

## Recent Advances in Studies of Stellar Mass Loss

A contribution by S. Owocki to IAU Commision 36 Triennial Report for 1996-9

Recent studies of stellar wind mass loss have included important conceptual advances in the nature of radiative driving, as well as application to a broader range of physical domains, including in rotating stars, and flows from disks in accretion systems.

A useful conceptual advance regards K. Gayley's recasting of the standard CAK line driving parameters in terms of a characteristic line-resonance quality factor,  $\bar{Q} \approx 2 \times 10^3$ , whose magnitude is expected to be roughly constant over a wide range of conditions. In addition to removing certain disadvantages of previous scalings (e.g. artificial dependence on a fiducial ion thermal speed), this provides a convenient means for estimating several key aspects of line driving, e.g. potential for instabilities, and a minimum Eddington parameter  $\Gamma > 1/\bar{Q}$  for effective mass-loss. Further detailed NLTE analyses of line-statistics by J. Puls and colleagues in Munich generally confirm the  $\bar{Q}$  picture for hot, O-type stars, but suggest key revisions are needed for the cooler B-type stars to account for a general mismatch between the spectral distributions of stellar flux and line-opacity.

R. Kudritzki and colleagues have shown that observationally inferred mass loss rates and terminal speeds of galactic O supergiants follow closely a wind-momentum-luminosity (WML) relation that is predicted from CAK line-driving theory, with a nearly constant, unique overall line normalization (corresponding to  $\bar{Q} \sim 10^3$ ) and slope parameter ( $\alpha' \sim 0.57$ ). Current observational programs for extragalactic stars are focussed on calibrating the metallicity dependence of this WML relation, with ultimate aim of applying it as an alternative standard candle for extragalactic distance determinations.

Observational analyses by H. Lamers and colleagues in Utrecht have revealed an abrupt decrease in the ratio of wind terminal speed to stellar escape speed for supergiants cooler than B2. Theoretical calculations in both the Utrecht and Munich groups are examining how such velocity changes may be related to the expected "bistability" shift in the line-driving distribution, particularly the slope parameter  $\alpha$ . Independent NLTE models in both groups are also focussing on quantifying earlier suggestions that such bistability shifts in the equatorial winds of rapidly rotating B-supergiants could provide a model for the B[e] stars.

For nonsupergiant B-stars, there has recently arisen a notion of failed winds. C. Howk and colleagues have proposed that reaccretion of wind blobs in  $\tau$  Sco can explain the red-shifted absorption seen in OVI lines, with reaccretion shocks also providing a means to produce the anomalous hard X-ray spectrum. Independent analyses by J. Porter suggest that such reaccretion might be a natural result of wind stalling due to runaway decoupling of the line-driven minor ions from the bulk proton-helium plasma.

J. Puls and S. Owocki have developed new escape integral methods for computing the line-driving force within numerical simulations of the strong line-driven instability of hot-star winds. An unexpected outcome has been to illuminate more clearly the limitations of the standard, Sobolev approach that forms the basis of the usual CAK theory. In particular, asymmetries in the escape probability in the transonic region of the flow lead to a breakdown in the usual local CAK/Sobolev approach. The effect is estimated to be most severe for lower density winds from B-stars. For O-type supergiants, coupling between line and continuum transfer in the transonic region tends to mitigate the breakdown, in accord with earlier comoving frame transfer calculations that had validated the CAK/Sobolev approach.

For Wolf-Rayet winds independent analyses by J. Hillier, T. Nugis, A. Cherepashchuk and colleagues indicate that extensive wind clumping may be causing a factor  $\sim 3$  overestimate in mass loss rates inferred from standard line emission measures. The implied lower mass loss rates have important implications for both WR star evolution, and for understanding the wind dynamics. Recent dynamical models by W. Schmutz and others focus on the role of "photon loss" in He II Ly-alpha in inducing a Helium-lead wind recombination, and on the general role of ionization stratification in filling gaps in line spectral distributions. Extensive wavelet analyses by S. Lepine of emission line bumps associated with wind clumps indicate that the WR wind acceleration must extend over a scale 10-50 times the estimate WR core radius. Reproducing this extended acceleration and the large WR mass loss remain substantial challenges for dynamical models.

Several recent efforts have centered on extending the CAK line-driving formalism to luminous accretion disk winds, with potential application to cataclysmic variables (CV) and the broad-line flows inferred from QSO/AGNs. Numerical simulations by D. Proga and colleagues indicate that disk winds can have an intrinsic variability associated with the lack of an unique, steady outflow solution. Analytic analyses by A. Feldmeier and I. Shlosman emphasize key differences in the wind solution topology arising from non-monotonic variation

of the effective gravity of disk winds. Despite these differences, the overall scalings of mass loss and flow speed are found to follow laws analogous to the CAK results for stars. For CVs, a key problem is that the disk Eddington parameters  $\Gamma$  are generally below the minimum value  $1/\bar{Q} \sim 10^{-3}$  needed for optically thick line-driving. For QSOs, a key problem is the shielding of the line-driven gas from the ionizing X-ray radiation of the central engine. Analyses by N. Murray and J. Chiang suggest that shielding of the outer disk wind might be provided by ionization of the failed wind from the inner disk.

For disks of classical Be stars, recent observational analyses by P. Hanushik and colleagues of disk emission lines indicate that Be disks must be in nearly static, Keplerian orbit, in strong contrast to predictions of the Wind Compressed Disk model proposed earlier by J. Bjorkman and J. Cassinelli. Smoothed particle hydrodynamical simulations by P. Kroll suggest an alternative picture in which material ejected isotropically from a localized surface region could feed a circumstellar disk. Observations by T. Rivinius and colleagues indicate a close connection between disk-feeding outbursts and resonances in the multiple modes of non-radial pulsation on the Be star  $\mu$  Cen. A key question regards how pulsations with a sound-speed velocity amplitude of order a few times 10 km/s can induce mass ejections with a speed of some  $\sim 200$  km/s needed to reach near-star orbit.