Chapter 1

INTRODUCTION

> Every man and every woman is a star.
>
> Every number is infinite; there is no difference.
>
> E. A. Crowley, *Liber A.L. vel Legis*

All stars possess expanding outer atmospheres known as *stellar winds.* This continual mass loss has a significant impact on stellar evolution, the mass and energy balance of the interstellar medium, and even the overall chemical evolution of the Universe. Although the hottest and most luminous stars (spectral types O, B, A, and Wolf-Rayet) are rare, their strong winds play a dominant role in this interstellar and galactic "ecology." By studying the physical mechanisms driving these outflows, as well as their interaction with such stellar processes as rotation, pulsation, and magnetic fields, we are able to better understand the importance of stellar winds to astrophysics as a whole.

The subject of this work is the dynamical interaction between stellar winds, rotation, and pulsation. By synthesizing spectral line profiles from multidimensional hydrodynamical models of winds, we are able to test and compare various theories of time-variable and nonspherical outflow. This Chapter introduces the subject of winds from early-type stars by discussing their astrophysical importance (Section 1.1), providing a brief historical review of the observation of stellar winds (Section 1.2), and outlining the research presented in the remainder of this dissertation (Section 1.3).

1.1 Motivation for Hot Star Wind Research

It is worthwhile to examine briefly how the study of winds from hot stars fits into the broader aims of astronomy. On the largest scale, each generation of stars contributes significantly to the chemical enrichment of its host galaxy. Stellar winds and supernova explosions release heavy elements that were produced by nucleosynthesis in the cores of stars, and the most massive ($M_* \approx 10$–$100\, M_\odot$) and luminous ($L_* \approx 10^4$–$10^6\, L_\odot$) stars, known historically as "early-type," lose mass at a rate of $\dot{M} \approx 10^{-7}$ to 10^{-4} solar masses per year. This implies that a substantial fraction of the star's initial mass can be dispersed during its main sequence lifetime. Maeder (1981) and Abbott (1982b) found that the effect of hot-star winds must be included to accurately model observed He, C, and O mass fractions in the interstellar medium. The high ^{22}Ne/^{20}Ne ratio observed in Galactic cosmic rays has been attributed to the predicted overabundance of ^{22}Ne in the winds of Wolf-Rayet stars (Casse & Paul 1982). Even the overall ionization state of the Galaxy is strongly influenced by wind-dominated H II regions around O stars (Miller & Cox 1993). The details of stellar mass loss are thus quite important to theories of galactic chemistry, structure, and evolution.

On smaller scales, stellar winds strongly affect the mass and energy balance of the interstellar medium in their immediate vicinity. The massive, but short-lived winds from pre-main sequence stars can disrupt the surrounding dense molecular cloud and induce additional star formation. The fast winds from hot main sequence stars and supergiants plow through the interstellar medium and evacuate "bubbles" of rarefied gas (Weaver et al. 1977) which also affect surrounding ionized H II regions (e.g., Yorke 1986). Even the comparatively feeble solar wind, with $\dot{M} \approx 10^{-14}\, M_\odot \mathrm{yr}^{-1}$, leaves its mark on the local interstellar medium (Holzer 1989).

As stars evolve, their mass loss usually increases dramatically. Low-mass stars are believed to form planetary nebulae by ejecting, and subsequently ionizing, the extended envelope of their red supergiant stage (Shklovskij 1956). More massive stars can evolve into luminous blue variables (LBVs), which can expel mass in episodic bursts of up to 1–2 $M_\odot$, or Wolf-Rayet stars, which are inferred to lose up to $\sim 10^{-4}\, M_\odot \mathrm{yr}^{-1}$ (see, e.g., Langer et al. 1994), before eventually becoming supernovae. The massive stellar ejecta associated with these stages of evolution often form observable emission nebulae which provide invaluable diagnostics of the history and dynamics of the star's evolution (Dorland & Montmerle 1987; Marston 1995; Garcia-Segura et al. 1996).

Mass loss also strongly affects the evolution of the stars themselves. Chiosi & Maeder (1986) review how stellar winds influence the internal structure, evolutionary tracks, and ultimate fate of massive stars. Main sequence lifetimes are somewhat longer when mass loss is taken into account, mainly because the progressive reduction of the star's mass reduces the mass of the convective core and decreases the luminosity. Whether a star evolves into a blue or red supergiant, an LBV, or a Wolf-Rayet star sensitively depends on the wind's history, but the more advanced and rapid stages of nuclear burning are less dependent on the dynamics of the outer envelope. Note also that mass loss in close binary systems has another consequence: accretion onto the companion. Some types of binaries (e.g., "semidetached" systems such as Algol or β Lyrae) undergo several evolutionary phases of mass transfer, and winds can be an important part of the overall budget of available circumstellar matter (Eggleton & Pringle 1985; De Greve 1986; Mazzali 1990).

Knowledge about the theoretical mechanisms of stellar wind driving, combined with detailed spectrum synthesis techniques, leads to valuable diagnostics of fundamental stellar parameters: mass, radius, luminosity, and elemental abundance. Such "quantitative spectroscopy" of hot stars is discussed by Kudritzki & Hummer (1990), and has been found to be a highly reliable means of determining these quantities for large samples of stars. This opens the way to using the winds of O, B, A, and Wolf-Rayet stars as standard candles to infer extragalactic distances (see, e.g., Kudritzki et al. 1992; McCarthy et al. 1995).

In addition to the above benefits of understanding hot-star winds to astronomy as a whole, there is another (perhaps more fundamental) reason to study these outflows: they serve as unique laboratories for *radiation hydrodynamics.* Although this term is often used in a broad sense to refer to the quite common situation where radiation affects the energy balance of a fluid (as in Mihalas & Mihalas 1984), here it applies more strictly to the case of photons imparting energy *and* momentum to the system. The physics involved in such coupling is relatively unexplored outside the field of hot-star winds, and we are just beginning to be able to apply results from these models to other luminous systems, such as protostellar jets, pulsars, and active galactic nuclei.

1.2 Overview of the Observations

1.2.1 The Existence of Stellar Winds

The first indirect observations of mass outflow from a star occurred in prehistory. When primitive peoples saw the crown-like solar corona during a total eclipse, and shimmering aurorae in the northern and southern skies, they were viewing the beginning and end points of the solar wind flow that intercepts the earth. Historical records of novae and supernovae also represent observations of dramatic bursts of mass loss from evolved stars, and some objects labeled as novae ("new" stars) were actually hot stars experiencing strong variability in their winds. In 1600, the luminous blue variable P Cygni first appeared as a second magnitude star, and Christian Huygens named it the *"Revenante of the Swan"* because of its ghostly variability (Allen 1899). Between 1830 and 1860, η Carinae experienced remarkable luminosity variations which we now interpret as characteristic of an episodic mass loss of 1–2 solar masses (see Humphreys & Davidson 1994).

However, the first scientific understanding of stellar winds came with the application of spectroscopy to starlight in the late nineteenth century. Many bright lines in the optical spectrum of P Cygni were observed to have redshifted emission peaks combined with blueshifted absorption troughs, and Beals (1929, 1931) interpreted this pattern in terms of continuous ejection of high-velocity material from various types of hot stars (see Section 3.1 for a quantitative derivation). Swings & Struve (1940) estimated the supersonic outflow velocities from several O, B, and LBV stars, and interpreted these as characteristic of an "expanding shell" several stellar radii from the photosphere. Adams & MacCormack (1935) and Deutsch (1956) identified narrow "P Cygni type" profiles in the cores of strong Fraunhofer lines from cool supergiants (spectral types G, K, M), and similarly inferred the presence of winds from these stars. Finally, the existence of a continuously outflowing *solar wind* was realized by Parker (1958, 1963), both from theoretical considerations and mounting observational evidence (see Hundhausen 1972 for a historical review), and was confirmed by *in situ* spacecraft experiments in the early 1960s (Brandt 1970; Ness 1987; Burlaga 1993).

Because stars hotter than $T_{\rm eff} \approx 9000\,{\rm K}$ (spectral type ∼A2) emit their peak radiation in ultraviolet, rather than optical wavelengths, it was not until the rocket ultraviolet observations of Morton (1967a, b) and Morton, Jenkins, & Brooks (1969) that the presence of strong winds from O and B supergiants was directly inferred. The broad P Cygni line profiles of, e.g., the C IV $\lambda\lambda$1548, 1551Å doublet indicate mass loss rates as high as 10^{-6}–10^{-5} $M_{\odot}{\rm yr}^{-1}$ and wind terminal velocities between 600 and 3500 km s^{-1}. Subsequent observations with the *Copernicus* and *IUE* satellites, as well as supporting radio, infrared, and X-ray measurements, have confirmed many details about the nature of winds around hot stars (Cassinelli 1979; Conti & Underhill 1988; Kudritzki & Hummer 1990; Moffat et al. 1994).

Early-type stars do not exhibit the strong sub-surface convection that is present in solar- and late-type stars, so there is negligible evidence for mechanically-heated chromospheres or ultra-hot ($T \approx 10^6$–$10^7\,{\rm K}$) coronae surrounding these objects. Thus, the high thermal pressure which drives the solar wind is not thought to be an important factor in hot-star wind dynamics. However, the relatively high luminosities of O, B, and Wolf-Rayet stars are of crucial importance to the dynamical and ionization states of the circumstellar gas. In this dissertation I will outline and derive the theory of *radiative driving* of stellar winds, i.e., of momentum transfer between the strong radiation field and the atoms and ions surrounding the star. This mechanism is presently believed to be the dominant cause of large-scale continuous mass outflow from all main sequence, giant, and supergiant stars hotter than spectral type ∼B5.

1.2.2 The Effects of Rotation

The study of rotating stars began with the telescopic discovery of sunspots, and their slow motion across the solar disk, by Galileo, Fabricius, and Scheiner in the early 1610s. However, the rotation of other stars was not thought to be detectable until Abney (1877) suggested that the Doppler effect could *broaden* stellar absorption lines from rotating stars. Wavelengths in the light coming from the approaching (receding) edge of the star are blueshifted (redshifted), and some of the weakest spectral lines may disappear below the threshold of detectability. Note that this Doppler broadening is affected only by the projected component of the star's equatorial rotation velocity $V_{\rm eq}$ in the line of sight of the observer. Thus, all that can be theoretically measured from this effect is the product $V_{\rm eq} \sin i$, where i is the inclination angle between the line of sight and the star's rotation axis. The Doppler effect interacts with stellar rotation in another manner in observations of eclipsing binary systems. During partial eclipses only one approaching or receding edge of the occulted star is visible, and the observed radial velocity shifts of spectral lines depart from their systemic values. Following the initial predictions of Holt (1893), Schlesinger (1909, 1910) and Rossiter (1924) confirmed this effect relatively independently.

The strong dynamical effect of *rapid* rotation was suspected when several early-type stars were measured to have projected rotational velocities of 200–400 km s^{-1}, in contrast to the relatively slow (about 2 km s^{-1}) equatorial rotation of the Sun. These extreme velocities, measured primarily in B-type binaries (Shajn & Struve 1929) and single stars (Struve 1930, 1931), are a significant fraction of the "critical" or Keplerian equatorial velocity, which occurs when the outward apparent centrifugal force balances gravity. The theory of the equilibrium form of rapidly rotating fluid bodies has been discussed since Newton's *Principia* (see Tassoul 1978), and the idea that centrally-condensed gaseous spheres will rotationally deform into *oblate* configurations was well-known when Struve (1931) applied it to stars with large $V_{\rm eq} \sin i$.

A distorted gaseous star in radiative and hydrostatic equilibrium exhibits a change in its net radiative flux which is proportional to the local gravity over its surface (von Zeipel 1924; Chandrasekhar 1933). Although this simple picture of "gravity darkening" is not completely time-steady (Eddington 1929; Sweet 1950) and does not take convection into account (see, however, Lucy 1967; Anderson & Shu 1977; Zhou & Leung 1990), it has been seen to provide reliable estimates for the flux variations from early type stars. Slettebak (1949) discussed the variation in effective temperature $T_{\rm eff}$ over the surface of rotationally distorted stars, and computed modified rotationally broadened line profiles. Further refinements in modeling the observable parameters from rapidly rotating stars are reviewed by Tassoul (1978), but note the more recent work of Collins, Truax, & Cranmer (1991) and Collins & Truax (1995).

Stars of spectral type B which exhibit emission in hydrogen Balmer lines are known as *Be stars,* and this subclass has exercised a fascination over spectrographic observers since the nineteenth century. Be stars are among the fastest rotators, and Struve (1931) explained the strong emission in terms of a dense circumstellar disk ejected by a critically rotating "lens-shaped" star. However, it is now generally accepted that most Be stars are rotating at only 60–80% of their critical equatorial velocity (see Slettebak & Snow 1987), and thus some other mechanism is required to produce a dense disk. Like other O and B stars, the ultraviolet spectral lines of Be stars show evidence for substantial stellar winds, with velocities of the order 1000 km s^{-1} and mass loss rates $\dot{M} \approx 10^{-11}$–$10^{-8}\, M_{\odot} \mathrm{yr}^{-1}$ (Snow 1981). Empirical models based on these observations thus generally suggest a two-component envelope, with a low-density, fast polar wind and an orbiting equatorial disk of high-density material with only slow radial outflow (Poeckert & Marlborough 1976; Waters 1986; Waters, Coté, & Lamers 1987; Waters et al. 1988).

The wind from a rapidly rotating star is significantly affected by centrifugal forces. The resulting smaller effective gravity tends to increase the mass loss rate and decrease the wind speed. Gerasimovič (1934) first predicted such a rotational wind enhancement for Be stars, and Limber (1964) constructed phenomenological models of axisymmetric Be-star envelopes based on such a "rotational ejection" paradigm. However, in actual dynamical models of wind acceleration over the equator, this effect is limited to factors of a few, and thus it fails to explain the quite strong (factors of 100–1000) observed equatorial density enhancements in Be star disks (Friend & Abbott 1986). Bjorkman & Cassinelli (1993) have proposed the simple and powerful "wind compressed disk" (WCD) paradigm, which is a two-dimensional model of how rotation can deflect wind flow streamlines toward the equatorial plane to possibly form a shocked disk. Although an important step forward, it seems that some added mechanism, such as magnetic fields or nonradial pulsations, must distinguish the extreme "Be phenomenon" from other, more ubiquitous rotational effects.

Although magnetic fields have only been observed in a relatively small fraction of hot stars (see Moss & Smith 1981; Bohlender 1994), the presence of even quite weak fields can have a strong impact on modulating the circumstellar material. In the solar wind, the detailed field structure in the lower corona determines how the density and velocity vary throughout the entire heliosphere (Hundhausen 1972; Zirker 1977). Models of open magnetic fields in O- and B-star winds have been limited to one dimension (Friend & MacGregor 1984; Poe & Friend 1986), and although the wind over the equator of a rotating and magnetic star is "spun up" by the field, only extremely rapidly rotating models ($V_{\rm eq} \approx V_{\rm crit}$) exhibit large equatorial density enhancements. A more complete magnetohydrodynamic treatment of the near-star *dipole* nature of the field is definitely needed, akin to the solar wind model of Pneuman & Kopp (1971), in order to accurately assess the importance of magnetic fields in rotating hot stars.

1.2.3 Variability and Inhomogeneity

The atmospheres and winds of most early-type stars are intrinsically variable on time scales ranging from hours to years. Periodic variability in photospheric absorption lines is often identified with radial or nonradial pulsations of the underlying star, while the more complex variability in P Cygni type wind lines is still poorly understood. Most theories concerning the origin of these variations involve the existence of highly-structured, non-spherically symmetric winds. Because there are many physical mechanisms that can lead to wind structure and variability, it is useful to distinguish between (1) *small-scale* stochastic fluctuations, intrinsic to the wind itself, and (2) *large-scale* quasi-regular variability, induced by changes in the underlying star. In the former category is the shocked structure arising from the strong instability of the radiation-driving mechanism (Rybicki 1987; Owocki 1992), which may explain black troughs in saturated ultraviolet P Cygni lines in O and B stars (Lucy 1982; Puls, Owocki, & Fullerton 1993), shock-heated X-ray emission (Cohen et al. 1996), and moving "bumps" in Wolf-Rayet optical emission lines (Robert 1994).

In this work, however, we will concentrate mainly on the latter, larger-scale wind structure that can be attributed to the dynamical effects of rotation, magnetic fields, or pulsations. This "wind activity" has been observed indirectly in the highly-variable emission lines of Be stars for almost a century (see Underhill & Doazan 1982; Slettebak & Snow 1987), but only recently has this variability been found to be so widespread in most O and B stars. Early repeated observations of wind diagnostics such as Hα (Ebbets 1982) and ultraviolet resonance lines (York et al. 1977; Snow 1977) showed drastic changes in line profile shapes and strengths. The relation between this wind variability and the rotation or pulsation of the underlying star has been suspected for some time, and the attendees of a workshop on Instability and Variability of Hot-Star Winds (Moffat et al. 1994) proposed that a long continuous time series was required to identify such a connection. This proposal evolved into the *IUE* "MEGA" campaign (Massa et al. 1995), which observed three hot stars nearly continuously for 16 days. This groundbreaking data set provides the major observational impetus for many of the theoretical models in this dissertation.

The most conspicuous of the variations in the blueshifted absorption troughs of ultraviolet P Cygni profiles are the *discrete absorption components* (DACs), which appear as narrow and localized optical depth enhancements in unsaturated lines, in some stars even dominating the "mean wind" absorption. DACs are present in a majority of O-star (Howarth & Prinja 1989) and Be-star (Grady, Bjorkman, & Snow 1987) winds, and are typically seen to accelerate to the blue wing of the profile over a few days, becoming narrower as they approach an asymptotic velocity. Prinja (1988) and Henrichs, Kaper, & Zwarthoed (1988) found an apparent correlation between both the recurrence and acceleration time scales of DACs (typically of the same order as each other) and the projected rotational velocity of the star, $V_{\rm eq} \sin i$. Corresponding and often temporally-correlated variability is seen in the blue edge fluctuations of saturated ultraviolet P Cygni lines, in the low-velocity variability of subordinate-level P Cygni lines, and in optical lines such as Hα and He II λ4686, suggesting a single dynamical phenomenon reaching down to very near the photosphere (Henrichs, Kaper, & Nichols 1994).

Attempts to model DACs have been progressively constrained by better observations. By studying lines of different ionization species, Lamers, Gathier, & Snow (1982) ruled out the early supposition that DACs might be caused by ionization gradients in an otherwise spherically symmetric and time steady wind. The episodic ejection of spherical "shells" of increased mass loss was an often-invoked model for a time, but the lack of both *emission* variability in ultraviolet P Cygni lines (Prinja & Howarth 1988) and significant infrared variability (Howarth 1992) seems to rule out a spherically-symmetric disturbance (see, however, the kinematic models of Waldron et al. 1994). On the other hand, to produce the observed strong absorption dips, the structure must be large enough to cover a substantial fraction of the stellar disk. This seems to rule out the small-scale wind instability as the source of most DAC clumpiness, since global averaging would weaken the observable signature (Owocki 1994). Also, Rybicki, Owocki, & Castor (1990) showed that small-scale, lateral velocity perturbations should be strongly damped, and so should not disrupt the horizontal scale size set by base variations. Altogether, these constraints suggest that DACs originate from moderate size wind structures, e.g., spatially-localized clouds, streams, or "blobs."

Of particular interest is the apparent acceleration rate of DACs. When compared to the acceleration of the mean wind inferred from line-driven flow theory and detailed profile fitting, some (typically weaker) DACs seem to be passively carried along the same velocity law (see, e.g., Kaper 1993). But most strong DACs accelerate much more *slowly* (Prinja 1994), suggesting they may not represent a single mass-conserving feature, but rather might arise from a slowly evolving *pattern* or perturbation through which wind material flows. The enhanced optical depth could result from either a higher density or a lower wind velocity gradient (a "plateau"), or by a combination of the two (Fullerton & Owocki 1992; Owocki, Fullerton, & Puls

1994), as is found in the dynamical models presented in this dissertation (Chapter 6).

Mullan (1984a, b; 1986) proposed that DACs and related phenomena could arise from "corotating interaction regions" (CIRs) analogous to those commonly observed *in situ* in the solar wind. In the solar corona, regions of open magnetic field cause the flow from coronal holes to be accelerated faster than the mean ecliptic-plane wind, resulting in colliding fast and slow streams strung into spiral CIR patterns by rotation (Hundhausen 1972; Zirker 1977). These nonlinear interacting streams eventually steepen into oblique corotating shocks, through which the wind flows nearly radially. Mullan (1984a) showed that CIRs can form in winds from a wide variety of stars, and depend primarily on a longitudinal asymmetry in wind velocity or density. Because hot stars do not have the strong surface convection and coronae known to exist in the sun, the "seed" mechanism for large-scale azimuthal perturbations may be quite different.

In this work we do not adhere to any particular model for these photospheric variations, but several plausible scenarios have been proposed. Underhill & Fahey (1984) modeled assumed time-steady DAC velocities in terms of varying acceleration above small patches of enhanced magnetic field. Henrichs et al. (1994) found that DAC accelerations correlate well with a corotating magnetic dipole configuration on the stellar surface. Indeed, Henrichs et al. (1995) have recently begun to detect these weak time-variable surface fields. Nonradial pulsations have also been observed in many OB stars, and have been shown to be able to induce localized increased mass loss and outward angular momentum transfer (Castor 1986; Willson 1986; Ando 1991). Henrichs (1984) discussed the possible connection between pulsations and DACs, and the ubiquity and strength of these oscillations in the outer layers of hot stars makes them likely to influence the wind. Also, circumstellar disks exhibit many natural large-scale instabilities, e.g. Okazaki's (1991) global one-armed normal modes, which may be correlated with DAC variability in Be stars (Telting & Kaper 1994). Finally, Dowling & Spiegel (1990) discuss the possible existence of Jupiter-like zonal bands and vortices in the atmospheres of hot stars, and give order-of-magnitude estimates of the flux enhancement over a "Great Red Spot" type of shear pattern.

Several qualitative attempts have been made to apply the CIR picture to observations of time variability in early-type stellar winds, but all have been *kinematic* in nature. Prinja & Howarth (1988) fit slowly-accelerating spiral streamlines to DACs in time series spectra from the O7.5 giant 68 Cyg, and showed that the narrowing of the absorption feature as it accelerates can be explained roughly by the decrease in the line-of-sight velocity gradient of the CIR. Harmanec (1991) extended this analysis and discussed possible observational signatures of CIRs in other classes of early-type stars. Rotationally-modulated gas streams or "spokes" have been proposed in models of Be star circumstellar material (see, e.g., Štefl et al. 1995) and in the time variability of Herbig Ae star spectra (Catala et al. 1991). Of course, the physics of circumstellar streams in Be and Herbig Ae stars will most likely be very different from that of corresponding structures around O stars, and we will focus mainly on the latter.

1.3 Goals of this Work

This dissertation represents research performed between 1992 and 1996 at the Bartol Research Institute. Herein I address several problems in the observations of hot-star winds by constructing radiation hydrodynamical models of these winds and synthesizing spectroscopic and polarization diagnostics to compare with observations. Chapter 2 outlines the current state of the theory of radiatively driven stellar winds and concentrate on spherically-symmetric solutions to the equations of radiation hydrodynamics. I derive the radiative force in the "Sobolev approximation," consider driving by various forms of continuum and line opacity, and present analytic and numerical solutions for the wind's velocity and density. In Chapter 3, I utilize such solutions for the purpose of synthesizing observational diagnostics of stellar winds. The major goal of this Chapter is the derivation of several techniques of creating theoretical ultraviolet P Cygni line profiles, but I also discuss the importance of the linear polarization of stellar envelopes, and provide a straightforward means of approximating this polarization for general circumstellar gas distributions.

The role of rapid stellar rotation is central to the formation of nonspherical and temporally variable circumstellar structures. In Chapter 4, I describe three physical consequences of the strong *centrifugal* force from a rotating star: (1) oblateness and gravity darkening in the interior and photosphere, (2) the modulation of the flux and effective gravity in the wind and the possible loss of steady-state flow solutions, and (3) the existence of nonradial line forces which can remove large amounts of angular momentum from a rotating and expanding wind. Another important rotational effect is discussed in Chapter 5: the two-dimensional "wind compressed disk" model of Bjorkman & Cassinelli (1993). This was the first original research with which I was involved at Bartol, and this Chapter outlines my contribution to the work of Owocki, Cranmer, & Blondin (1994), Cranmer & Owocki (1995), and Owocki, Gayley, & Cranmer (1996).

Subsequent research has been concerned with modeling the complex variability observed in P Cygni spectral lines, and Chapter 6 contains the results of hydrodynamical simulations of corotating interaction regions (CIRs) in the equatorial plane of a rotating wind. We find that a "bright spot" of enhanced mass loss from the photosphere leads to rotating circumstellar structure which reproduces many of the observed properties of discrete absorption components (DACs) in ultraviolet P Cygni profiles. This work has been published as Cranmer & Owocki (1996). Chapter 7 begins to address the question of the physical origin of the photospheric base perturbations of Chapter 6, and I outline the theory of *nonradial oscillations* in the interior, photosphere, and wind of a rotating star. Some of the insight gained from the recent results of Owocki, Cranmer, & Fullerton (1995) and Cranmer, Massa, & Owocki (1996) is included, but this work is still in progress. Finally, Chapter 8 contains a brief overview and discussion of this dissertation work, as well as an outline of future research that would address important questions about the radiation hydrodynamics of rotating hot-star winds.