SUMMARY OF SYMPOSIUM

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The task I have would appear to be an impossible one. The assembled company is to be congratulated. In the ten years since the last WR Symposium, you have systematically investigated every correlation that appeared at that time to be emerging, and found most of them untrue: The WR spectra are no longer pure emission spectra (Conti et al., 1979); the WN sequence is not a simple sequence of ionisation (Leep, this symposium, session I, henceforward referred to by session number only) or of H abundance (Willis, II; Perry & Conti, II) or of mass loss rate (Barlow; Hogg; Abbott et al., III). The Of, WN and WC stars are no longer discrete classes but are bridged by intermediate types (Conti, I; Willis and Stickland, VI; Williams, IV) and there are now WO stars (Hummer & Barlow, I & V) and supermassive stars (Cassinelli et al., V) as well. The Ring Nebulae are no longer around only strong-line, single WN stars, but are found around any type of WN star, WC stars and binaries (Heckathorn et al.; Chu; Lortet et al., VI). At best, I can hope to highlight a few things about which the majority of us will agree and to point out a few contradictions.

1. THE WR PHENOMENON is indeed a "phenomenon"! Maeder (V) and Conti (I) have rightly emphasised that there are at least five possible ways of reaching the WR state - six, if you include planetary nuclei. In 1971, duely provoked by Dick Thomas, I remember saying something like "Give me a pure-He, He-burning star greater than 10 $M_\odot$ and I will give you a Pop I WR star; give me a pure-C, C-burning star greater than 1.4 $M_\odot$ and I will give you WR nucleus of a planetary nebula". That still appears to be a sufficient condition, but it is argueable that some WR stars (the WN7 stars in particular) may still have a significant amount of H and may still be H-burning.

2. CHEMICAL COMPOSITION: I believe we are agreed that:
- The abundance ratios of He:C:N in WN atmospheres are essentially the equilibrium ratios expected from the CNO cycle; the amount of H present appears to vary widely (Willis, II; Smith and Willis, II;

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Perry and Conti, II).
- The C:N ratio in WC atmospheres is very much greater than 1; H is absent (Willis, II; Smith and Willis, II).

These abundances are consistent with Paczynski's concept (1971 Symposium) of the WR star as an O star that has been stripped of its H-rich envelope down to various depths. The other possibility that is becoming a serious contender is that the stars are somehow mixing the products of nucleosynthesis to the surface (Chiosi, V; Maeder, V; Vanbeveren, V; Bisiacchi et al., V). This appears particularly necessary in order to account for the intermediate WN-WC stars. The exact mechanism of the mixing is a matter of dispute.

You have now added the WO stars (Hummer & Barlow, I & V; Williams, I) in which there is no N and even He is depleted such that He:C:O is about 20:10:1; these ratios are consistent with yet further stripping of the star.

The major observational uncertainty remaining is the upper limit to the amount of H that can be present and still permit the star to be a WR star. It has been shown that the ratio of H^+/He^{++} varies from approximately zero to approximately infinity within one subclass (e.g. WN8, Perry & Conti, II). The critical quantity is the ionisation equilibrium of helium in these stars. Binary evolution gives X=0.2 (H:He-1:1) immediately after RLOF (De Gréve et al.78)Is this the maximum value for a WN star: my guess is "yes" - because there exist post RLOF binaries (e.g. BC+40°4220, Bohannan & Conti, 1976) in which the stars are still O stars.

3. THE MASS LOSS RATE for WR stars is 3 10^{-5} $M_\odot$ yr^{-1} - independent of: mass, luminosity, spectral class, H/He ratio, and terminal velocity (Barlow, III; Hogg, III; Abbott et al., III). That is quite an impressive achievement for a group of otherwise such diverse objects!

The theories presently advocated to account for the mass loss rate include:
- Radiation pressure - which appears to need both very high UV flux and multiple scattering in order to account for mass loss rates that exceed the Eddington limit by up to a factor of 10 (Panagia, III; Cassinelli, III);
- Magnetic acceleration, suggested by Cassinelli (III);
- Pulsational instability (Maeder, III, has reminded us) is still a contender because the stars are well above the instability mass limit for pure-He stars.

So, what makes WR stars different from O stars? Abbott (III) confronted the question after amphasising that O stars can exceed WR stars in both mass loss rate and luminosity - although not in the ratio. His answer: "The WR stars need a higher density in the atmosphere and a slower acceleration" at least clarifies the questions "how?" and "why?".

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In the following discussion, Cassinelli (III) emphasised that the smaller core size of WR stars (compared to an O star of the same luminosity) goes in the right direction to give you a higher density wind. Panagia and Felli (III) quantified the velocity law for LMC stars as proportional to r^{α} where α is less than 1.

Myself, I would, with Maeder (III), emphasise that a 10 $M_{\odot}$ pure-He star is unstable to pulsations (epsilon-mechanism). Appenzeller (1970) has shown that (for a H-star ab ove its instability limit) the pulsations do not necessarily appear as such at the surface of the star. We know that the presence of H on the outside of a pure-He core will stabilise it. However, we also know that many WR stars are pure-He, with no H, and are over 10 $M_{\odot}$; they must therefore be unstable. The presence of this unstability must affect the structure of the star fundamentally. I would therefore submit that ALL WR stars must be subject to the epsilon-instability.

This being the hypothesis, I would be looking for a correlation, within a given subclass, between mass (luminosity) and H-abundance (since these two parameters will have to be balanced to produce a given degree of instability); I would also be looking for a correlation between both (or a combination) of these parameters and the line strength (also within a subclass).

4. BINARY WR STARS: I think we would agree that:

- Some WR stars have OB companions (Massey, IV; de Loore, V);
- Some WR stars have compact companions (Moffat, IV; Lamontagne & Moffat, IV);
- Some WR stars must be single (Various, V);
- There is no immediately obvious correlation between binary nature and subtype or anything else.

This appears to be very trite summary. I do not mean it to be, and it would be grossly unfair to the people who put in ten years of blood, sweat and tears to bring us to this point. I think it is fair to say that the demonstration of the above diversity has brought the WR stars from being a curiousity to being an important part of the "main stream" evolution of all massive stars.

5. RING NEBULAE: Here, I must confess, my thoughts are in confusion. I thought, until yesterday afternoon, that what I was going to be able to say was that Ring Nebulae are a part of the story of the evolution of binary WR stars and that the scenario goes as follows:

- O + O + cluster - which ionises the surrounding gas and blows it away;
- WR + shed gas + cluster - which ionises the shed gas and blows it away;
- Compact + O - which runs away from the cluster;
- Compact + WN + shed gas - which expands slowly away from the system, and the wind from the WN star packs it into a ring;
- Compact + WC - but not before the ring - whose ages (until yesterday

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afternoon) were calculated at about 10^4 years - has dissipated.

The new rings presented to us (VI) by Joy Heckathorn, You-Hua Chu and Mme Lortet have thrown this picture into dissarray. Some of the new objects are associated with stars that are still embedded in the clusters and gas with which they were formed. The rings are perhaps bigger, more massive and possibly older than those previously known. It is not clear to me whether these rings are different from the "old seven" and represent windpacking of the nearby part of a larger cloud which has little directly to do with the WR star - and whether the bright (OIII) observed by Heckathorn reflects the high UV flux that Nino (III) suggests to be a property of the stars, or whether they contradict out interpretation of the previously known rings altogether. It must be left to those who have identified these intriguing objects to explain to us their significance.

One aspect that Chu showed us deserves special comment. That is the much greater size of the rings in the LMC than those in the Galaxy. This is all the more remarkable considering the lower metal abundance in the LMC which we expect to produce lower mass loss rates from the stars (Maeder, V).

6. PLANETARY NUCLEI. The relevant information was very clearly summarised by Sally Heap and Alvio Renzini (VI): I would like only to emphasise two points:
- The planetary nuclei produce no WN stars;
- Mendez (VI) suggests the reclassification of the nuclei previously called C6 or 7, this would leave only WC classes earlier than 4 or later than 8! (WC2-4, WO and OVI are alternate designations of the same type of spectra).

7. EVOLUTION. To assign the WR stars to their place in evolution is perhaps the main goal of most of us. Before progressing, I would like to make a couple of general comments.

Formation of a WC star is assisted by two things:
1) A high metal abundance: this is expected to increase the mass loss rate and hence peal off the H and N rich layer more rapidly, increasing the lifetime ratios of WC to WN stars (Maeder, V). Note: observational verification of this difference in mass loss rate would be desirable; it is presently inhibited by the great distance to the stars in the galactic center which we believe are metal richer.
2) Late formation of the WR star: so that the core is more evolved when the H envelope is removed to make the WN star. This means that WC stars will be favoured in single stars which form WR stars in the post RSG stage. WC stars will also be favoured in widely separated binaries. The separation of binaries is a parameter that has been disregarded since the last Symposium, perhaps because we do not, theoretically, expect it to make very much difference. However, it seems

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to me to be a case in which it makes a difference to the stars even if it doesn't make a difference to the models. Using the binary systems and their probable inclinations as listed in Massey's thesis, plus the systems presented by Virpi Niemela (IV), I find that all of the WC binaries have separation greater than 80 $R_\odot$ and all but one (HD 190918) of the WN binaries have separations less than this figure.

Secondly, I would like to say that I do not think that the smooth progression of the classification parameters through the WC sequence (in contrast to the irregularities in the WN sequence) necessarily implies that the WC stars all evolve by the same scenario. I think that the smoothness may be a simple consequence of the uniformity of their chemical composition, in contrast to the WN stars which have a wide range of H abundance within each subclass.

That being said, it seemed to me, as I was writing this last night, that someone would have to go "where angels fear to tread" and try to assign subclasses to some of the evolutionary scenarios we now accept as possible. To my amazement, the assignments I came up with agreed to a remarkable degree with those suggested this morning by Firmani (VII). You may call this "science by consensus" or you may regard it as a demonstration that the subject has now reached a point where two people can independently draw the same conclusions from the data available.

I have modified the scheme I map ped out last night to include the division of the WN6 stars into Early and Late types, as suggested by Firmani (VII). Otherwise, the determination was independent. There are still a few significant differences between his divisions and mine. I suggest that :

The WN7 and WN6L stars are massive stars (greater than 50 $M_\odot$ is suggested by the lack of red supergiants (RSG) above this number, Maeder, V) at the end of core H-burning and/or the beginning of core He-burning. They may be binary or single - it appears to make no difference to these massive stars (perhaps because the tracks for massive stars with mixing veer back to the left and these stars would rarely reach their Roche lobes). Less massive stars that are in binary systems also seem able to become WN7 stars. (I think we are going to have to accept that binaries can do nearly ANYTHING!). Evidence for this assignment is that WN7 and WN6L are the most luminous stars in all of the youngest and most massive H II regions: 30 Dor, NGC 604, Carina Nebula, Sco OBI (Melnick, VII; Conti, VII; d'Odorico and Rosa, VII). In these regions the stars have probably not had time to evolve to the red giant region and back again.

These stars appear to evolve into WC5 (or 4?) stars. Evidence : in most of these regions we are seeing intermediate types WN7-C5 (ibid; Phillips, 1981). This is surprising because we believe that the absolute magnitudes of the WC5 stars are significantly lower than those of the WN7 stars, but that is the way the evidence points at this time.

WN6E stars evolve into WC9 stars and are the product of post RSG

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evolution in massive stars with high initial metal abundance. Evidence: they only occur in regions near to the galactic center where the metal abundance is highest (Smith, 1968; Hidayat et al., I; Firmani, VII); there are none in the LMC or the SMC. They are more luminous than most of the other subclasses indicating higher masses. The planetary nuclei give WC8 and 9 stars and are likewise post red giant objects (Heap, VI). Both groups appear to contain predominantly single stars. The WN6 and WC8 stars have the same ratios of M_{WR}/M_{OB} (Moffat, VII); one of the lines across Moffat's diagram linked these types. (Although, in view of the"single" nature implied for this scenario, this may be a coincidence).

WN3, 4 and maybe 5 evolved into WC5, 6 and maybe 7 and are the products of case B binary evolution or of post RSG evolution of intermediate mass, single stars. Evidence: it is my impression that there is a smooth distribution of stars between the classes WN3-4 and WC5-6, moreso than between other classes. These classes share similar distributions in the Galaxy with respect to galactocentric distance and with respect to clusters and associations (Hidayat et al., I; Lundstrom and Stenholm, VII). These classes share similar ratios of M_{WR}/M_{OB} (Moffat, VII).

If this is true, then these should be a dependance of the relative numbers of WN and WC stars in these classes on metal abundance (i.e. on galactocentric distance, Maeder, V).

WC7 stars seem to fall intermediate in properties between the earlier and later types of the WC sequence. They are not especially concentrated to the galactic center (Hidayat et al., I) but are not found in the LMC or SMC. They sometimes have dust shells (e.g. Williams, I) like WC9 stars. They show no special preference to be single or binary. In other words, I am uncertain about including WC7 stars with the WC5 and 6 stars above.

WN8 stars. I was glad to hear the general assertion (e.g. Lortet, V) that they are different from WN7 stars and should not be lumped under the WNL title. I suggest that they are only found in the WR plus compact phase of binary evolution. Evidence: they are more luminous (massive) than the earlier classes, but are not found in clusters like the WN7 stars (Lundstrom and Stenholm, VII). They are frequently associated with Ring Nebulae. WN5 stars may share this scenario.

I have left out WO stars (equals WC2-4 stars). I simply do not have, in my head, enough information about these classes to hazard any guesses. But I would like to point out one surprise. If we believe that the WO stars are the most evolved (stripped off) of the WR stars, it is surprising to find one of them in the SMC where the metal abundance (therefore mass loss rate is expected to) be the lowest (Maeder, V).

There is one important point that is not accounted for in the above: binaries are more concentrated to clusters than single stars

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(Lundstrom and Stenholm, VII). Does the evolution of a single star through the RSG stage take long enough that the cluster disbands? Are RSG also often outside of clusters? Or do massive single stars form outside of cluster while massive binaries do not?

8. QUESTIONS FOR FURTHER RESEARCH. Following logically from the above throughts, I summarise the followi ng questions :

1) What is the ionisation balance of He in the WNL stars and hence the upper limit to the H abundance in WN stars?
2) Is there a correlation between mass (luminosity) and H-abundance within a given subclass?
3) Is there a correlation between mass, H-abundance and line strength within a given subclass?
4) Why are the ring nebulae in the LMC larger than in the Galaxy?
5) Observational verification of the dependence of mass loss rate on metal abundance;
6) Is there the same correlation of WR type with radial position in other galaxies?
7) Do the WC stars in M33 have systematically lower line widths than galactic stars in the same excitation class? and, if so, why?
8) How exclusive is the assignment of subtypes to one scenario? e.g. are all WC9 and WN6E stars post RSG single stars?

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