Recent Progress in Theory of Stellar Mass Loss

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Over the past few years, there has been significant progress in extending the standard CAK theory for radiatively driven mass loss from hot, luminous stars to include many additional processes, e.g.: instability and variability; large and small scale structure; rotational distortion and modulation; photospheric shadowing and ion separation (e.g. in thin B-star winds); and NLTE optically thick transfer and multiline scattering (particularly in dense WR-star winds).

Regarding wind variability there has emerged a consensus that the associated flow structure must generally exist on both large and small spatial scales. Small-scale, stochastic structure can arise intrinsically from the inherent instability of the radiative driving. There has been progress in calculating the energy transfer in instability-generated shocks, and in estimating the associated X-ray emission. But the reverse shocks that arise directly from the instability yield only a quite small X-ray fillng factor, and so achieving the observed X-ray luminosity, particularly from low-density winds, requires additional, stochastic collision between dense clumps within the wind. Synthesis of UV wind lines from time-dependent instability simulation models have recently proven quite successful in reproducing key profile features, like the extended black absorption troughs of saturated P-Cygni lines. Such relatively small-scale stochastic structure might also explain the multiple "moving bumps" seen in relatively high signal-to-noise spectra of optical emission lines formed in Wolf-Rayet winds, which recent wavelet transform analyses suggest may even be represented by a characteristic scaling law analogous to that found in turbulent flows.

On the other hand, for the most common form of explicit wind variability – namely the recurring "Discrete Absorption Components" (DACs) often seen in unsaturated UV wind lines detected with low S/N IUE spectra – recent modelling has centered on multi-dimensional dynamical simulations of Co-rotating Interaction Regions (CIRs), in which *large-scale*, spiral wind structure is explicitly induced at the wind base by some disturbance from the underlying rotating star. The apparent slow evolution of DACs can arise in such models from either the relatively slow acceleration of the denser, compressed wind structures, or from velocity-gradient "kinks" that propagate upstream at the relatively fast speed of radiatively modified acoustic waves. Spiral streams of enhanced density also provide a possible explanation for the sometimes upwardly, bowed "banana" shape contours of periodic absorption modulations detected in the recent IUE 'Mega' campaign for long-term monitoring of UV wind line variability.

Much recent work has also examined the role of rapid stellar rotation in focussing wind material into an equatorial "Wind Compressed Disk" (WCD). Dynamical simulations that assume strictly radial line-forces have generally confirmed this wind compression process, but have shown the disk density buildup is limited by leakage of material through both inner-disk infall and outer-disk outflow. Application of this WCD paradigm to Be stars has thus required quite high mass loss rates in order to achieve sufficient disk density to produce, e.g., the observed level of H-alpha emission or continuum polarization (although recent Monte Carlo simulations show that multiple scattering can have the somewhat surprising effect of *enhancing* the polarization over that predicted from a simple, optically-thin analysis). Subsequent work has analyzed the potential role that such wind compression effects could play in wide range of mass outflows, e.g. from Wolf-Rayet stars, Asymptotic Giant Branch stars, B[e] stars, and novae. For outflows with a sufficiently slow initial acceleration, a milder equatorial density enhancement (a "wind compressed zone', or WCZ) can occur even in relatively slow stellar rotators, with rotation speeds well below either the critical "breakup" speed or the outflow terminal speed. For line-driven outflows, however, recent dynamical simulations have indicated that *nonradial* components of the line-force can play a surprisingly strong role, effectively reversing the equatorward flow and thus completely inhibiting formation of a WCD or WCZ. Paradoxically, these simulations have even suggested that, if gravity darkening is taken into account, then the flow from the equator could actually have a *lower* mass loss rate and density than that from the poles!

Apart from such effects of variability and rotation, there has also been considerable effort toward extending spherically symmetric, steady-state wind models. In relatively thin B-star winds, this has focussed on the dual effects of the ion separation and photospheric shadowing. Analysis has shown that the low collision rate from Coulomb friction can lead to ion runaway and thus a multicomponent nature to low density winds. In addition, photospheric shadowing by the Stark-broadened photospheric profile can significantly affect the force from the few strong lines that dominate the driving of such winds. Taking this into account, the predicted domains delineating the progressive transition from single-fluid to multicomponent to neglible wind seems in good general agreement with the occurence of photospheric abundance anomalies.

For the opposite extreme of the very dense, optically thick winds from Wolf-Rayet stars, there has been considerable progress in understanding the multiline scattering processes necessary to drive the flow. Within an idealized model in which the spectral distribution of lines is assumed to be "effectively gray", both Monte Carlo and nonisotropic diffusion treatments have shown that the standard CAK approach can be extended straightforwardly to the multiline scattering case in which the radial momentum of the wind significantly exceeds that of the photons. This emphasized that the usual WR wind "momentum problem" could be better characterized as an "opacity problem" of identifying enough strong lines with sufficiently broad frequency spacing to avoid large gaps in the spectral distributions. More realistic models based on actual atomic line-lists have indicated that the radial stratification of ionization stages could a key role in filling such spectral gaps. General efforts have focussed on how this ionization stratification is controlled by line-blanketing effects, with particular emphasis on the possible role of effective photon destruction in the He II Ly-alpha transition in fostering recombination in helium, and thus also in a host of elements whose ionization is controlled by the He I continuum.

For O-star winds recent efforts have been toward extending unified wind-atmosphere models and testing these against observations, with emphasis on calibrating a wind-luminosity relation that could provide a standard candle for extragalactic distance determination. Through interactive application of fast NLTE codes to match observed line diagnostics of wind mass loss rates, particularly H-alpha, in large sample of O-stars, the wind momentum numbers from theoretical models have been found to have significantly weaker luminosity dependence than inferred from observations. Recent efforts have focussed on examining the role of rotationally induced wind compression effects on the use of H-alpha emission as mass-loss-rate diagnostic.

Finally, there have been continuing efforts toward understanding the consequences of mass loss for the overall structure and evolution of massive stars. This has included initial efforts to develop unified models of interior-atmosphere-wind that take account of the effect of the systematic wind depletion of the stellar mass. There have also been dynamical models of the effect of various phases of evolution on the successive layers of wind-blown nebulae, in some cases also including the effects of rotationally induced wind compression in producing the observed nonspherical shapes. Other studies have focussed on the role of such wind blown nebulae and bubbles in triggering further star formation, including the starburst epochs apparent in many galaxies.