SUMMARY OF THE CONFERENCE - PROJECTS FOR FUTURE RESEARCH

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I have attempted to summarize what we have learnt during this most fruitful week and to destill from this a number of possible target points for future research.

1. MASS LOSS

One of the most important sessions of this symposium was the panel discussion on tuesday afternoon, where the various stellar wind theories were confronted with one another and with reality. Apart from the excellent chairman of that session - a Dutchman of course -, one of the most brilliant stars of that day was Alpha Geminorum (also known by the name of Castor), which produced a stable steady-state self-consistent outflow of arguments precisely fulfilling the boundary conditions set by the chairman. Although this outflow passed through a critical point - when Dick Thomas jumped into the discussion - it never became turbulent or overheated, and it gave us a quite convincing picture of how winds from early-type stars can be produced. Some of the other stars in that discussion exhibited recurrent strong outbursts of counter arguments, and several of them showed rapid profile changes, on timescales ranging from a few seconds to several minutes.

The discussion produced a considerable amount of acoustical heating, the excess heat being radiated out into the audience, causing certain individuals to reach very high states of excitation. Some opponents could even be heard threatening one anothers lives. For example, Anne Underhill to Joe Cassinelli in the discussion on line formation in hot corona's: "You go in to at least optical depth two....", and when Joe did not like to do so: "You will see, if you go in you will never meet two points with the same temperature". Indeed, already at the first point poor Joe would have been completely evaporated. Some other highlights of that discussion:

- Cassinelli pointing out 580 problems with Lamers' warm coronal model;
- Thomas receiving zero out of ten for the confrontation of the predictions of his theory with the observations;

P. S. Conti and C. W. H. de Loore (eds.), Mass Loss and Evolution of O-Type Stars, 491–498.

and, very appropriately:
- the chairman of the local organising committee announcing a (Lucy and) Sol(o)mon barbecue for wednesday night.

Altogether, it appears from this discussion, that a reasonble concensus is arising about the mechanisms driving the mass outflow. All speakers seem to agree that once the flow is going, radiation pressure will do the job of pushing it further to the high observed terminal velocities. Also, all appear to agree that the highly ionized species present in the wind, such as OVI, NVI, etc., indicate the presence of a thin warm, possibly even hot, corona. Its temperature may be as low as 3.10^5 K, with a positive temperature gradient, as in Lamers's model; or as high as 5.10^6 K, as Cassinelli has proposed. In the latter case there are definite predictions about soft X-ray emission which will be observable within the near future with HEAO-II. The unknown source of the heating may be Aflvén waves, meridional currents, turbulence in the stellar envelope, etc. A number of us are convinced that this hot corona provides the basic starting mechanism for the outflow. Others - although agreeing about the presence of such a corona - are not sure whether it is the cause, or just the result of the wind, or whether or not it has anything to do with the driving mechanism. It seems that the time is not yet ripe to resolve this problem, although as Olson has shown us, line-strength ratios for various ions provide an important diagnostic means for testing the coronal temperature and density structure and, hence, of its importance in driving the wind.
It is encouraging to see that wind models including rotation are being developed by Castor and his associates; this may be of great importance for understanding the Oe and Be stars. And to see the application of the radiation-pressure driven wind model to stars in other parts of the Hertzsprung-Russell diagram, by Abbott; an especially interesting suggestion by him was that possibly the wind problem is related to the problem of the peculiar A and B stars, by causing selective depletion of certain elements from their atmospheres.

The reviews by Snow and Barlow showed us that impressive progress is being made in the gathering of empirical data on mass loss rates. Especially the IR and radio parts of the spectrum promise to have great potentials as was also illustrated by the contributions of Hyland, Schwartz and Morton. Quite surprisingly, the mass loss rates from Wolf-Rayet stars obtained in this way - and confirmed by the UV observations presented by Willis - are about 10^{-4} $M_{\odot}$/yr, which is some one or two orders of magnitude larger than previously thought. Several years ago Peter Noerdlinger already derived a mass loss rate of this order for γ Velorum, by using the CIIIλ1909 Å line, as presented at this meeting. This result was at that time found hard to believe, but seems now fully confirmed.

Important areas for future investigation in the field of winds and mass loss seem to me:
Theory:
1. The stability of radiation pressure driven winds (Castor is working

on this).

2. The origin of the time variations in spectrum and luminosity observed in almost all bright supergiants - of which Vreux and Andrillat as well as Wolf and Sterken gave us nice examples.
3. Models of winds in other parts of the HRD.
4. The origing of the mass outflow from Wolf-Rayet stars and especially: the duration of the phase of strong mass loss in these stars.

Observations:

5. Search for the possible presence of soft X-ray emission from coronas; measurements of temperature gradients.
6. Study of ratios of linestrengths of various ions in order to derive the temperature and density structure in the corona/wind (cf. Olson).

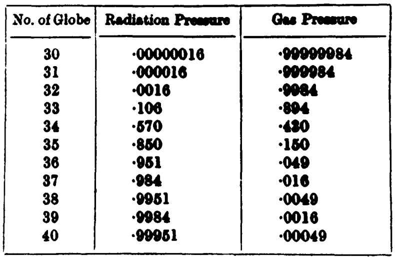
It seems to me that within one or two years we will have sufficient observational data available on stellar winds to enable one to make a critical review of observed stellar wind parameters as a function of the position of a star in the Hertzsprung-Russell diagram. Such a review would be very useful for our theorists who study the influence of mass loss on the evolution of early-type stars.

2. EVOLUTION

It seems quite clear from the work of Chiosi, De Loore et al., Sreenivasan and Wilson, Dearborn and Falk that the empirical properties of O and Of stars as well as of supergiants can - at least qualitatively - be understood in terms of mass loss rates of several times 10^{-6} $M_\odot$/yr right from the beginning of the evolution. For the hot stars such mass loss rates are indeed observed and we have in the CAK theory a plausible basis for understanding their origin. However, one point which still worries me is the rather ad hoc nature of the mass loss laws employed in the cooler parts of the HRD, where we know in fact very little about the physical mechanisms driving the mass loss - nor about observed mass loss rates. It is just the mass loss in this part of the diagram which determines whether or not a star will lose sufficient mass to return to the blue part of the HRD, where, as was stressed again by the beautiful observational work of Conti and of Leep presented today, the most luminous stars appear to turn into WN7 or WN8 stars. As many of these stars appear to be single, it appears that single stars can blow away enough matter to reach the WN7,8 region. Now, the observed mass loss rates in the blue part of the HRD are - as shown by De Loore's computations - not large enough to make the star directly go towards the WN7,8 box without first moving towards the red part of the HRD. Whether or not it will become a WN7,8 therefore depends completely on the mass loss rate which is - ad hoc - assumed in the red part of the HRD. One rather would like to have a more fundamental understanding of why and how the star becomes a WN7,8 object. Why does the star just shed the right amount of mass to become a WN7,8 star? May be an important clue to the answer is given by the beautiful observations presented by Mrs. Pismis, which show that some of the WR and Of stars are surrounded by massive expanding shells which recently must have been ejected by them. Such WR stars appear to be always of the WN type and appear - as far as one can tell - to be always single. The massive shells indicate that there must have been a short-lasting phase of very heavy mass loss, perhaps as much as 10^{-1} or 10^{-3} $M_\odot$/yr. Why? The answer to this question has perhaps nothing at all to do with stellar winds and atmospheric phenomena, but may perhaps be situated in the more fundamental stability properties of the star as a whole.

In Eddington's (1926) book on stellar structure, there is a most interesting passage which perhaps is relevant to this problem. *) Eddington shows that the structure of a gaseous sphere with an internal radiation field is that of a polytrope of index 3; in such a star the ratio of gas pressure to radiation pressure is completely determined by two parameters: the mass M and the mean molecular weight μ.

> "We can imagine a physicist on a cloud-bound planet who has never heard tell of the stars, calculating the ratio of gas pressure to radiation pressure for a series of globes of gas of various sizes, starting, say, with a globe of mass 10 gm., then 100 gm., 1000 gm., and so on, so that the n^{th} globe contains 10^n gm. The table shows the more interesting part of his results.



No. of Globe	Radiation Pressure	Gas Pressure
30	·00000016	·99999984
31	·000016	·999984
32	·0016	·9984
33	·106	·894
34	·570	·430
35	·850	·150
36	·951	·049
37	·984	·016
38	·9951	·0049
39	·9984	·0016
40	·99951	·00049

Table 1. Fractional gas pressure and radiation pressure in globes of gas of increasing mass (Eddington 1926).

> The rest of the table would consist mainly of long strings of 9's and 0's. Just for the particular range of mass about the 33rd to 35th globes the table becomes interesting, and then lapses back into 9's and 0's again. Regarded as a tussle between gas and radiation the contest is overwhelmingly one-sided except between numbers 33-35, where we may expect something interesting to happen. What 'happens' is the stars.
> We draw aside the veil of cloud beneath which our physicist has been working and let him look up at the sky. There he will find a thousand million globes of gas all of mass between his 33rd and 35th globes - that is, between ½ and 50 times the sun's mass."

The reason why we don't see hydrogen-rich stars more massive than roughly 100 to 150 solar masses must be, indeed, that stars which are completely dominated by radiation pressure are dynamically unstable, since according to the virial theorem a star with $\Gamma = 4/3$ (radiation)

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*) My attention to this passage was drawn by Chandrasekhar (1975), International School of Physics "Enrico Fermi" nr.65, Varenna).

cannot be in stable hydrostatic equilibrium. The upper limit M_L at which the ratio of radiation pressure to total pressure becomes virtually unity depends only on the mean molecular weight μ (and on some basic constants of physics), and is given by

$$M_L = M_0/\mu^2 \qquad (1)$$

where M_0 is constant. Because of the rather schematic theoretical model underlying this equation (a polytrope with $n = 3$), the best procedure seems to determine M_0 from the observations, which for hydrogen-rich stars ($\mu = \frac{1}{2}$) suggest that M_L is about 150 $M_\odot$. This would imply that for helium-stars ($\mu = 4/3$), M_L must be around 22 $M_\odot$.

Equation (1) together with the fact that in hydrogen-burning stars with $M \gtrsim 40\ M_\odot$ the burning core contains more than half of the stellar mass may be the key to the problem of the large rates of mass ejection from evolved massive stars. Because, consider for example a hydrogen-rich star of 100 $M_\odot$, which has a burning core of about 60 $M_\odot$. At its birth the star is stable against radiation pressure. However, neglecting for the moment mass loss by stellar wind, it would at the end of hydrogen burning have a helium core of 60 $M_\odot$, which is far above the upper limit for stable helium stars. So, the star must become vibrationally unstable and shed its excess mass to regain stability. Even if during hydrogen burning this star were to lose half of its mass by stellar wind (implying $\dot{M} = 10^{-5}\ M_\odot/\text{yr}$) it would still be left with an unstable helium core of more than 25 $M_\odot$, and therefore, presumably, would still eject its outer layers by vibrational instability.

In such a case one would always be left with a (single) Wolf-Rayet star with a mass slightly below 22 $M_\odot$, and surrounded by a massive expanding shell. This would, at the same time, explain why the WN7,8 stars have such high luminosities, as one would always expect them to be located at the upper end of the stable helium main sequence.

Of course, this picture is a rather rough one, and instability may already set in before the end of hydrogen burning, as during hydrogen burning μ increases and a previously stable star may gradually move into the unstable region, thereby continuously ejecting its excess mass in order to regain stability. This may, in fact, be the reason why we see all kinds of transition types between Of stars and WN7,8 stars, always located in the top of the HR diagram, as was shown today by the beautiful work of Conti and of Leep. At the same time it may be the reason for the irregular light and spectrum variations exhibited by almost all of the most luminous stars, as was shown by Wolf and Sterken, Vreux and Andrillat, and for the large mass loss rate from P Cygni, as discussed by Luud.

If the above speculations have any value, the path of employing atmospheric stellar winds to "explain" the existence of WN7,8 stars and the transition Of stars may well lead to a dead end.

After this detour let me resume the summary and turn to the work presented by Lamb on pre-supernova mass loss from the progenitor of

Cas A, which showed us how continuous mass loss may leave its traces even after a supernova event. A further highlight was the statistical work on O-type binaries by Garmany, which presents us a number of interesting evolutionary problems, notably the absence of low-mass secondaries. This may also have considerable consequences for our understanding of the characteristics of Wolf-Rayet and X-ray binaries.

Detailed studies of individual binaries are of great value as they are the basic source of fundamental stellar parameters. It is therefore stimulating to see the work going on at several places, notably in Boulder under the inspiring guidance of Peter Conti (on what aspect of the O-stars is he *not* working?), at Goddard (Kondo and Rahe), at Buenos Aires (Niemela and Sahade), and at the University of Nebraska (Leung). Nancy Morrison's striking close triple system presents us with a mystery - probably also regarding stability - but makes triple-star models for Cygnus X-1 seem less unlikely now.

The first results of the systematic survey for Wolf-Rayet stars in the Magellanic Clouds presented by Breysacher showed us a doubling of the known number in the Small Cloud, and an additional dozen new ones in the Large Cloud. We are most eager to see his further results. Concerning the evolution of binaries the work of vån Beveren showed us that continuous mass loss during the entire lifetime of massive binaries has to be taken into account if we wish to understand the Wolf-Rayet binaries. The works of Tutukov and of Delgado, on the other hand, showed us the possibilities for the final evolution of massive binaries in which one of the components is already a compact star. The problem of whether or not the compact star will spiral down completely into the center of its companion appears to depend on the initial conditions, but - as convincingly argued by Tutukov - the absence of large numbers of red supergiants shows us that the resulting objects cannot be very long lived.

The work of Moffat and Seggewiss showed us that there are several runaway Wolf-Rayet stars, one of which is a binary with an unseen low-mass component. Some four to five years ago it was conjectured by Tutukov and Yungelson (1974) and by ourselves (1973) that massive X-ray binaries might evolve into exactly such systems. The fact that such objects have now been found is of great importance for our understanding of the origin of the binary pulsar as well as for testing the spiral-in scenarios.

Some important projects or problems in the field of evolution that deserve further investigation are (numbers continue from those of the problem-list in section 1):

7. Application of the fine-grid (Iben-Lamb) evolutionary calculations to mass-losing stars.
8. Reasons for the high incidence of double-lined systems among the O-type spectroscopic binaries.
9. Further study of the evolution of common-envelope binaries; observational search for such systems.

10. Study of duplicity among LMC and SMC O-binaries and Wolf-Rayet binaries.
11. Study of mass outflow properties from runaway and halo O-type stars, in order to test the hypothesis of Carrasco et al., that part of these stars may belong to population II. Sarah Heap's work suggests that such stars may be distinguished from massive O-stars through UV spectroscopy.
12. Study of possible unresolved multiplicity of lumious OB stars and WR stars in the LMC and SMC, by using Space Telescope. Bolton mentioned that 30 Doradus may be an unresolved cluster of five stars, and - as pointed out by Underhill - there may be many more such systems.
13. Further work on determining the position of WR stars in the HR diagram.

Before terminating, may I ask you to memorate with me one of the pioneers in the field of O-stars, Su-Shu Huang, who died last September in his homeland, China. Much of the work presented here this week is based on foundations laid by him and Struve several decades ago (one minute silence).

Additional Topics for future investigations

In the subsequent discussion the following list of additional topics for future investigations was suggested by the audience.

14. Accurate determination of energy distributions of OB stars through absolute photometry from space.
15. Determination of mass loss rates also for stars less massive than 15 $M_\odot$.
16. Further concentration on measurements of radio emission from stellar winds; this is probably the most powerful technique for determining mass loss rates; VLA will be very suitable.
17. Study of the evolution of rotating massive protostars.
18. Incorporation of hydrodynamical atmospheric boundary conditions in evolutionary programs.
19. Study of the correct outer boundary conditions for massive red stars, in order to understand the discrepancies between the evolutionary tracks obtained by different investigators.
20. Study of changes in orbital periods of WR binaries in order to determine the mass-loss rates from their components.
21. Search for non X-ray emitting O stars with low-mass (presumably compact) companions.
22. Study of abundance anomalies in mass-losing stars, to determine how much mass has been lost.
23. Study in the UV of the mass-loss properties of luminous stars in the Magellanic Clouds.

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