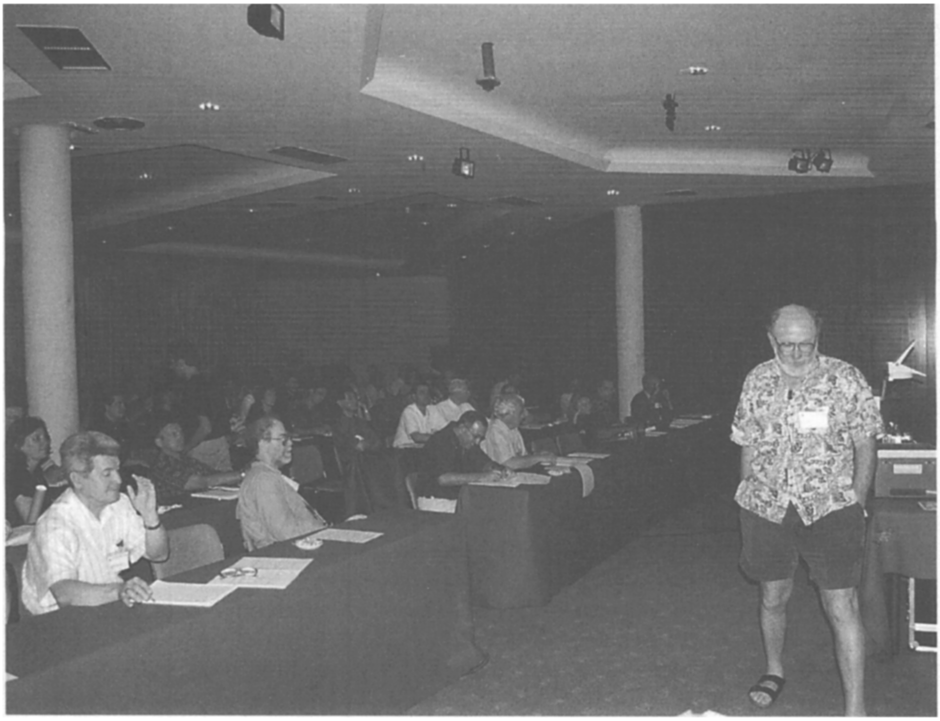
Part 5

Ending the Symposium



Peter Conti summarizing: all's well that ends well

A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © 2003 IAU
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Summary of the symposium

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Abstract. I have put together a necessarily limited summary of the main threads of this Symposium.

1. Introduction

This has been a very exciting and comprehensive IAU Symposium which has touched upon diverse areas of stellar astrophysics. We have heard presentations and viewed posters from a substantial fraction of the 'hot star' community, astronomers concerned with the end points of stellar evolution and those whose interests are primarily directed towards nearby and the most distant starbursts. Massive hot stars have been present since the first generation of star formation. ('In the beginning ...')

The time allocated to a summary talk does not lend itself to be able to include reference to all oral papers, let alone the extensive poster literature. I would barely have time to read to you the titles of all the papers, and certainly not their abstracts or interesting portions thereof. I shall instead try to extract what I feel are the highlights of the conference which are almost certainly different in both tenor and depth from what others might select. To save time and space I will not refer to individual authors or give references as these may readily be found in these Proceedings.

This Symposium can be divided into four parts, following in rough order the schedule put together by the SOC. These topics are labeled as follows: PARAMETERS (observations and models of stellar winds/atmospheres for OB, LBV, WR, and RSG stars); EVOLUTION (observations and models of stellar structure for single and binaries coming from variable Z — metal abundance — environments along with the pre-supernova stages and relationship to the origins of Gamma Ray Bursts); ENVIRONMENTS (feed-back of stellar energy, momentum and enriched elements, observational aspects of wind-wind collisions, and dust production); and DISTRIBUTION (galactic structure as evidenced by obscured clusters — including the Galactic Center — individual stars in nearby (Local Group) galaxies, super star clusters — SSC — starbursts and integrated galaxy spectra at low and high redshifts). A careful examination of the meeting schedule will reveal that most papers appear in this order but several do not. I shall discuss the latter in their scientific place.

2. PARAMETERS — cooler, smaller, fainter

Substantial revisions to some of our most cherished parameters of luminous hot stars have appeared at this conference. To begin with, a new 'early' spectral type has been indentified, labeled O2, based not on the He I/He II ratio (which is insensitive at the hottest end) but upon the ratios of selective emission lines of nitrogen. Additionally, intermediate type O3.5 has been introduced. These emission lines now need to be modeled so that stellar parameters may be derived. It was pointed out that previously unrecognized close visual binaries might give composite spectra leading to incorrect classification and analyses. In particular, HD 93129A has been found to be double with high spatial resolution, the components are each hotter and cooler than that derived from the previously assumed single star (composite) spectrum.

New stellar atmosphere/wind models have been constructed independently by three groups, and they give consistent results. The most important addition has been the inclusion of line-blanketing on the emergent spectrum, specifically including the effects of iron lines. Note that the overall metal abundance (Z) now plays a major role in the predictions of the models. The effects of non-sphericity and rotation are not yet included but, aside from the necessity to address the determination of the $v \sin i$, these are not expected to be large effects.

The results of applying these new models to spectoscopic observations, including those from the far-UV with *FUSE*, are substantial. The $T_{\rm eff}$ scale for the O-type stars has gone *down* and that for the WR stars has gone *up*. Thus the luminosities L have likewise changed (and by a substantial amount as $L \propto T_{\rm eff}^4$). These changes have the following consequences: since the inferred mass loss rates for WR stars have been gradually dropping (due to the inclusion of wind inhomogeneities) — but now the L are larger —, they can probably be radiatively driven by multiple scattering. In other words, the previous serious wind-momentum problem for WR stars has apparently been solved. It may also be noticed that decreasing the L for O-type stars brings the spectroscopically inferred masses (from $\log g$) and those from the H-R diagram, into agreement.

An extensive listing of binary masses of OB stars from SB2 and eclipsing systems and from double-lined systems which are spatially resolved was presented. The masses inferred from binary studies and from the location on the H-R diagram are now in good agreement. The highest mass so far found is about 60 $M_\odot$ but the most extreme O-type stars have not yet been included in binary studies. The upper mass limit may go up to 100 $M_\odot$ but I would now bet it is not going to be substantially higher.

An abundance study of B-type stars in our Galaxy and an examination of that obtained by H II regions reveals good agreement in the oxygen abundance. The radial gradient, at least for that quadrant of the Galaxy near the sun (but excluding the Galactic Center), seems to be 0.07 dex kpc^{-1} from both studies.

The spectra of WR stars with different initial Z have been analyzed over a large wavelength range to determine their parameters. It is already well known that WN star winds show nitrogen enriched material and WC stars the products of helium burning. In addition to a previous finding that the WN subtype has a Z-dependence, an analogous effect was shown for the WC subtypes. The leading optical classification line of λ5696 C III is extremely sensitive to wind conditions which are governed more by the initial Z than by the $T_{\rm eff}$. Thus the well known observation that the WC subtype distribution in the Magellanic Clouds differs from that in the Galaxy can now be understood in terms of a wind effect (rather than an evolutionary one). Additionally there appears not to be a dependence of the C/He ratio on the spectral sub-type, in contrast to previous less sophisticated studies.

3. EVOLUTION — rotation, rotation, rotation

It was clearly demonstrated that the rotation of massive stars plays a major role in their appearance and evolution (thus a $f \propto M, Z, \Omega$). Stellar rotation induces mixing of material from the core outwards and for high mass stars this time scale is less than the evolution time scale. One would then predict that as luminous stars evolve, in those with lower Z the mixing efficiency will go up, a larger N/C ratio will be obtained, and a larger CO core mass will occur (note the impact on the predicted progenitor masses of supernovae). Furthermore, for lower Z the WN phase lifetime will lengthen and that for the WC will shorten, thus affecting the WN/WC ratio.

Extensive observations of luminous evolved stars in Local Group galaxies of various Z, when compared to these predictions, reveal reasonable agreement for the WC/WN number ratio and the distribution of these stars in the H-R diagram (; IC 10 is an exception, but see below). None of the predicted RSGs are quite as cool or as luminous as predicted, and neither the BSG/RSG or RSG/WR number ratios yet agree all that well with the models. However, progress has been made. It was pointed out that the WR/O-star number ratio is not currently measurable given the difficulty of evaluating the denominator.

Radiatively driven wind models have been extrapolated to very low Z values using a scaling relation of mass loss $\propto (Z/Z_{\odot})^{0.69}$. Below $Z \approx 10^{-4}$ a wind can no longer be radiatively driven. There are no examples yet of massive stars with this composition, but as the look-back times increase some integrated features in starburst galaxies might eventually be found. It was suggested that rotation might play a role in forcing mass loss in the first generations of stars. Simulations of the the formation of the first generations of (massive) stars, that is with hydrogen and helium only, were reported. These would appear to occur in 'micro'-galaxies with masses of $\sim 10^6 M_{\odot}$. These entities are very much like luminous clusters.

There was extensive discussion of the process of core-collapse of a massive star, eventually to a neutron star or black hole. The first models to include rotation were presented. The end point of a supernova, 'hypernova', or 'no explosion at all' depends on the initial conditions of M, Z and Ω. The explosion mechanism of core collapse appears to be aspherical in some cases.

It appears that long duration gamma-ray bursts (GRBs) arise from supernova events, in some cases with a WR star progenitor. If the GRB are colimated, they can be produced by a rotating object, but not from collapsing stars in which magnetic fields are important; those would produce pulsars.

4. ENVIRONMENTS — sheets, bubbles, rings

O and WR binary system wind-wind interactions produce non-thermal emission from X-ray to radio wavelengths. As yet unanswered questions are: (*i*) Is strong non-thermal emission always from a binary interaction? (*ii*) Do single stars only produce thermal emission? Episodic or persistent IR emission is observed in WC stars, the former from hotter WC types, the latter from late type WC stars. This emission comes from dust production in the vicinity of the wind interaction zone between the WC star and its companion, or from the carbon rich stellar wind itself. The exact process by which this occurs is not yet well understood. Questions here are: (*i*) Is persistent dust present around *all* late-WC stars? (*ii*) Do *all* WC binaries show episodic IR emission? Beautiful pinwheels of dust producing WC binaries obtained from high-resolution IR imaging were presented to the delight of the audience.

Ring nebulae and CS bubbles can be put into the following two categories: (*i*) interstellar *ring nebulae* — material swept up by O-type stellar winds; and (*ii*) circumstellar material — LBV *nebulae*; RSG *envelopes*; WR *bubbles*. The latter three have anomalous nitrogen abundances as the matter is dominated by the stellar ejections. The former have normal composition.

Recent modeling of H II regions, used to test the new atmospheric/wind models of hot stars, was reported. Abundance determinations from H II regions are relatively straightforward and can probably be trusted. There are still many assuptions in H II region modeling and the atomic physics computations are not yet fully in hand. New line-blanketed atmospheric/wind models were applied to predict the strengths of nebular lines in H II regions, which can potentially be used also for starburst analyses. These new models with solar Z have little effect on previous model predictions for Q_0 ($= N_{\rm Lyc}$), but do predict a smaller Q_1/Q_0 ratio. The Q_2/Q_1 is also diminished. An important result is that as Z goes down, both of these ratios will get larger. The presence of nebular λ4686 He II in low-Z galaxies (or surrounding individual stars) is then predicted, as observed.

5. DISTRIBUTION — location, location, location

In other galaxies, there is a good spatial correlation between the location of the GMCs, the Hα emission (GH II regions), and the OB star distribution which defines the spiral arms. It is difficult to obtain the same information from stars throughout our own Galaxy due to the dust extinction along the line of sight, although nearby stars can be observed and their distances inferred from their photometry and spectral types. More typically, radio observations are used to map the presence of Galactic H II regions (and CO clouds) from their radial velocities, utilizing a Galactic Rotation model. A thorough investigation into Galactic structure, using combinations of these methods, was reported. A separate study, using WR stars as spiral arm tracers, also was presented. Even in the optical, these can be detected to larger distances than OB stars given their strong emission line spectra. Methods of spectroscopic parallax were used to map these WR stars in the Galactic plane. It is noteworthy that using this method (in the near-IR) for five WC stars near the Galactic Center led to a distance of 8.0 ± 1.4 kpc, a remarkably accurate result.

While we appear to be in a three arm system, the various spiral arm indicators do not fit neatly into a pattern. Part of this might be the severe incompleteness of the OB and WR star populations, although the latter is more complete than the former. The problem may also be the inadequacy of the Galactic Rotation model as random motions might well scatter the radio-determined distances. In the future, utilization of near-IR photometry and spectroscopy for luminious hot stars might enable astronomers to identify and classify them at substantially larger distances than can be obtained optically.

Population studies of WR stars in Local Group Galaxies were shown. In IC 10, the nearest blue compact galaxy, there appear to be many more WN stars than had previously been reported. This might help the problem with the previously observed value of the WC/WN ratio, as it had been anomalously high compared to model predictions. The burst of star formation as traced by these stars seems to be widespread over the face of IC 10.

Programs are underway to investigate the exciting stars of UCH II regions with near-IR photometry and spectroscopy. These are newly born stars which are hot enough to produce an H II region detected in the radio, but they are still surrounded by their birth cocoons. In nearly all of them, the cocoon is optically thick in the near-IR thus the star remains obscured. This material will be very luminous at longer IR wavelengths as the reprocessed stellar radiation heats the reprocessed dust. IR line predictions from the new atmospheric/wind line-blanketed models are being prepared.

Near-IR investigations of a sample of radio selected but optically obscured GH II regions in our Galaxy have led to the discovery of star clusters in all of them. Nearly all contain some massive stars with evidence of birth material still surrounding them, but with different fractions and in different proportions. The more stars with birth material, the younger the cluster. The sample differs from an optically selected one in which few, if any, would contain massive stars with left over natal material. Thus the radio selected GH II regions are, on the average, younger than those known to us optically.

The discovery of buried clusters of newly born hot stars in other galaxies was reported. They are more luminous than but analogous to UCH II regions. They are detected by their optically thick thermal radio emission but are optically invisible. These so-called ultra-dense (UD) H II regions are the cluster counterparts of newly born individual O-type stars. The most luminous, with 100 O-type stars or more, are referred to as buried super star clusters (SSC). Mid-IR emission for several UDH II regions in He2-10 was presented, demonstrating the presence of warmed dust from the buried SSC.

Properties of luminous Galactic clusters were presented by several authors. NGC 3606, Cyg OB2, and Wd 1 have similar masses but substantial age differences (from youngest to older). Cyg OB2 is much larger than the others, possibly indicating a different mode of cluster formation. Each is similar to, but a little less luminous than, R 136 in the LMC. These objects are older than the newly born clusters aluded to above. In particular, Wd 1 appears to represent a phase in the evolution of luminous star clusters in which both WR stars and late type supergiants are present; the latter are by far the brightest stars in the optical. The age would then be over 5 Myr, but not so old as 10 Myr.

A sample of luminous stars of the Galactic Center and two nearby clusters have been observed with near-IR spectroscopy and their inferred properties studied. All were born within the last 5 Myr, indicating substantial star formation during that time. The compositions appear to be solar, thus the Galactic Center does not follow the increase in Z with decreasing galactocentric distance indicated by the H II regions. The detection of thermal and non-thermal radio emission from the stellar winds of the stars of the Galactic Center clusters was announced and their spectral and spatial properties presented.

The galaxy M 82 represents the nearest starburst, but the center is buried under optically opaque clouds of dust. Near- and mid-IR photometry reveals the presence of about 100 SSC; two sets appear to be bursts with ages of 5 and 10 Myr. A somewhat older population which formed over a substantially longer lifetime is also present. Star formation is a complicated process which can differ dramatically from galaxy to galaxy.

Massive stars create numerous elements during their core burning and eventual supernova explosions. Galactic chemical evolution is highly dependent on these products and their dispersal. Modeling of this interstellar process was presented, indicating that this mixing process is dominated by turbulence. Feedback mechanisms in the superbubble N 51D were illustrated.

An investigation into the IR properties of starbursts using certain nebular line properties was reported. The [Ne III]/[Ne III] ratio is a nice indicator of the 'hardness' of the spectral energy distribution (SED) in the extreme-UV. In IR-luminous galaxies the inferred SED appears to be quite 'soft', suggesting few if any very hot (massive) stars are present. This could be interpreted as indicating an anomalously low upper mass cut-off in such systems, or else the burst production time is short and they are typically being observed after that process has ended. There are no data yet which would indicate which of these explanations is correct. There appears to be a consensus that the IMF for the formation of stars more massive than $1\,M_\odot$ in bursts (or clusters) has a Salpeter slope, independent of Z or the environment. The $M_{\rm up}$ also appears to be independent of Z in regions where it can be found directly (*i.e.*, through star counts).

Star formation histories (SFH) in galaxies of the local universe have been obtained by a balloon-borne instrument which can image in the mid-UV (at 2100 Å). A sample of UV-bright galaxies with redshifts less than ~ 0.1 was investigated. The UV flux is goverened by the population of hot stars, but is dominated by those of spectral type B rather than type O which dominate below the Lyman limit. The latter are estimated from radio free-free or Hα measurements. These UV or Hα fluxes result in estimated star formation rates (SFRs). These wavelengths sample the earliest SFH, as the Ly-continuum flux drops first with age, followed by the UV continuum (and only much later by the optical continuum). Typically the UV-SFR > Hα-SFR, which can be understood if the SFH is *not* constant but rather occurs in bursts.

Detailed studies of galaxies at high redshift have been undertaken. The strong stellar wind lines in the UV are shifted into the optical and near-IR, allowing estimates of the numbers of luminous massive stars to be estimated. In starburst galaxies, SFRs of 10 - 15 $M_\odot \mathrm{yr}^{-1}$ are found. The numbers of massive stars produced during these episodes have a significant impact on their environments.

We can look forward to further studies of these objects at even larger redshifts in the coming few years, thus tracing the SFH at very early times.

6. CONSEQUENCES — things that might bite

Several issues that seemed to be resolved appear to have raised new questions which will need to be addressed downstream.

For example, if the O-type star $T_{\rm eff}$ is revised downwards by 10%, then the ionizing radiation ($N_{\rm Lyc}$) is also lower (by 40%). Then in clusters and starbursts, where the number of O-type stars is being evaluated by the $N_{\rm Lyc}$, nearly twice as many ionizing objects are needed. Consequenty, nearly twice as many stars of all types are present and twice the mass is required. While this is not a large effect, it probably cannot be ignored. Less luminous O-type stars also have a longer MS lifetime with as yet unexplored consequences for their evolution.

On the other hand, we have seen that the WR star $T_{\rm eff}$ has gone up considerably. Therefore their $N_{\rm Lyc}$ numbers have also increased. Is it now possible that these stars, when present, dominate the cluster and starburst ionization states? Perhaps not, but these relationships all need to be re-evaluated.

In the extensive tabulation of binary masses the O-type star spectral types were also listed. From these data, one would be hard pressed to find any good relationship (*e.g.*, O6 stars span a factor two of mass from their orbits). If spectral types and masses are not related, how can one reasonably construct spectral synthesis models? It might be that the lack of a one-to-one relationship is merely an indication that massive star evolution tracks cross in the H-R diagram, partially due to mass loss but more importantly due to rotationally induced mixing.

Along with these problems, I should note the result of a higher $T_{\rm eff}$ for WR stars now puts them nicely on the helium-burning MS, whereas before they had always been too cool. This sets to rest an evolution issue which had confounded us in the past.

For an overview of these last few days I would assert that the program has been very broad, the topics extensive, and the importance of luminous hot stars is beginning to be seen over wide areas of astrophysics. The coming together of new and old friends and the potential initiation of future collaborative ventures confirm that this has been a quite extraordinary Symposium. Finally, the intensity of the past few days of a very full meeting and the depth of feeling of various participants about their, and others contributions, suggest to me a light and possibly amusing thought. I will call this 'Peter's Principle': *'The more dogmatic the statement or interpretation, the less likely it is to be correct'.*

Rolf-Peter Kudritzki, inviting us to Hawaiʻi: Aloha! Wela ka hao. Mai molowā, mai makaʻu. Mai hilahila! E aho ia. Hoʻomanawanui. Kipa mai. Me ke aloha, mahalo.