Chapter 8

SUMMARY AND CONCLUSIONS

Small and transitory is man.
Already he is behind you, and
once again ye find yourselves in endless space,
in the smaller or innermost infinity.

At immeasurable distance standeth
one single Star in the zenith.

C. G. Jung, *Septem Sermones ad Mortuos*

8.1 Overview of Current Work

The purpose of this dissertation has been to explore how rapid stellar rotation and pulsation affect the radiation-driven winds around early-type stars. Here I present the most important results and conclusions from this work and outline some ongoing and future projects related to the topic of rotating hot-star winds.

After a brief motivational introduction in Chapter 1, the theory of radiatively driven winds was presented in Chapter 2. One important new result is the impact of *limb darkening* on the line radiation force as discussed in Section 2.2.4. The intensity distribution from a limb-darkened star is intermediate between a purely-radial "point source" and the traditional uniformly-bright "finite disk." We thus expect a $\sim$ 10–15% increase in theoretical mass loss rates, and a similar decrease in theoretical terminal velocities compared with the current standard mCAK-type models. Also, in Section 2.3.2, I introduced a new approximation method for estimating the terminal velocity v_∞ (eq. [2.120]) which, despite a relatively insensitive dependence on the assumed β exponent, gives results of similar accuracy as the more complicated (but widely used) Kudritzki et al. (1989) so-called "cooking recipe." In addition, the present approximation for v_∞ (in, e.g., eq. [2.123]) concisely illustrates the phenomenon of the loss of steady-state wind solutions for large mass loss rates.

In Chapter 4 we began to examine the interaction between stellar rotation and winds, and we found that the presence of von Zeipel *gravity darkening* governs the latitudinal variation of mass flux from a rotating oblate star. The resulting decrease in the equatorial mass loss runs counter to the expected increase due to the centrifugal weakening of gravity. The accurate computation of *nonradial* Sobolev line forces in Chapters 4 and 5, which tend to point latitudinally away from the equator and azimuthally opposite the rotation, seems to lead to the weakening or inhibition of the Bjorkman & Cassinelli (1993) "wind compressed disk" phenomenon. More work needs to be done to ensure that all relevant physics has been included, and Owocki, Gayley, & Cranmer (1996) have constructed preliminary two-dimensional hydrodynamical models incorporating these effects.

The intrinsic time variability of rotating hot-star winds is beginning to be addressed by use of dynamical models, and in Chapter 6 we verified Mullan's (1984a) suggestion that corotating interaction regions (CIRs) can give rise to spectral variability very similar to the observed discrete absorption components (DACs) in ultraviolet lines. By varying the Sobolev radiation force over a bright (dark) "star spot" in the equatorial plane, we produce an increase (decrease) in the localized mass loss. This in turn affects the wind's acceleration and leads to nonlinear shocks and "kinks" in the radial velocity. These kinks, or gradient discontinuities, contain the greatest optical depth, and their supersonic inward propagation (in the frame of the wind; see Abbott 1980) results in a *slow* outward propagation that reproduces well the $\beta \approx$ 2–4 acceleration seen in DACs.

An interesting link between the meridionally-symmetric rotation models of Chapters 4 and 5 and the CIR models of Chapter 6 is the importance of the nonlinear *feedback* in line-driven winds between the radiative flux, the mass flux, and the wind acceleration. Darker regions on a star, for example, are given a lower mass flux and density, but the resulting velocity depends sensitively on various competing terms in the equation of motion. When von Zeipel gravity darkening causes the flux dimunition, the wind velocity will probably decrease along with the escape speed, but if some other mechanism leads to a dark, but finite, star-spot, the velocity will eventually increase as it leaves the spot's influence. A recurring theme of these models, then, is that the *dynamics* (i.e., the accurate computation of forces and their impact on the wind) must be modeled consistently to be able to predict the consequences of any large or small scale perturbations on a wind.

The physical mechanisms responsible for producing the wind structure that leads to time variability, however, are far from clear. In Chapter 7 we outlined the theory behind nonradial stellar pulsations and their wavelike propagation into the wind, and in some cases this can provide the required "photospheric connection" between interior and wind variability. There are three current projects with which I am involved that apply this pulsational theory to currently unexplained spectroscopic wind data:

1. **IUE "MEGA" Observations of HD 64760:** In addition to slow DACs, many stars also exhibit a faster periodic type of wind modulation that appears to simultaneously accelerate and decelerate in time. Owocki, Cranmer, & Fullerton (1995) explained these "banana" shaped modulations in terms of corotating spiral streams passing in and out of the absorption column in the line of sight towards the star. For the B supergiant HD 64760, variations appear to occur on a time scale of 1/4 of the rotation period, and it is unclear whether these are $|m| = 4$ modulations rooted to the star, or are due to some other NRP mode with only $\omega_{\text{observed}} \approx 4\Omega$ (see eq. [7.66]).
2. **IUE Observations of BW Vul:** The slowly-rotating β Cephei pulsator BW Vulpeculae has been observed to exhibit transient mass loss in the form of strong DACs which propagate out to $\sim 1000\,\text{km s}^{-1}$ every pulsation period ($P \approx 4.8\,\text{hr}$). Cranmer, Massa, & Owocki (1996) constructed a 1D time-dependent dynamical model of a B-star wind perturbed by a strong nonlinear gravo-acoustic wave at the subsonic wind base. The resulting spherical kink/shock structures (similar to the "dark spot" Model 2 of Chapter 6) qualitatively reproduce the DAC variability and discontinuous radial velocity curve of BW Vul, but more work needs to be done to accurately determine the wind and pulsation parameters from detailed fits to the spectra.
3. **GHRS and ORFEUS Observations of γ Cas:** In collaboration with M. A. Smith, I am assisting in the interpretation and modeling of highly-variable absorption line spectra from this bright Be star. By comparing DACs and other "migrating subfeatures" in lines from many different ions, the wind dynamics can be traced as a function of velocity/distance from the star. For example, by use of the "Van Hoof effect" (see Mathias & Gillet 1993), the phase lag between different ions can provide accurate information about the propagation of waves and shocks through the wind.

In addition to exploring the effects of rotation and pulsation on hot-star winds, I have worked on various other projects relating to observations of early-type stars. The radiative transfer in close and contact binary systems is a fascinating and complex field. Incident light from one photosphere to the other can heat up the upper regions of each stellar atmosphere and alter observed light and polarization variations (Cranmer 1993). Also, in binaries containing an O star and a Wolf-Rayet star, the ram pressure balance between the two *winds* can be strongly affected by the momentum flux of photons from the (usually brighter) O star (Gayley, Owocki, & Cranmer 1996).

8.2 Future Research Goals

There remains much work to be done, both in continuing the theoretical work outlined in this dissertation and in incorporating new physics into models of rotating hot-star winds. Ongoing research is focused into two major areas: the effects of rapid rotation (i.e., models with meridional r,θ symmetry) and the photospheric mechanisms responsible for time variability (usually, models in the equatorial plane, varying r,ϕ). As mentioned earlier, Owocki, Gayley, & Cranmer (1996) have constructed 2D hydrodynamical models which incorporate the oblateness, gravity darkening, and nonradial Sobolev forces into the computation of the wind around an axisymmetric rotating star. In contrast with the WCD paradigm of Bjorkman & Cassinelli (1993), these models show a net *poleward* deflection of wind streamlines, resulting in enhanced density and mass flux over the poles and a low-density depletion around the equator. In addition to O and B stars, these models may be pertinent to the evolution of luminous blue variables (LBVs) such as η Carinae, which exhibits very prominent bipolar lobes in addition to an equatorial disk-like structure (see, e.g., Mac Low, Langer, & Garcia-Segura 1996).

Although the WCD model was originally intended to explain the dense disks around Be stars, it is growing clearer that some other mechanism is necessary to produce this dramatic phenomenon. We plan to investigate the physics responsible for these Keplerian ($v_\phi \propto r^{-1/2}$) and negligibly expanding ($v_r \lesssim a$) disks from the standpoint of three possible effects. First, magnetic fields are suspected to exist in all stars, and even fields below current observational thresholds (typically 100 Gauss) can have a significant influence in channeling the wind in complex ways. Specifically, a dipole field aligned with the rotation axis may redirect wind streamlines toward the equatorial plane as in the solar model of Pneuman & Kopp (1971). Second, Osaki (1986) and Saio (1994) discuss the outward transport of angular momentum by nonadiabatic NRPs, and we suspect that even *adiabatic* pulsations can spin up the equatorial wind if they have the proper phase behavior. The presence of the accelerating medium and the existence of complex toroidal oscillations may result in the gradual buildup of dense, critically-rotating circumstellar material. Third, the actual rotational velocity fields of Be stars need to be re-examined carefully; differential rotation and gravity darkening can alter observed $V_{\rm eq} \sin i$ values to mask a possibly "super-breakup" rotating equator (see, e.g., Collins & Truax 1995).

Besides this current work on the effects of rotation on winds, we are also continuing efforts to better understand observed *variability* (DACs, blue-edge variations, "bananas," Wolf-Rayet emission subfeatures) in terms of physical processes linking the interior, photosphere, and wind. Over the past decade, as observations of spectral wind diagnostics have improved, the sheer complexity of these quasi-regular large-scale variations have become evident (Massa et al. 1995; Kaper et al. 1996; Prinja et al. 1996). Many stars, such as HD 64760 (see above), have shown epochal variations in both their photospheric pulsations (e.g., individual modes appearing and disappearing) and their wind variability. Other stars, like EZ CMa (HD 50896; WN5) have preserved a consistent, possibly rotational "clock" over the years, but the variations have appeared qualitatively different. St-Louis et al. (1995) interpret this in terms of small-scale evolving magnetic field regions carried around with the stellar rotation. Whether most DAC-like variability is due to NRPs or magnetic fields, it is important to better understand both the periodic *and* transient behavior that is expected in such winds (see Wang, Ulrich, & Coroniti 1995).

One "transient" physical mechanism neglected in this dissertation has been the line-driven instability of hot-star winds (OR-I, II, III; Owocki 1991, 1992, 1994). Despite the conjecture that this intrinsic instability will result only in *small-scale* variability (which gets averaged out over the entire stellar disk), it is not clear how the various large-scale photospheric perturbations mentioned above will react with the instability. Fullerton & Owocki (1992) and Owocki, Fullerton, & Puls (1994) performed numerical experiments with large 1D base perturbations in an unstable wind, and found significant, possibly observable transient spectral variability. It is now becoming possible to incorporate the full non-Sobolev line force (e.g., Owocki & Puls 1996) into 2D and 3D hydrodynamical models, and it will be important to verify the results from the multidimensional Sobolev models presented in this dissertation.

The importance of simple physical models, however, should not be underestimated. Breakthroughs in computer technology allow us to simulate nature in more and more detail, but this demands more and more critical understanding of the physics behind these models. The standard progression in theoretical astrophysics from a simple "cartoon" paradigm to numerical simulations should be followed whenever possible by a *return* to an analysis of the basic physics of the problem. Hopefully in this dissertation I have laid the necessary groundwork for such understanding of the selected aspects of rotating and pulsating winds.

Finally, then, the research presented here raises many more questions than it answers. This may surprise those that consider stellar astrophysics to be a "mature" field with few fundamental issues left unknown. In fact, this characterization refers only to the standard, early twentieth century picture of stars as spherical, static, and closed systems. The *actual stars,* however, continue to reveal new and fascinating physical processes with each new observation, and this enlivens the development of new theory and insight.