Wolf-Rayet Stars
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Concluding Remarks

P. S. Conti[1]
[1] *JILA, Univ. Colorado, Boulder, CO 80309, USA*

Selected remarks concerning Wolf-Rayet (W-R) stars in the framework of this workshop are given. The rich history of international conferences over the past four or so decades is summarized, important issues concerning W-R stars are considered, and some outstanding problems are reviewed.

I begin briefly with the very first international conference on W-R stars, IAU Symposium #49 held in Buenos Aires, Argentina in 1971. I believe I am the only participant at that meeting who is also at this one; a picture of the participants is shown in Fig. 1. (Curiously, it was not included in those proceedings, but a similar shot at an oblique angle was shown at a 2006 conference in honor of Dr. Virpi Niemela; Niemela 2008).

Three women in the first row, Drs. Neimela, Underhill, and Smith, are well known in the study of W-R stars, and represent ∼10% of the participants at that meeting. There has been a substantial increase of women working on this topic, as may be indicated by the ∼25% fraction attending this conference. Of course, there is still room to go, but I was glad to see that this fraction was similarly represented on the meeting's SOC, the fraction of chairs, and the number of speakers. I was also very pleased to see all of the young people who are presenting their work here.

I would characterize IAUS#49 as both very stimulating, and very frustrating, as most of the senior participants there were unconvinced there were *any* abundance anomalies in these stars, despite the fact that hydrogen lines were either weak or not present. We juniors were much more excited about the new work being done by Paczynski, and others, on "mass exchange binaries," which had the potential to uncover stellar interior products of nuclear reactions (helium, carbon, nitrogen, oxygen) in massive stars as they evolved and interacted. One can get the flavor of the discussions by reading the published proceedings, but I will say in hindsight that much of that material was tedious, repetitive, and, often just plain wrong.

The big issues at that time concerned the evolutionary status of these stars; it appeared to some that perhaps they were pre-main sequence stars with normal composition, to others the spectra suggested highly evolved objects with abundance anomalies consistent with the products of core nuclear reactions visible in the stellar winds. Mass loss rates were, at the time, difficult to determine. Detailed and predictive wind codes, non-LTE, radiative transfer codes, statistical equilibrium calculations were all in the future and by now have been found to be more or less in reasonable agreement with the observations.

For example, it is feasible to predict the WN/WC star ratio, which depends on the initial metal abundance, and compare it with observations of W-R stars in Local Group galaxies in which they have been identified. This prediction seems to hold for all galaxies so far studied, with the possible exception of IC10 (see contribution at this conference by Massey et al. 2015). Furthermore, the W-R/O star ratio ought to be near to 0.1 (the helium to hydrogen burning lifetimes) in a random sample of massive stars; this is much harder to test observationally due to the difficulties in identifying O stars (Massey 2010), although it can be done locally (Conti et al. 1983).

Advances in scientific fields are mostly noted by publications in refereed journals, of which you are all familiar. Not as well known is the role conferences play in advancements in the field. In dealing with W-R stars, and more generally hot massive stars in general, there have been a series of IAU Symposia, which originated in the late 70s on these topics, which were held near to beaches, thus receiving a certain notoriety from the OC of the relevant IAU Commissions judging the proposals. I was involved in organizing the first of these (see below) with the eager participation of my Canadian colleagues. A beach location creates a marvelous level of informality for the interactions of the participants, thus providing an open and often speculative set of conversations. In addition, when one informs ones spouse of the location of the conference, there is often a request to also attend, with the result that strong bonding occurs between the participants families, leading to life-time scientific relationships. Personally, these conferences were a major positive impact on my work over these past four decades.

They were also fun. And do not think that non-beach Symposia are not fun too! Here we have lake water all around us, and I have observed intense personal interactions going on while the formal sessions are not in progress. I have only listed the IAU Symposia, there were also a handful of Colloquia, conferences and Workshops on these topics.

Listing of IAU (Beach) Symposia (IAUS) Involvement with W-Rs:

- **IAUS 83 Mass Loss and Evolution of O-Type Stars,** 5–9 June 1978 Qualicum Beach, Canada.

Fig. 1: Participants at IAU#49: *First Row:* Marita Chidichino, Dora Goniadsky, Virpi Niemela, Anne B. Underhill, M. K. Vainu Bappu, Lindsey F. Smith, Peter S. Conti, Bengt Westerlund, Humberto Gerola. *No Row, at Left:* David J. Van Blerkom, Marcos Emilio Machado, Hugo Gustavo Marraco, Roberto Hugo Mendez, Juhan Frank, Leonard Kuhi. *Second Row:* Gonzalo Alcaíno, Richard N. Thomas, Ana María Hernández, Julio C. Duro, Nolan R. Walborn, Robert J. Altizer, Willem Seggewiss, Robert J. Havlen, Mart De Groot. *Third Row:* H. John Wood, Bohdan Paczynski, ??, Horacio Ghielmetti, Donald C. Morton, Luis Lopez, Jorge Sahade, Hugh M. Johnson.

- **IAUS 99 Symposium on Wolf-Rayet Stars: Observations, Physics, Evolution,** 18–22 September 1982 Cozumel, Mexico.
- **IAUS 116 Luminous Stars and Associations in Galaxies,** 26–31 May 1985 Porto Heli, Greece.
- **IAUS 143 Wolf-Rayet and Other Massive Stars in Galaxies,** 18–22 June 1990 Bali, Indonesia.
- **IAUS 163 Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution,** 2–6 May 1994 Elba, Italy.
- **IAUS 193 Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies,** 3–7 November 1998 Puerto Vallarta, Mexico.
- **IAUS 212 A Massive Star Odyssey, from Main Sequence to Supernova,** 24–28 June 2002 Lanzarote, Canary Islands, Spain.
- **IAUS 227 Massive Star Birth: A Crossroads of Astrophysics,** 16–20 May 2005 Catania, Italy.
- **IAUS 250 Massive Stars as Cosmic Engines,** 10–14 December 2007, Kauai, Hawaii, USA.

Some of you will recall your own attendance at these meetings, which still resonate in my memories. I hope such pleasures will also be found by the younger of you attending this conference.

Let me now turn to the current status of W-R research concerning their origin and fate. Not to trivialize the latter, it appears clear that when their evolved stellar cores give out of nuclear fuel and cannot support the remaining overlying material the star will collapse, resulting in a supernova! These have been associated with SNe of type Ib and Ic, which collectively have no hydrogen remaining. Many of our colleagues here are working extensively in this area, and so I leave the subject of the deaths of W-Rs in their capable hands, and instead concentrate on the origins question.

For quite some time after the extensive research into the evolution of exchange mass (massive) binaries, it became clear that this was a way to uncover the products of nuclear reactions in their stellar cores. But was it the only way? For this to be

the case, ALL W-R stars had to be binaries, and, furthermore, they had to have had an acceptance of mass from their companions. But was there another "channel"? Here I need to relate a very personal story. In 1975 I was very involved with an observing program at CTIO to obtain high dispersion spectra of all the bright (∼8th mag) southern O type stars (I had already obtained the northern ones at Lick Observatory). I had just obtained spectra of several Of and WN stars in the Carina Nebula, and it popped into my head they looked very similar with absorption lines, and weak to strong W-R WN type emission features of Helium and Nitrogen. But their type of star labels were not the same, rather they were called Of and WN. Was there a connection?

It was already clear from rocket observations pioneered by Don Morton (Morton 1967) that hot massive stars had winds. These stars also contained spectral indicators for winds and perhaps at a level to remove enough material to uncover their cores. I developed and talked about this scenario at the Liege Symposium that year (Conti 1975) and the concept was well received. Thus opened up a single star mass loss channel to produce W-R phenomena.

It has been claimed that all W-R stars are in binary systems, similarly there have been extensive arguments that all massive stars are binaries. I would tend to doubt this as the brightest O star in our sky, Zeta Pup, appears to be single. Furthermore, the brightest W-R, γ^2 Vel, while a binary, has its companion in a several month elliptical orbit. I had always understood that mass exchange led to a circularization of the orbit. Thus how could it have been interacting? For this star, an investigation of the spectrum of the companion O type supergiant (Conti & Smith 1972) revealed *no* anomalies in its lines. In particular, *if* there has been an interaction, nitrogen atoms would have been earlier preferentially been removed from the WC star and deposited on the companion. There is *no* evidence of this. I would like to suggest that other WC binaries with known companions ought to be investigated for evidence of past mass exchange. While clearly the short period ones could have interacted, the mass peeled off the initial primary might well have been completely ejected from the system.

Another important unsettled issue is the role of rotational mixing in massive stars. This might well aid in the mass loss process, in single and in binary stars, thus a channel to provide W-R phenomena. For example, it might affect the Humphreys-Davidson luminosity limit for massive stars, above which stars turn back to the blue and below which they become red supergiants. This affects the minimum mass for W-R star production. Related to his is an unsettled issue of whether or not RSG can end up as W-R stars. The jury is out on this question at present. What is the role of Luminous Blue Variables (LBVs) in W-R production? Are all W-R post LBV stars?

Let me list some outstanding problems still with us in considering our understanding of W-R evolution.

W-R stars ought to define the spiral arms of our galaxy, but typical placement of them does not readily lend itself to clearly defined arms. Also, we live in a barred galaxy, which ought to have *two* well defined arm features. This is not seen in a face-on view. It might be that the distance determinations are still insufficiently accurate to give us a clear picture.

Are massive stars born in isolation? IR imaging of isolated UCHII regions, the precursors of massive O stars typically result is the discovery of fainter stars in the immediate vicinity. Might these objects play a role in further W-R evolution?

In the very luminous galactic cluster Westerlund 1, 23 W-R stars and 3 red supergiants are found. It seems likely given its size that these stars are coeval. But how can this be, given an HD limit? Individual stars may have different rotational mixing properties. Higher values would push more to W-R production and lower values would tend to produce a red supergiants. At a certain time both types might be present together.

Finally, I would like to strongly suggest that someone devise a observation that would demonstrate that a close W-R binary had, indeed, gone through a mass *exchange* to its companion, rather than a mere mass *loss* during the interaction.

In closing, all of us Wolf-Rayet "stars" would like to thank Professor Wolf-Ranier Hamman for conceiving of and organizing this conference.

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Peter Conti