A Massive Star Odyssey, from Main Sequence to Supernova
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Special session on recent advances in nebular diagnostics

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Abstract. Nebular emission-line spectra offer fundamental tests for models of stellar atmospheres, and ultimately, they offer important probes of massive star properties in situations where the stars themselves are unresolved or obscured. Presentations in the first half of this special session focused on the impact of revised stellar properties for O-type and Wolf-Rayet stars on the effective temperature scale and on their Lyman continuum fluxes, whilst the second half emphasized the relationship of nebular diagnostics with stellar atmospheres.

1. Part one

Conti began the session with a brief discussion of the discrepancy between results from infrared nebular studies of the ultracompact H II region G 29.96–0.02 which indicate a late-O ionizing source, with those from recent K-band spectroscopy, which *reveals* a mid-O-type star. He proposed that the nebular analysis could be at fault, which might only be resolved once IR nebular studies are compared with optical nebular techniques of the same object, whose stellar properties are well established. However, as pointed out by Schaerer, taking various uncertainties and especially the still uncertain spectral type and luminosity class determination into account, the different indicators can reasonably be reconciled (Morisset *et al.* 2002). Puls presented a new substantial grid of theoretical models calculated for O-type stars with the FASTWIND code (Herrero *et al.* 2002) which include sphericity and line blanketing. For Galactic O-type stars, a downward revision of up to 8 000 K in stellar temperatures was indicated relative to previous unblanketed plane-parallel results, with the greatest effect for early O-type stars. At lower metallicity, downward revisions are no greater than 3 000 K and negligible for late O-type stars with weak winds. F. Martins provided a comparison of the ionizing flux distributions obtained with the spherical, line-blanketed codes CMFGEN (Hillier & Miller 1998) and WMbasic (Pauldrach *et al.* 2001). An overall good consistency between these two codes was found, and the former have already revealed a reduction in stellar temperatures for O-type dwarfs (Martins *et al.* 2002). Norris discussed revisions in ionizing flux distributions of Wolf-Rayet stars. The success of CMFGEN line-blanketed models in reproducing the nebular ionizing flux distribution of M1-67 was summarised, which has a WN8 central star (WR 124). The nebular He II λ4686 strength for the H II region associated with BAT99-2 (WN2) in the LMC was also well reproduced with CMFGEN. These results give confidence in the use of such ionizing fluxes in evolutionary synthesis models (Smith *et al.* 2002).

Crowther led the subsequent general discussion. A larger sample of compact or ultracompact H II regions needs to be studied for which the characteristics of the ionizing source are known, in order to investigate whether there are systematic problems with IR nebular diagnostics. Perhaps young massive stars such as the central source of G 29.96–0.02, are rapidly rotating, non-spherical, with hotter poles than equators. Might such a system viewed pole-on have an apparent spectral type which is earlier than that inferred from the integrated Lyman continuum flux? Consistency between current model atmospheres appears to be rather good, at least in some cases. The effect of a substantial reduction in stellar temperatures for O-type stars was discussed. For typical early O-type supergiants, the Lyman ionizing flux distribution is reduced by a factor of two, with the He I ionizing flux reduced by a factor of three relative to standard calibrations (Crowther *et al.* 2002). Since the effect is greatest for O-type supergiants, most young stellar populations would not be dramatically affected. Are such revisions in better agreement with H II regions? Probably, although the lack of well constrained H II regions with one or two well-known ionizing sources hinders attempts at definitive tests.

2. Part two

The second part of the session began with Schaerer who compared observed mid-IR emission-line ratios from *ISO* data with predictions from several different sets of stellar atmosphere models; this wavelength range ($\sim$2.4 - 200 μm) offers numerous line ratios, especially involving bright fine-structure lines and different ions of the same species (*e.g.*, [Ne III]/[Ne II], [Ar III]/[Ar II], [S IV]/[S III]). While overall all non-LTE line blanketed models including stellar winds can roughly reproduce the observed sequences, some difficulties remain (Giveon *et al.* 2002, Morisset *et al.* in preparation). Bresolin examined stellar atmosphere diagnostics in metal-rich H II regions, whose metallicities are determined directly from auroral lines of O^{++} and S^{++}. [S II]/[S III] *vs.* [O II]/[O III] diagnostic diagrams and, especially, He I λ5876 *vs.* EW(Hβ) suggest that stellar atmosphere models (CoStar; Schaerer & de Koter 1997) are slightly too hard around 0.5 - 1.5 $Z_\odot$ (*cf.* Bresolin & Kennicutt 2002). Luridiana demonstrated that density structure affects the inferred nebular ionization parameter (U) in specific spatial apertures. This thereby affects ionization correction factors and inferred abundances, especially for S, Ar, and Cl. Castellanos examined diagnostics of very metal-rich H II regions. [S II]/[S III] *vs.* [O II]/[O III] still offers some leverage on the stellar $T_\star$, suggesting higher $T_\star$ in circumnuclear H II regions (Castellanos *et al.* 2002). This result needs to be confirmed because of worries caused by degeneracies between metallicity and T_e; the latter needs to be determined from lower ions like O^+, N^+, and S^{++} in these cool objects. Beckman examined the escape of ionizing radiation from H II regions by modeling the diffuse radiation around classical H II regions in 20 galaxies. The results suggest either a constant escape fraction of 0.3 or a larger fractions for more luminous regions, depending on clumping geometry (Zurita *et al.* 2002). J. Maíz-Apellániz emphasized the complexity of radiation transfer in the dynamically active region 30 Doradus, where much of the ionized region exists on the surface of molecular clouds and associated PDRs, with associated second-generation star formation.

The ensuing discussion, led by Oey, focused on: (*i*) the sensitivity of nebular diagnostics to the various input parameters, with respect to isolating the effect of $T_\star$; and (*ii*) stellar parameters that are most easily manifested in nebular diagnostics. While $T_\star$, U, and Z are commonly identified as the dominant nebular parameters, additional conditions are also emerging to be important, as seen in the above presentations. While the wealth of IR lines potentially offers more constraints on nebular and stellar parameters, this regime is also more sensitive to non-equilibrium conditions such as ionization fronts, shocks, and PDRs. Dust physics also plays a significant role at these wavelengths. As illustrated above, nebular geometry with respect to both density structure and photon escape needs to be further examined, both empirically and theoretically. Besides such nebular parameters themselves, G. Stasińska emphasized uncertainties in atomic parameters, in particular the role of charge exchange reactions and di-electronic recombination.

The simplest nebular diagnostics of stellar atmospheres are perhaps predictions for nebular He II and, to a lesser extent, [Ne III]. An outstanding problem is the existence of O-type star nebulae emitting He II λ4686 although no O-type star atmospheres currently predict this. The simplest nebular diagnostics of stellar atmospheres are perhaps predictions for nebular He II and to a lesser extent [Ne III]. One puzzling problem is the existence of at least one O-type star nebula with nebular He II (LMC N 44C: Stasińska *et al.* 1986; Garnett *et al.* 2000) Although O-type star models have been described in which nebular He II emission is predicted (Gabler *et al.* 1992), these require $T_{\rm eff} > 50$ kK, for which no examples are now known amongst massive stars, given the recent downward revisions. Predictions for absolute H-ionizing emission rates also offer leverage, as these could be more carefully compared to H II region luminosities. In addition, the dependence of stellar energy distributions and properties upon metallicity can be tested with nebular diagnostics; the atmosphere properties are especially sensitive to C, O, and Fe abundance. Expected differences between dwarfs and supergiants can also be probed in this manner.

3. Conclusions

With the advent of a new generation of model atmospheres for O-type and WR stars including a detailed non-LTE treatment of line blanketing and stellar winds, important progress has recently been achieved. The present session has allowed the participants to learn about the first important implications on issues such as the effective temperature scale of O-type stars and the sensitivity of nebular diagnostics to the improved ionising fluxes. We also see the continued extension of both observational and theoretical parameter space, in particular to metal-rich objects, and multiple gas and density phases. In short, continued study of the intricate relations between massive stars and the ISM is essential for accurate diagnostic leverage of these components on each other.

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Daniel Schaerer and Claus Leitherer, discussing hot star atmospheres

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