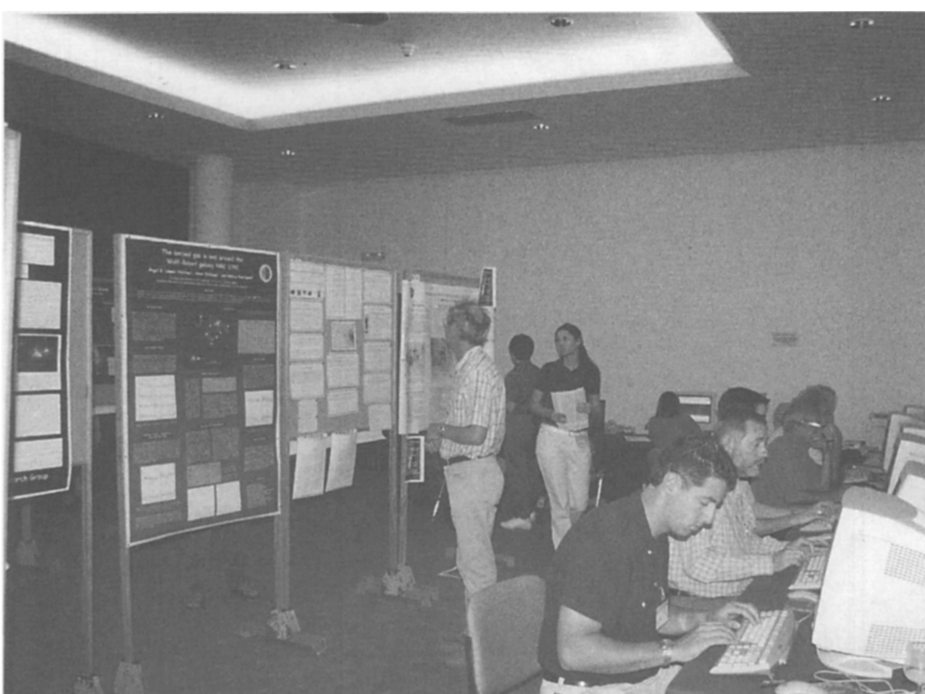
Part 6

Reports on Special Sessions



Georges Meynet, scanning the posters

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A Massive Star Odyssey, from Main Sequence to Supernova
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Special session on the masses of the most massive stars and the Ω-limit

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Abstract. This is a brief report on the highlights of this informal session attended by over 50 symposium participants for three hours on the day preceeding the symposium.

1. Preamble

An unsolved problem that has been nagging the massive-star community for some time is the question of what the actual masses are of stars in the upper H-R diagram (using the term loosely; strictly speaking an H-R diagram is luminosity or magnitude *vs.* spectral type and nothing else). Given that the most fundamental parameter of a star is its mass, this is clearly unacceptable! It is also very exciting, since the most massive stars are also the most luminous and they are becoming key probes in early cosmology.

The most direct observations of masses, based on Keplerian orbits in binaries, have never yielded a mass above $60\,M_\odot$. Less direct techniques based on spectroscopic analyses tend to give a fairly large spread of masses. But both of these have tended to yield masses that are lower than those based on evolutionary tracks, which indicate that stars up to well over $100\,M_\odot$ exist (*e.g.*, the most massive star in the Galaxy is often claimed to be the Pistol Star with $\sim 200\,M_\odot$; then there's η Car ...). In other words, the mass-discrepancy problem, which grows with increasing mass, still appears to be with us.

All of these techniques have their problems. In the case of binaries, selection effects may have prevented us from finding the most massive stars in a binary and then there's always the question of whether stars in binaries behave like their single cousins. Spectroscopic analyses are less direct for getting the masses, but at least one can then look at single stars. Here, as well as for the case of evolutionary masses, there's again always the question as to how complete and reliable the physics is that goes into the models. Besides some aspects which have been neglected until recently and which are able to increase the spectroscopic masses to a certain extent (inclusion of wind effects and line blanketing), two recent factors come to mind: clumping has reduced mass loss rates for WR stars (and maybe others, too!) with potentially dramatic effects on evolutionary tracks off the main-sequence, and rotation still has not been included in the

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most-used isochrones, probably because it is extremely complex and how to implement it has not yet been agreed upon.

Presently, a strong debate is still raging concerning the incorporation of rotational effects in a consistent way, if stars are severely affected by mass loss (this clearly includes all the 'most massive massive' stars), and if they have non-negligible Eddington luminosities (again true for these objects). The debate can be summarized under the buzz-word 'Ω-limit'. Recent advances seem to provide a 'final' solution for this debate, and one of the objectives of this session was a discussion whether this is actually the case or whether there remain additional problems.

2. Stellar masses in the upper H-R diagram

At initial metallicity $Z < 10^{-4} Z_\odot$ all stars are massive, since there is little opacity to brake accretion in the formation process. The proof is that we don't see low-mass members of this early generation locally (Abel). This makes the determination of masses of massive stars at all Z's an interesting and urgent problem. Recent observations of binary motion among some of the potentially most massive, resolved nearby stars (*e.g.*, low-luminosity O3V stars) have still not uncovered anything above 60 $M_\odot$ (Massey, Gies).

When selecting apparently single stars for spectrosopic analysis, one should be aware that multiplicity can be an important factor (Walborn). Very recent *HST*-FGS work by E. Nelan *et al.* has revealed, *e.g.*, that the star at the 'top of the list' in Carina, HD 93129A, is a very close visual binary with masses of $\sim$78+49 $M_\odot$ rather than $\sim$120 $M_\odot$ as a single star, according to non-rotating models. These could come down even more if even more components are revealed and/or rotation is included in the models. One is reminded of R 136 in the 1980's, when masses up to 3 000 $M_\odot$ were being touted (Niemela)! Imagine if the Pistol star were found to break up into equal components: $1\times200\,M_\odot = 2\times100\,M_\odot = 4\times50\,M_\odot$! (Gies; note that for the most massive stars, L scales as M.)

Perhaps one should concentrate on looking for massive stars in massive young open clusters / OB associations such as the Arches Cluster or Cyg OB2, where one is statistically and physically (especially in a high-density environment) more likely to encounter the most massive stars (Figer). Cyg OB2 may be somewhat more promising, since it does not require IR data, where the conversion of luminosity into mass is less secure.

Now that atmospheric models correctly account for line blanketing, it appears that any previous *systematic* trend has vanished and that the mass discrepancy is no longer a problem up to some 150 $M_\odot$, except for a few isolated cases (not due to rotation!) (Herrero). This applies even for supergiants, that yielded the largest discrepancies before. There is not entire agreement on this, however. Note that $T_{\rm eff}$ has dropped by some 10%, with corrections largest for the most massive, hottest stars. The corresponding reductions in L are about 40%.

3. The Ω-limit

The basic, simple idea of this stems from Langer in 1995. After Glatzel's counterarguments in 1998, both approaches have now been unified by Maeder in

2000. Basically, one now refers to the '$\Omega\,\Gamma$'-limit: as long as the (usual electron scattering) Eddington factor Γ is small, the global mass-loss rate is hardly affected even for rotational rates close to critical; on the other hand, when the Eddington luminosity is significant, rotation can drastically increase the mass-loss rates, compared to non-rotating stars. For example, for Γ relatively high (*e.g.*, ~ 0.9), Ω does not have to be at critical (in the conventional sense) to have matter leave the star (Maeder). This may explain some relatively low-luminosity LBVs.

Additionally, the symmetry of the wind should be strongly affected by rotation. For hot stars, gravity darkening (or brightening at the poles) dominates, and the winds are expected to be prolate (large velocities and mass-loss at the poles). For cooler stars, there might also be a chance to obtain an oblate, disk-like wind structure, due to the increase of opacity towards the cooler equator (Maeder). However, since (multi-)scattering will favour the escape of photons out of any dense disk, it remains questionable whether such a disk might actually form from the interplay of radiative driving and rotation alone (Owocki). Magnetic fields might help in such a situation.

The main problem currently is of practical nature: one needs clearer observational criteria to distinguish the basic parameters of slow *vs.* fast rotators. A recent very clever observation in this context was carried out by N. Smith *et al.* (these Proceedings). They obtained *HST*-STIS long-slit spectra of the η Car central star in scattered light from its surrounding dusty reflection nebula. This enabled them to trace the azimuthal and altitudinal dependence of the wind. Most interestingly, both the wind speed and density appear to be highest at the poles, which is opposite to expected in bi-stability wind models, however in accordance with the prolate wind models as discussed above.

Unfortunately, bubbles and superbubbles around OB stars cannot be used to deduce such wind structure in general, since they tend to be rounded out by the pressure-blown situation even if the driving winds are asymmetric. As O-type stars evolve to WN and then WC, they do tend to be spun down though, so that WC stars in particular tend to have symmetric winds (Hillier). Perhaps more promising would be to look for constraints of chemical mixing (especially B and N abundances) via rapid rotation in OB stars. However, most stars analyzed so far have intrinsically slow rotation (Lennon).

4. Consequences for stellar evolution in the upper H-R diagram

Rotation or binary? Accretion from a companion can spin up the rotation. Thus, the correlation of increasing N abundance with rotation among 'single' stars could be due to binaries (Langer). Once accretion leads to critical rotation speed, the star becomes unstable and cannot accrete any more (Ω-limit!). According to Langer, this might lead to ejection of high angular-momentum material. This idea is controversial but does deserve more attention.

For massive stars, one used to say that mass loss is the critical parameter. Now with the importance of rotation, it appears that the critical parameter is rather $\dot{M}/v_c(\mathrm{rot})$ (Maeder). Thus, at $Z=0$, stars do not lose much matter via winds, but rather are spun up and lose mass via rotation. Low-mass stars have lower $\dot{M}$s due to radiatively driven stellar winds on/near the main sequence but can reach $v_c(\mathrm{rot})$ more easily. At low Z, even massive stars can reach break-up

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velocities, with the possibility of a higher freqency of Be stars among B stars, as observed in the SMC.

5. Conclusions

If one were pressed for 'bottom lines' in each of the above Sections 2 - 4, they might be as follows:

S2. There may be general agreement on the masses now, but the fact remains that no star in a binary has yet been found with a mass exceeding $\sim 60\,M_\odot$ (Moffat). Is this a real limit or selection bias? One should look at more luminous O2/O3 stars as well as WNLh stars, refered to as 'Of stars on steroids' by Massey. In fact, one may have strived for mass agreement that is now *too good*, since the comparisons have not yet allowed for rotation in the evolutionary calculations (Maeder)!

S3. Observations are urgently needed of rotating and non-rotating stars to constrain models and the $\Omega\Gamma$-limit as well as the angular distribution of the mass-loss. Large samples are required in order to beat down various sources of 'noise' (*e.g.*, inclination of rotation axis) (Kudritzki). Observations of both B and N abundances should help to distinguish between rotation *vs.* binarity as the dominating mechanism in individual cases.

S4. Stellar evolution among massive stars is now clearly a function of mass, metallicity, mass-loss rate and rotation (M, Z, $\dot{M}$, Ω), and the impact of the angular dependency of mass-loss (affecting, *e.g.*, the loss of angular momentum) has been recognized. It is already fairly clear that soon-to-come revised models including rotation will be able to explain the hitherto mysterious behaviour of the BSG/RSG and WN/WC ratios as a function of metallicity, as well as accounting correctly for the WR progenitor masses of gravitational-collapse supernovae and maybe even when/how the long-duration GRBs form, probably from the collapse of very fast rotating, massive stars.