SUMMARY TALK

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Abstract. A personal, but *critical* summary of the papers at this conference is presented.

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1. Introduction

We have had a very full five day program with over 50 Invited and Contributed Oral Papers, and more than 60 Posters. I hope you will recognize that in the 30 minutes I am alloted here it is not possible to allude to every one of them, unless I were to the take the 15 seconds available for each and simply read the titles (but you can do that as well). It is, rather, my assignment to summarize the "high" points of the Symposium, and you must understand this will necessarily be from a very personal perspective. I hope you will forgive me if your work is not mentioned in what follows and I will not formally reference ANY papers that are already found in the pages that proceed this contribution.

My outline is as follows (the significance of the headings will become apparent in my presentation):

Setting the Record Straight... I would like to consider briefly the historical record having to do with the evolution of *single* WR stars by mass loss. These remarks should only be taken very lightly and with a picture in one's mind of how Professor Zwicky might have presented them, in a heavily flavored "Schwyzer-Deutsch" accent, starting with one of his favorite phrases "...tventy years ago, I told dose...".

I don't think we're in Kansas anymore... This phrase comes from Dorothy in the marvelous movie version of "The Wizard of Oz" where after she and her dog, Toto, are picked up in a tornado in Kansas, whirled around and around (this all in black and white on the screen), they suddenly find themselves in a forest, now in technicolor, with a "yellow brick road" seen off in the distance to which they will march off to seek the "wizard".

High Opacity... It's not that the papers concerning dust formation were difficult, it's more that we are moving into a new realm of physics, or more properly, chemical physics.

K. A. van der Hucht and P. M. Williams (eds.), Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, 565–572.

Are we having fun yet...? You and your spouse are on a lengthy car trip with your two sub-teen age children in the back seat. They have been prodding and poking each other, and fighting, for a good part of the day. You have seen many tourist sites and there are a few still to go, along with quite some more miles to drive. Your spouse turns around to the back and asks "Are we having fun yet?"

It takes two to tango... A popular American phrase, this has to do here with binary WR stars.

The dog(s) that did not bark... In one of the Sherlock Holmes mysteries, a *critical* clue is ultimately provided by the realization that at a certain time and in a certain place a dog did *not* bark.

Are we there yet?... This is the same car and occupants as above, but it is uttered by one of the two kids about *30 minutes* after the trip begins.

2. Setting the record straight...

I am particularly pleased to see so many new faces in this audience; clearly we are working in an exciting and burgening field of astrophysics. Drs. Niemela, Seggewiss, Smith and myself are the only "remnants" of the Buenos Aires IAU Symposium No. 49 (which took place in 1971) who are still with you today. A subsequent quarter century of work has defined the appearance of WR stars as a class of objects in a reasonably well understood phase of massive star evolution that we know and love so well.

IAU Symposium No. 49 ended with (nearly) all of us agreeing that "all" WR stars were binaries, and their anomalous masses, luminosities, and compositions could readily be understood as the effect of close binary interactions and Roche Lobe overflow leaving the remnants of H-burning, or He-burning, products on the surface of the initially more massive star. This conclusion rested upon an assumption, that *all* WR stars were binaries, and made a prediction; namely, that the *companions* of WR stars should show anomalous composition from the mass overflow of the helium burning star. I had already begun thinking and working in the area of O-type stars; I was especially concerned with the question "what does a *normal* O star look like" (so as to address the prediction above). I was also concerned with the presence of *single* massive O-type stars. What do *they* evolve into? Was it indeed true that *all* WR stars were binaries?

(Now, in "Schwyzer-Deutsch" accent) I believe the *first* paper addressing these issues was Conti (1976). Here was laid out the idea of *single star* evolution of the most massive O-type stars to the WR stage by stellar wind mass loss (and a "P-Cygni" phase). This later became known as the "Conti" scenario (Maeder 1983), so that while it is *my* scenario, I am not responsible for its name. The original paper makes no reference to a *number* for the lower mass limit of single star WR evolution, except to hint at its probable

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existence. I have spent time on this today since some authors have persisted in denigrating "my" scenario as only applying to stars so massive as to not exist. My personal advice to all of you: read the literature!

It appears that *most* WR stars get to their advanced evolutionary state by previous episodes of mass loss during the O star and LBV phases. *Close binary* stars *may* proceed by the RLOF channel. *Standard Models* for such single star evolution are sufficiently advanced as to make testable predictions about WR/O star ratios and WN/WC/WO type populations, in rough agreement with observations of stars in various galaxy environments. Two independent proposals concerning the precise "channels" taken by single stars were given, but, unfortunately, differed in their details.

3. I don't think we're in Kansas anymore...

Standard Models for the stellar winds were presented for the first time four years ago at the Bali IAU Symposium No. 143 and were considered a major advance in our understanding of the emergent spectra of WR stars. Well, we are now going to have to put aside these playful things and move forward again! We have heard discussion of some *simple* modifications to the atmospheric and wind models which might be needed:

i. Velocity law $\beta \geq 1$ (perhaps even increasing outwards).
ii. More complete line identifications and improved relevant atomic physics parameters for the abundant elements, particularly iron.
iii. Non-LTE line blanketing, taking full account of line spacing.
iv. The effects of rotation and asymetrical structure as it might affect the radiation field and stellar spectrum (density enhancement model).

These advances can be done with current knowledge and computer technology, but lots of work! We also find that *New Physics* and much more effort will be needed to address such problems as:

v. Clumping and inhomogeneities in the stellar winds.
vi. Effect of shocks on the ionization balance; production of the X-ray emission in the winds.
vii. Physically consistent radiative hydrodynamics treatment of the outflow, which is probably *not* smooth.
viii. A newly proposed Bowen Mechanism process for the interaction between an Fe VI line and the λ 303 He II transition, which I will call a "Swiss Cheese" model (it looks good, it smells right, it tastes great, but it's still full of holes).

It is already clear that a *combined* evolution/wind model approach will be necessary and the first steps along this path are already being taken. The *Standard Models* give line predictions of *some* lines in *some* stars in agreement with the observations. We need to use *all* lines in *all* stars! Given all this, how *trustworthy* are the current predictions of luminosity, $T_{\rm eff}$, and

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mass loss rate from the *Standard Models*? I would urge caution in setting too great a store, as yet, on these numbers. Furthermore, why do the WN star *models* imply bimodal behavior (" strong" and "weak-lined") while the observations (*e.g.,* continuum slopes) *do not*?

Extensive wavelength coverage and analysis of many (single) WR stars suggests a power law continuum longward of the $R-J$ peak, but with a (log-log) slope nearer to −3, rather than the canonical $R-J$ limit of −4, and slightly different from star to star.

4. High opacity...

Circumstellar dust is observed around most WCL stars, but not all. Why is this? Several WC stars have *episodic* dust formation. At least some of these are binaries, which presumably influences the event. Are *all* of the episodic dust emitters binaries? If not, what drives their activity? There have been more questions raised than answers given. Dust seems to be associated exclusively with WC stars, presumably because of their high carbon content. Why don't we observe *silicate* based dust in WN stars?

We heard and saw much about the variable dust activity in WR140; is this object a *freak* or a *prototype*?

A new and exciting chemical kinetic approach to the formation of dust surrounding WC stars has been presented. The factor 10^3 discrepancy in the required density might be regarded as excessive for *any* theory but it might point the way to deficiencies in our knowledge of the stellar winds. For example, the "persistent" dust formation might require clumping; the "episodic" events might require a disk to be present, possibly a natural consequence of a binary interaction. Is "smog" present? In other words, does the radiation field play any role in the dust *formation* process?

5. Are we having fun yet?...

The answer to this is yes! I was most impressed with some of the really "fun" observations we have heard about. In particular, the *polarimetry*, only recently begun in any systematic manner, can now give us unique information for both single stars and binary systems. For *single* stars one finds cases where the wind is:

i. Spherical and homogeneous.
ii. Spherical and *in*homogeneous.
iii. *A*spherical and *in*homogeneous.
iv. The *A*spherical and homogeneous case has *not* been observed.

Additional observations are critically needed to get information on the statistics of these cases. For example, is there a spectral subtype dependence? What is the *quantitative* degree of *a*sphericity and *in*homogeneity?

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In a completely different area, we heard and saw the use of ring nebulae as tracers of the properties of their exciting WR stars. One may use the nebulosity to:
i. Derive a chemical composition consistent with the predictions of the evolution models.
ii. Estimate the $T_{\rm eff}$ of the exciting star.
iii. Infer an initial asymmetry to the stellar wind in several cases.
iv. Deduce the presence of collapsed companions (but see **7**).

Several papers addressed the connection between WR *phenomena* in Symbiotic Stars and in the Central Stars of Planetary Nebulae as compared to our nominal Population I stars. The former objects are far removed in an evolutionary sense, yet showing somewhat similar physics. We can certainly each learn from each other in our studies of these complicated systems.

A good part of the meeting was devoted to the relatively new topics of high energy astrophysics, both theory and observation. Much of this involves binaries...

6. It takes two to tango...

Binaries provide fundamental data on masses that can be obtained in no other direct fashion. This work is fraught with pitfalls, but the potential payoff in our understanding of the stellar parameters of WR stars is enormous. An important assumption, one not easily amenable to confirmation, is that binary and single stars with otherwise identical spectroscopic characteristics will have similar masses. We can only *hope* this is true.

As contrasted to past meetings, there was little presented here concerning the *evolution* of binary WR systems, aside from the useful contribution of modeling with *half* the mass lost from the system, and *half* gained by the secondary. Is the concept of RLOF even viable in the presence of strong stellar winds? Perhaps one should attempt RLOF modeling with *all* the mass lost from the system. This extreme case might better mimic what happens in real stars. Note that such a "sudden" mass loss is distinct from what is currently being played out in single star models of evolution! My guess is that the results might prove significantly distinct from what has been found in previous cases. Binary interactions clearly play some role in massive star *evolution*, even if they do *not* dominate the statistics.

Detailed examination of several close binary WR plus O-type systems gives one information on the period changes and mass loss rates. The latter numbers are typically a factor two lower than those inferred from spectroscopic analyses or considerations of the electron densities. The interpretations is that the stellar winds are *not* uniform, but clumpy, a conclusion that appears in several other guises during this meeting.

There was a considerable effort devoted to the physics of interacting bi-

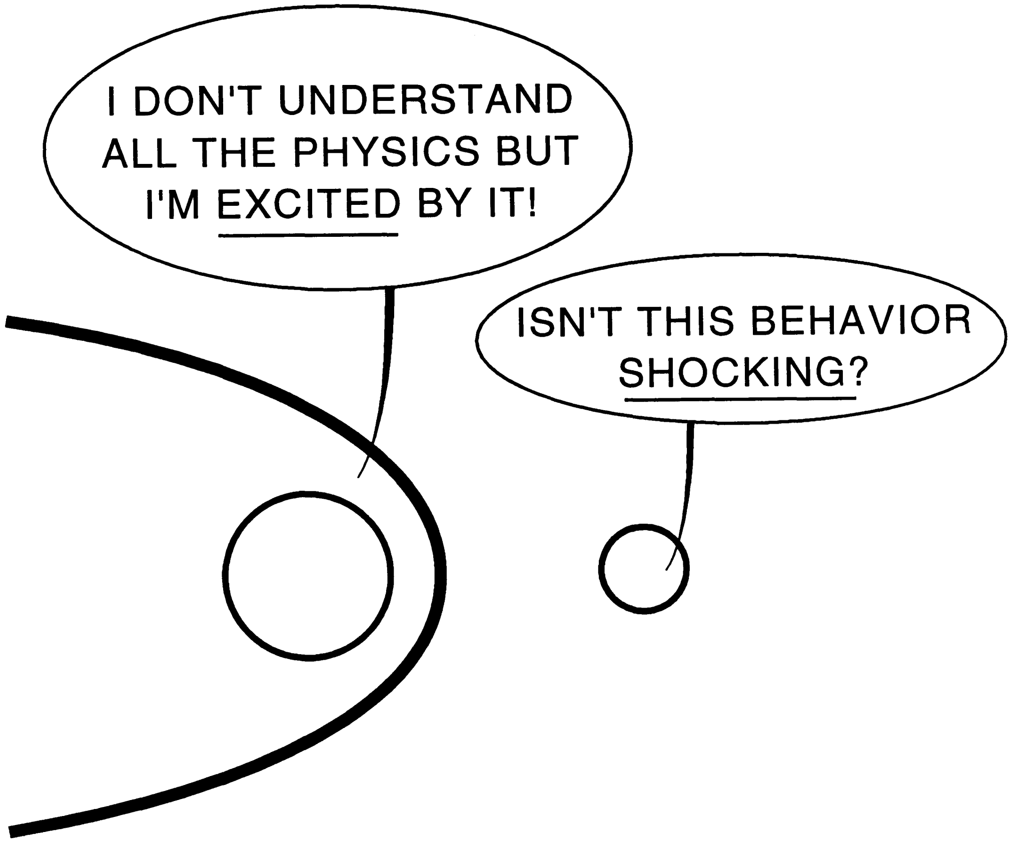

Fig. 1. Schematic View of WR plus O-type Binary Systems

naries at this conference and, for me, a very exciting aspect was the number of astrophysicists presenting results on this topic. I show in Figure 1 a schematic view of the *shock cone shaped cavity* that represents the framework for colliding winds, with consequences for high energy astrophysics. Let me mention (only) a few of these:

i. Strong, periodic, phase dependent variable X-ray signature in γ Vel.

ii. Periodic, phase dependent, spectroscopic variability in such objects as CQ Cep, CX Cep, etc..

iii. Use of colliding wind phenomena to give information on stellar wind inhomogeneities (clumping).

iv. 2D, 3D modeling of the hydrodynamics.

v. The necessity of a *magnetic field* in at least one binary, due to innovative utilization of the *Razin Effect.*

We heard much about HD 193793: *e.g.,* the multi-wavelength, multi-year

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observations, the suggestion of disc morphology but *not* aligned with the orbit. How would such a binary system form with such a long period, highly eccentric orbit, misaligned axes? Is this object a *freak* or a *prototype*?

7. The dog(s) that did not bark...

A question that had been with us for quite some time was "What is the driving mechanism in WR stars?" This had come about because of the very strong winds and the implied inordinate momentum forces needed for radiative processes to be acting alone. "Other" physical driving mechanisms have been looked for, without success, for well over 3 decades. At this meeting we heard: "It's not a momentum problem, it's an *opacity* problem!", and we were additionally presented with a new ("Swiss Cheese") model addressing that issue. Of course, difficulties remain, but my personal feeling is that this longstanding non-issue should finally be laid to rest.

Both *radial* and *non-radial* pulsations have been searched for (see above) for literally decades and have not yet been found for certain in the data. Could this be another case of a dog *not* barking? If these phenomena play any role, why are they so difficult to observe? I must mention the 6.8 hour period found for WR46 by two independent investigators. What does this very short period represent? Is this exceptional star (WNE *plus* strong O VI lines) really an initially massive Population I object?

WR plus compact companions ("*cc*") have been predicted on evolutionary grounds for two decades but (until recently?) not identified. Many candidates have been put forward: EZ CMa was the first and the "easiest" case. The problem with all these objects has been the lack of a strong X-ray signature and the absence of the "Hatchett-McCray"effect (periodic variability in the strong stellar wind lines due to an ionization cavity from the *cc*). The absence of any observations matching these predictions has, in the past, been "hand-waved"away with what I feel is completely inadequate physics. We now have the example of Cyg X-3 put forward as the "missing link", as the newly detected stellar companion has strong helium and nitrogen emission lines in the near-IR just like classical WN stars. In the spirit of "If it walks like a duck, quacks like a duck, and associates with other ducks", I will call Cyg X-3 a duck. (Of course, geese also have superficially similar properties.)

For the "ducks": Cyg X-3 is the missing link; *then* all the other WR+*cc* candidates fail since they have *no* strong X-rays nor Hatchett-McCray Effect, which Cyg X-3 certainly shows. For the "geese": Cyg X-3 is *not* the missing link, but rather a low mass Population II object masquerading as Population I. Then the other proposed WR+*cc* remain viable candidates. But, if the Cyg X-3 system is *not* a "duck", then what is it? Amid all the quacking and fluttering of feathers, there was no consensus at this conference on the nature of the companion (but my personal bet is still for the "duck").

8. Are we there yet?...

Well no, we still have a great deal to do. At the risk of subsequently looking foolish, I would single out several questions which struck me as particularly in need of work and which might have the most significant payoff:
i. What is the place of mixing in massive star evolution (this refers also to the O star phase)? Better understanding of the LBV phenomena and its episodic mass loss for use in modeling massive single star evolution would be very helpful.
ii. How important are non-homogeneities and asphericities in the winds of WR stars? How will the addition of these parameters to the models shape our understanding of the overall properties of the stellar winds, and, ultimately, our knowledge of the underlying star?
iii. What role do discs play in the physics of single stars? They seem to be present in some, but (curiously) not all, objects. Is their role major in shaping the emitted spectrum or is it merely a perturbation on the radiative driving forces? Why should *single* WR stars have discs anyhow?
iv. How relevant is the 2D modeling of colliding winds as indicated schematically by Fig. 1? Do we need to proceed immediately to 3D? Wind compression models in binary systems are in their infancy, but very exciting physics is already resulting.

DESIDERATA for the future include:
i. Multiwavelength coverage, and extensive observational programs aimed at fully understanding the nature of the variability in at least a few single, and, of course, binary stars.
ii. More detailed modeling and improved physically consistent theory of the stellar winds.
iii. Finally, let us look forward to another nice IAU Symposium in a pleasant venue to report on our collective and collaborative efforts concerning these enigmatic but delightful stars in the next few years!

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