption can be observed. However, different physical conditions that exist close to the star (temperature, density, and ionization) might
also prevent observation of the low-velocity features in the UV. (Compare the model calculations of Prinja and Howarth (1985).)

Significant in this respect, therefore, might be the transient absorption features observed in the Lyman δ and ε lines in several OB stars by Gry et al. (1984) with the Copernicus satellite. Figure 4-50 gives an example of α Vir, B1 IV, in which low-velocity absorption components (~80 and ~140 km/s) disappeared within 8 hours. Gry et al. found a similar behavior in a major fraction of their sample (5 of 8 stars). The authors concluded from these observations that an expanding high-density shell, more or less similar to the model described previously, could fit the observed behavior and that these lines might be the precursors of the high-velocity narrow absorptions as described in this review. In addition, they tentatively suggested that the phenomenon may be related to an instability of the outer envelope of the star, similar to the well-known instability proposed for the β Cep (or β CMa) stars, which are situated in the HR diagram between spectral types B0 and B2. (See for example, Lesh, 1982.) It is well known, however, that the region in the HR diagram where the discrete components occur is much wider; moreover, a physical relation between the Be phenomenon and the β Cep stars has never been proposed. However, variable nonradial pulsation, which many investigators now consider to be the origin of the variable behavior of many stars in this region of the HR diagram, is attractive as a possible mechanism for stellar-wind variability.

1. Nonradial Pulsations. Evidence that the study of nonradial pulsations might help us to understand the origin of the discrete absorptions has been suggested (Henrichs, 1984) on the basis of existing (accidentally) simultaneous optical and UV observations of the O9.5 V star, ζ Oph. Vogt and Penrod (1983) presented persuasive arguments that the observed transient distortions of the He I λ6678 line in this star can be explained by high-order nonradial pulsations. Furthermore, they found a clear correlation between the observed amplitude of the oscillations from season to season with the well-documented outbursts (as seen in Hz) of this star. Vogt and Penrod suggested that “sporadic release of pulsation energy during mode switching might provide a plausible explanation for these outbursts and for the occurrence of the Be phenomenon in general.” Henrichs (1984) noted that the drastic changes in the discrete absorption components in IUE spectra of ζ Oph found by Howarth et al. (1984) actually occurred more or less simultaneously with the changes in amplitude of pulsations reported by Vogt and Penrod. This implies that structural changes in the outer layers (the subatmosphere) of the star, in this case seen as changes in nonradial pulsation behavior, are coupled to structural changes far out in the wind, seen as varying discrete absorptions. Similar cases (as found by Henrichs, 1986) are λ Eri, B2 IIIe, and 6 Cep, B2.5 Ve, for which Barker and Marlborough (1985) described drastic changes in the UV C IV profiles and noticed their covariability with Hα-emission activity, whereas simultaneous changes in the nonradial pulsation behavior had been reported independently by Smith and.
Penrod (1985). (See also Penrod (1986).) A montage of Hα, C IV, and nonradial pulsation behavior in He I λ6678 (after Penrod, 1986, and Barker and Marlborough, 1985) is shown in Figure 4-51. Baade (1985) discusses implications of the widely encountered variable nonradial pulsations for modulating mass fluxes in Be stars. See also his review about O stars in the present volume.

2. Nonradial Pulsations and Stellar Winds. Given that in ζ Oph the pulsational amplitude (peak to peak) is about 6 percent in stellar radius and 21 km/s in velocity with a period in the range of 7 to 15 hours (Vogt and Penrod, 1983), an interesting question is whether there can be a smooth, continuous, isotropic wind under such conditions. The location of, and the physical conditions at, the sonic point (or its analog in the case of radiation pressure (Abbott, 1980)), play a crucial role in any super-sonic flow. The base of the wind (i.e., on the surface of the star) moves up and down over different parts of the surface with a velocity

![Figure 4-51. A montage of (unplanned) approximately simultaneous Hα, C IV, and nonradial pulsation behavior in He I in the B2 IIIe star, λ Eri (after Penrod, 1986, and Barker and Marlborough, 1985). Note that, when Hα began to develop emission, discrete components in C IV absorption appeared (rest wavelengths are indicated). According to Penrod, the amplitudes of the nonradial 1 = 2 and 1 = 8 modes decreased roughly a factor of 2 in the same period (observed profile shown as dots, theoretical fit shown as solid line). These observations suggest that the energy lost in pulsation might be directly transferred to the stellar envelope.](image-url)
comparable to the local speed of sound. The region where the wind becomes supersonic must have a very irregular as well as time-dependent shape, making a stable continuous flow highly unlikely. Some theoretical considerations by Castor (1986b) indicate that a shock front will form below where the sonic point would be in the wind of a nonpulsating star. If the pulsation period of the star is longer than the typical flow time scale (roughly 10 to 1 in the case of ζ Oph), the wind will be relatively insensitive to the motion of the photosphere, but the detailed effects on the flow are still subject to considerable study. (See the references cited in Section E.)

A second point to be made is a remark on Vogt and Penrods' (1983) suggestion of mode-switching as a cause of release of pulsational energy. The origin of switching between different oscillatory g modes is not known. (See for example, the reviews by Unno et al. (1979), J. P. Cox (1980), and A. N. Cox (1983).) The point is that pulsational energy being liberated in the outer layers during such a switch might trigger enhanced mass loss for which, unfortunately, no quantitative calculation exists. The occasionally reported examples of mode-switching sometimes appear to be questioned (Penrod, private communication), but variations in pulsation amplitude seem to occur rather often. These are also associated with changes in pulsational energy (of the typical order of 10^{44} erg), but whether and how such energy can be deposited in the stellar wind is not clear. Finally, it should perhaps be stressed again that it is the variability in the pulsation behavior of the star that is proposed to be connected with the formation of discrete components. For other issues related to pulsation and stellar-wind behavior, see papers referred to in Abbott et al. (1986).

3. Discussion. There are additional attractive features for suggesting future investigations of a possible connection between amplitude-changing and/or mode-switching of nonradial pulsating stars and the occurrence of discrete components. First, spectroscopic studies indicate that the presence of nonradial pulsations in many O, B, and Be stars is well established. (See for example, Bolton (1982), Baade (1983, 1984a, 1984b, and private communication), Smith and Penrod (1985), and Penrod (1986).) In addition, the well-known irregular photometric behavior of almost all luminous early-type stars (e.g., Maeder, 1980b, and de Jager, 1980) can be explained by (nonradial) pulsational behavior. (See for example, the discussion by Cox (1983, p. 146).) Of course, the uniqueness of such interpretation is a serious matter of discussion. (See for instance, Baade's chapter in this book.) From a nonradial pulsation point of view, Penrod (1986) asserts that the difference between Be and B stars is that most Be stars pulsate in a long-period \ell = 2 mode and usually in a short-period high mode as well, whereas “normal” B stars pulsate in one or two short-period \ell = 4–10 modes. The apparent existence of this difference in energy reservoir of these two types of stars is another interesting indication that might help us to understand the variability in He emission and its relation to the more frequent UV outbursts (here identified with discrete absorption-line episodes) which do not occur in the low-luminosity non-Be stars. (See Section B.) Extension to the hotter O stars, however, has yet to be established. Significant in this respect is that Baade (1985, and this volume) has found clear evidence for nonradial pulsations in ζ Pup, O4 I(n)I, for which a detailed record of its discrete-component behavior exists (Prinja, 1984). Simultaneous optical and UV observations are clearly needed. At this point, a speculative remark regarding the role of rotation in Be stars can be made. It is well known (in theory) that the presence of rotation allows both nonradial and toroidal modes to be excited and also widens the frequency range in which a star can pulsate, as compared to a similar but nonrotating star. (See any textbook.) It is therefore suggestive to speculate that variability in pulsational behavior is a more common phenomenon among the rapid rotators simply because it seems “easier” to excite a certain mode in a star.
with a wider range of frequencies and modes, thus marking the significance of rapid rotation to the Be phenomenon. As long as no excitation mechanism is known, however, such a point of view is difficult to prove.

Another point is that the time scales of nonradial pulsation are of the same order (hours) as the flow time scales, which can therefore cause drastic changes in the base of the flow of the wind which might trigger enhanced mass loss and/or instability in the flow as discussed previously. Furthermore, the observed but unexplained irregular behavior of velocity-amplitude changes and/or mode-switching of many nonradially pulsating stars follows a pattern similar to the transient activity of the discrete components in some stars. The longer time scale, mentioned before, might be identified with the long time scale involved in changes in pulsation behavior.

The nonspherical symmetry induced by introducing nonradial pulsations as an additional mechanism to trigger or regulate mass loss is another favorable aspect. In rotating stars, the amplitude of nonradial pulsations with modes $l = 1$ is strongly peaked toward the equatorial plane, where the gravity is also reduced, hence favoring a preference plane. From the observational side, particularly from the polarization and infrared data, it seems unavoidable that, in the case of Be stars, the mass flux is not spherically symmetric. A link between those two configurations must be established, however, before conclusions can be drawn. For an additional discussion, see Stalio and Zirker (1985).

Note that one aspect of the description given above in some sense approaches the view expressed by Thomas (e.g., 1973, 1982, 1983, and many other papers) that the mass flux of a star is, in fact, a parameter which does not depend only on the radiative properties of its atmosphere, in contrast to the approach of the pure radiatively driven mass-flux theory. Baade (1985) describes in detail a working hypothesis of how variable nonradial pulsations can modulate the mass flux in Be stars and how the stellar-wind structure will be influenced by such effects. Other discussions about nonradiative activity in hot stars can be found in Underhill and Michalitsianos (1985).

G. Concluding Remarks

We wish to add a few points to the previous issues. First, the very important related question of superionization in stellar winds and the possible association with X-ray generation must be mentioned. (See for example, Odegard and Cassinelli, 1982, and Marlborough and Peters, 1982.) For example, much of the superionized C IV absorption in most Be stars appears to exist in the form of high-velocity features. On the other hand, intrinsic X-ray emission from Be stars has been studied only fragmentarily (e.g., Peters, 1982a), and any possible connection between them is unknown. Some aspects of this problem might be studied by comparing the time-dependent behavior of variable discrete absorption lines arising from different ionization stages in connection with X-ray studies. Another point worth mentioning is the possible connection between UV discrete absorption activity and the long-term Be-B-shell-B sequence as observed in many Be stars (e.g., 59 Cyg and γ Cas; e.g., Doazan et al., 1983; Doazan et al., 1985, and Doazan and Thomas, 1986).

Also of clear importance are simultaneous studies in different wavelength bands, which include polarization measurements, as carried out for instance for ω Ori by Sonneborn et al. (1987). Intrinsic polarization variability in O and B stars on time scales of days to months appears to be common (Lupie and Nordsieck, 1987). Simultaneous UV and polarization modeling might give some clue to the degree of spherical symmetry and/or latitudinal dependence of stellar winds (e.g., Brown and Henrichs, 1987). Such latitudinal effects are most likely to occur in the case of Be stars. (See for example, the discussion on μ Cen by Peters in Stalio and Zirker (1985). Binarity is another possible means for studying the narrow line phenomenon. Howarth (1984) did not find any change in the velocity of the discrete absorptions in the B0 supergiant, V861 Sco, in spite
of the clear binary motion of the star. McCluskey and Kondo (1981) note that, in the interacting binary system, AO Cas (consisting of two type O stars), the discrete components definitely vary, but that their data were not with sufficient time resolution to establish whether or not a binary orbital phase exists. It might be difficult to untangle the secular from orbital effects. Narrow lines are also found in at least one X-ray binary (4U0900-40, Sadakane et al., 1985) containing a B supergiant and an X-ray pulsar, opening the possibility of probing the stellar-wind structure by observation of pulse-period changes (van der Klis and Bonnet-Bidaud, 1984). (For a review of the available data and theory on the response of the rotation rate of a neutron star accreting from a stellar wind, see Henrichs (1983).)

Also of interest are the observations by White et al. (1983), who reported rapid X-ray spectral variability from the X-ray binary, 4U1700-37, which was interpreted as being caused by small-scale inhomogeneities in the stellar wind of its optical counterpart, HD 153919, O6.5 Iaf. Unfortunately, the C IV, N V, and Si IV lines in the UV are completely saturated in this star, but similar studies in other wind-fed massive X-ray binaries might be more successful.

Finally, we want to emphasize that one has just begun to realize that variability is a basic signature of stellar winds of all early-type stars and that understanding this phenomenon is essential for a complete understanding of stellar-wind structure. In this chapter, we have tried to focus on the observational evidence for wind variability and have reviewed suggested interpretations and possible related issues. "The best possible data set" to prove or disprove our present thoughts has yet to be constructed. It is the author's hope that this review might help to reach this goal.

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Note added in proof: After this review had been completed, new observations have shown that the reoccurrence time scale of discrete-component episodes in O stars might well be correlated with the stellar rotation period (cf. Figure 4.44b).