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CONFERENCE SUMMARY

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RESUMEN

En este resumen hablaremos brevemente sobre la mujer cuyo trabajo nos ha servido de inspiración y nos ha traído hasta aquí. Luego describiremos lo que creemos que hemos aprendido esta semana y finalmente plantearemos los interrogantes más importantes que quedan por resolver.

ABSTRACT

In this summary we will first talk a little bit about the woman whose work so inspired us and brought us here. We will then describe what we feel we learned this week, and finally we will pose some of the big questions that we are left with.

Key Words: stars: atmospheres — stars: early-type — stars: evolution — stars: mass loss — stars: binary — stars: Wolf-Rayet

All week long everyone has been telling us that conference summaries are hard to do. And you know what? They are right! You can't include everything, and the final result is bound to be idiosyncratic. Ours will be in three parts: a little bit about dear departed friend Virpi, a little bit about what we learned this week, and a little bit about what might be the Big Questions that we're left with.

1. VIRPI NIEMELA: 35 YEARS STUDYING MASSIVE STARS

Looking at the literature, the first glimpse we catch of Virpi is in the list of attendees of the 1971 meeting on "Wolf-Rayet and High Temperature Stars" held in Buenos Aires. Other notables at that meeting who are also in the audience today include Roberto Terlevich and Nolan Walborn. Next, if we check ADS, we find that (as of the time of this meeting), Virpi had 232 publications. Let's consider her first two published papers:

• Niemela 1972, "On the Wolf-Rayet Stars HD 90657 and HD 117688", PASP 84, 450. In this, we see a foreshadowing of a topic that would be near and dear to Virpi for the rest of her career, namely her first discovery of a WR spectroscopic binary.

• Niemela 1973, "The Wolf-Rayet Spectroscopic Binary HD 92740", PASP 85, 220. In this paper, Virpi presented an orbit for HD 92740. Let us quote a critical passage: "The higher members of the Balmer series of hydrogen are seen in absorption only. The plot of the radial velocities of H9 an H10...seems to indicate that very probably they do not have their origin in the companion star but share the orbital motion of the WN object". Here was a real paradigm shift. Virpi found that the absorption lines in HD 92740 followed the orbital motion of the emission lines: the absorption lines thus originated in this "Wolf-Rayet star". To the youngsters here, maybe the historical significance isn't clear, but this discovery was one the primary impetus for the "Conti scenario"—that there was a progression from O-type star to Of star to Wolf-Rayet star.

Next, one of the authors (PM) has to drop into the first-person voice, because I have to describe the first time I ever met Virpi, and what it meant to me. I was a grad student at the time, working with Peter S. Conti at the University of Colorado, and I was at my first-ever scientific meeting, IAU Symp. 83, held at Qualicum Beach on Vancouver Island, in June 1978. (This was the first of what was to become many "beach symposia".) I had just come up with the idea for my thesis: take the known Galactic WR with absorption lines in their spectra (presumably meaning they were binaries!) and get high dispersion observations and hence (I hoped) orbits and masses. I remember standing on the beach the first evening, at the reception, having just described this to two of the participants, who told me that (a) it was a dumb idea, and that (b) they were already doing it. I was pretty crushed! (I was also amused at their argument that they were doing this at low dispersion because that made the broad lines "easier to measure".) But, suddenly this woman popped up beside

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me. She had heard part of the conversation, and introduced herself. Virpi and I talked some about my project, including which stars I was going to do, and she said, "Oh, I have a lot of spectra of some of those stars—would you like me to send you the plates, or if you want I can measure them and send you the numbers". She was willing to help out in any way she could (and SHE thought the project was GREAT). So, anyway, it convinced me that there were some incredibly nice people in the field. I didn't know then how lucky I'd been, that Virpi was exceptional this way, but anyway, it made a real impression on me. Virpi and I went on to co-author 6 papers together: 5 of them in 1980-1984, and then one in 2002.

Once I reminded myself of the number of papers I'd done with Virpi, it made me curious how this stacked up with other Virpi collaborators that I knew would be here. The winner turns out to be Nidia Morrell, with 51 papers co-authored with Virpi, starting with a study of "DW Car" in 1985, and the most recent being a study of "FO 15" in 2006. Tony Moffat comes in second with 35; Roberto Gamen with 21, and Cristina Cappa with 13, all beating out my 6 and co-author GK's 5.

The other tidbit I can offer, is that If one searches for various key words in the titles of Virpi's papers, one finds that "Binary" wins hands-down at 113. So, my conclusions are:

1. Virpi's written *a lot* of papers over the past 35 years.

2. They've been *important* papers, presenting fundamental measurements of the masses of O and WR stars by application of basic "clean" physics, and

3. Virpi always had something interesting to say.

Still, despite all of this important work, it seems to me that Virpi's biggest legacy is all of the young astronomers she helped to train and worked with over the years. I know that when I interact with a student, I remember the lesson from the beach that day in 1978, and how a real astronomer should behave. Virpi, I'm really going to miss you.

2. SO WHAT DID WE LEARN THIS WEEK?

The first thing we learned is that the Local Organizing Committee has done a great job: this is one of the best organized and *nicest* meetings we've been to. There were the right number of days, the right number of talks, the right mixture of subjects, plenty of good people to talk to, and a nice beach on which to run every morning.

Science-wise, we are going to list what we thought were some of the highlights of the meetings. Things that ran through our heads or which we picked up from other participants, are indicated in italics. Some of these are intended as provocative (the comments, not the participants), and some are thoughtful. Well, and some may be provocatively thoughtful, or thoughtfully provocative. You decide.

Let us begin by quoting a former President of the United States named Bill who would begin his "State of the Union" speeches with these encouraging words: the state of the union is GOOD!

• Stellar atmosphere models are matching spectra. Stellar evolutionary models describe the placement of stars in the HRDs, and also their abundances. *Together, these suggest that while our work may not be done, we are generally on the right path.*

• Recent determinations of the effective temperature scale of O-type stars generally agree, despite being done by different workers using different samples of stars and different data. *But, so far these have been based primarily on FASTWIND, and we really need to compare the results of modeling the same stars by different codes, such as CMGEN and WM-basic, and compare the results from modeling of the UV lines vs. the optical lines.*

• There is still a mass discrepancy for the hottest O stars. *Is this an issue with some stars being overluminous for their mass, as Andre Maeder suggested we call it, or it is a problem with some of the "spectroscopic masses" being too low? (i.e., a surface gravity problem)?*

• With 8-10 m telescopes, one can now do model fitting of OB stars in Local Group galaxies and beyond, yielding abundance determinations. *How well do these really agree with nebular abundances? If they differ, then we need to understand why.*

• One can do this for B- and A-type supergiants too. *The success in fitting spectra is remarkable, and the small discrepancies may be due to deficiencies in our knowledge of the atomic data. Such fitting provides important constraints on stellar evolutionary models.*

• "Qualitative morphology" of spectra in the optical often agrees with that of other wavelength regions. *But, we really need to understand how this can possibly extend to the X-ray region—that seems a bit too good to be true, and its hard to understand what physics would lead to that. In any event, quantitative analysis is essential for the interpretation: two stars with different metallicities can have similar looking spectra despite different effective temperatures, surface gravities, mass-loss rates, and luminosities.*

• The location of red supergiants in the HRD agree well with the evolutionary calculations for the Milky

Way, LMC, and SMC metallicities. *If clumping changes the mass loss rates by factor of 10, this good agreement is going to vanish.*

• There have been great strides in measuring the rotational velocities in O-type stars (FLAMES survey, FUSE, STIS). The $v \sin i$ distributions are about the same in the SMC, LMC, and Milky Way. Older stars rotate more slowly, even in the SMC. *But we really need larger sample sizes for robust results.*

• Rotation should have a very profound effect at extremely low metallicities, where the mass loss can be rotationally induced rather than radiatively driven. *Are the initial rotation velocities reasonable? See previous point about the need for more $v \sin i$ measurements!*

• Photometry can be useful in determining the physical properties of O stars, if you really understand your filter system. *But are the answers you get unique? One needs to do a lot of comparisons to stars that have been carefully modeled by a variety of techniques in order to test this.*

• Pismis 24-1 (O3.5 III) is a double system separated by 0.4″, consisting of an O3.5If*+O4III(f+) pair. Most of the He I comes from the O4 III star. *Would we recognize such systems if they were located in more distant locations, such as the LMC or SMC? Almost certainly we would! If we tried to model the spectrum of such a composite system, we would not get consistent fits for the He I and He II line strengths. In fact, it's pretty hard to hide such discrepancies.*

• The WR binary frequency is about the same in the Milky Way, LMC, and SMC. *How much does being a binary help you become a WR? Probably not much! We've known for decades that the distributions of eccentricities and periods look about the same for O-type binaries as for WRs, suggesting that mass transfer hasn't played much of a role in creating the WRs in WR+O systems.*

• Great strides are being made in studying the radial velocities of Galactic O-type stars. *But, it seems we know a lot more about the binary frequency of WR stars than we do about O-type stars.*

• We can use hot massive eclipsing binaries to get distances to nearby galaxies. *But distances aren't in good agreement with better accepted methods. Only a few have been done. And the errors associated with these distances really must incorporate the effects of tidal interactions, mass transfer, ellipsoidal light curves, and all the other problems that plague massive star binary work. Would stars of lower masses and temperatures be brighter visually, as well as more numerous?*

• There's been a lot of progress in understanding HD 5980: hitting the bi-stability limit seems to be what is triggering the eruptions. The maximum activity in HD 5980 occurs after periastron passage, consistent with the predictions of a one-layer tidal-interaction model. *What was the role of tidal interactions in the 1993/1994 eruptions? Could this mechanism have made the star hit the bi-stability limit? Is a really big eruption still to come?*

• Nine out of four stars in the Trapezium is a binary. *Maybe there were four sub-clusters formed. Multiple systems seem to be the rule among the brightest R136 binaries as well, maybe for the same reason.*

• None of the close binaries in the R136 system are in the central core. *This is probably* not *a selection effect. It must be telling us something profound.*

• The binary frequency of O stars is said to change drastically from one cluster to another, from 14% in Tr14 to 80% in IC 1805. *If this is true, it's absolutely remarkable. This result needs some careful checking to substantiate it is not simply a selection effect, and if it is true, then we need to see what the binary frequency correlates with—stellar density?*

• The velocity dispersions of clusters need to be corrected for stars with binary motion. *Do younger clusters have larger velocity dispersions due to the presence of more massive binaries?*

• The characteristics of pinwheels can be effectively described with wind-wind collision (WWC) models. Among the recent advances in these models is the inclusion of clumping. *Is clumping more than a free parameter? Wind theorists really have their work cut out for them.*

• HD 93403 and Cyg OB2 No. 8 have similar spectral types, orbital eccentricities, and periods, and yet have different phase-dependence to their X-ray emission: one has minimum emission near apastron and the other at periastron.

• In WR140, the location of dust has now been spatially resolved and is not consistent with maximum dust formation near periastron.

• Analysis of the X-ray spectra of WR 140, WR 125, and γ Vel leads to the conclusion that there are significant eclipse effects, accounting for some of the variability. In θ Mus, the X-ray emission is constant.

Some random thoughts on the last few points: The WWC paradigm still needs to be tested. X-ray emission line profiles would be helpful to further constrain the models of WWC systems. VLBI observations provide good constraints on WWC physics.

• Radio observations of O8-B3 supergiants suggest that the wind mass-loss rate efficiency has a local maximum at an effective temperature of 21,000 K, consistent with the bi-stability limit. *But, more data with higher S/N would help to better establish this.*

• Magnetically confined wind shock model applied to θ^1 Ori C is promising. *The physics sure is complicated, though!*

• Maybe a lot of high mass close binaries with compact companions have jets (mini-quasars). *For years it seemed like SS433 was unique, but now it turns out to just be one of the crowd. Maybe all O stars with non-thermal radio emission are binaries with WWCs.*

• Bo 7 is a previously obscure cluster with lots of newly found O and B stars, including a massive binary and even an HI supershell. *Our knowledge of nearby, bright ($V = 10$) O-type stars remains woefully incomplete.*

• Such incompleteness also rules our knowledge of the O star content of the Magellanic Clouds, as demonstrated by the nice poster on N159/N160.

• HD 93162 (WR25) is a very high mass SB2 system. *There still need some work to dig out the masses and inclinations. Such long period systems can actually tell us something about single stars, if the spectral lines can be sufficiently de-blended to yield a clean orbital solution.*

• Very nice success of new "self-consistent" WR models in matching the observed spectra; this work emphasizes the importance of the Eddington limit. *It does, however, require depth-dependent clumping to give a good fit to the observed spectra. What is the physical mechanism for this?*

• The nebulae around massive stars range in size form a few tens of parsecs (interstellar bubbles) to a few thousand AUs (red supergiant circumstellar nebulae). *Such studies promise to not only help us understand the interaction of stars and their ejecta with the ISM, but also help us probe the star's evolution.*

• Nebular diagnostics can help us better test the FUV flux distribution of different stellar atmosphere models. *But the model fitting really has to be done with a great deal of care as the FUV distributions are quite sensitive to temperature. One also needs to use nebulae which are excited by a single star, and which are clearly radiation-bounded and not density-bounded.*

• In η Car all emission indicators (radio, X-rays, He II λ4686) "crash" to minimum just after maximum outburst. At the same time, X-ray absorption is important in these phases. *The question finally needs to be asked in public: Does η Car tell us* anything *at all about other LBVs? Or is it like the muppet Gonzo, cute and interesting, but a one-of-a-kind creature, a "Whatever"? Wouldn't P Cygni make a more attractive poster-star for LBVs?*

• We expect to see 2000 supernova remnants (SNRs) in the Milky Way, but we have found only about 200. Is this telling us that there's something wrong with our assumptions? *Most massive stars are found in OB associations, and the low density of wind-blown bubbles will not result in a classical SNR. Still, the X-ray emission should be unaffected by this.*

• Spectra of AG Car can be better fit with time-dependent atmosphere models than with a stationary model. *The eruption involves changing the wind structure of the star.*

• It seems likely that the beautiful equatorial ring and bipolar nebula seen around SN 1987A is not proof that the progenitor was a post-RSG blue loop object, as many have claimed. There are just too many problems with this picture, plus there are too many other examples of similar rings where the star is just as unlikely to be a post-RSG. *Four examples is still small. Let's go find some more.*

• Wolf-Rayet stars are detected in some galaxies via He II λ4686 emission and now C IV λ5808. To be found against the integrated light of an entire galaxy requires a lot of WRs! *What causes the intense nebular He II λ4686 lines in these and other emission-line galaxies?*

• Emission-line galaxies and super star clusters are telling us about star formation at the extreme. *This presents a big challenge, both observationally and theoretically.*

• Star formation rates in massive galaxies have dropped over time, while less massive galaxies are (on average) as active now as they were at the start. *Another way to put this is that starburst galaxies were more luminous in the past.*

• Westerlund 1 is an AMAZING place, with something for everyone: WRs, LBVs, RSGs, yellow hypergiants, eclipsing binaries, and presumably a whole lot of O-type stars. *Are there similar clusters waiting to be found, in the Milky Way, in M31 and/or M33, or elsewhere in the Local Group? If so, what would such a cluster look like at at a distance of 800 kpc?*

3. SOME BIG QUESTIONS

One of the really fun things about science is that if you do your job right and find out a bunch of stuff, at the end you still have a whole bunch of questions—some of them that you didn't anticipate. This provides very good job security for us all. Anyway, we'd like to end this summary by posing some of the questions that we're left with. We are grateful to several of our colleagues (and in particular Hans Zinnecker) for contributing to this list. We're sure you'll have your own to suggest.

1. Why is it that different emission lines in WR binaries give different orbital parameters than others, including phase delays? Which is "right"? How can the contribution from the WWC region to the emission-line intensities be determined (and corrected for)?

2. What is the distribution of initial rotation velocities of massive stars? How does it depend upon metallicity, and other environmental factors, such as shear?

3. How much mass is lost in the LBV stage, compared to other mass-loss mechanisms?

4. Is the fact that η Car is a binary have *anything* to do with it being an LBV, or it is simply incidental (and confusing)?

5. What is the upper mass limit? What physics determines it?

6. There are *isolated* massive stars (from O3s through WRs). Is this fact evidence of isolated star formation, or are these stars all runaways?

2. Is there a statistically significant lack of massive binaries in the cores of dense young clusters, such as R136 and NGC 3603? If so, what is this lack telling us?

3. P Cygni's last big eruption was in 1600. η Car's last big one was in the late 1800s. If these stars were instead located in the Magellanic Clouds, M31, or M33, would we know of them today? What, then, are the actual statistics of LBVs in nearby galaxies?

4. What kinds of massive stars really are the progenitors of supernovae (Type Ib, Ic, II), and what exactly are the progenitors of the gamma ray bursters?

These questions will hopefully convince you that there is still a lot of fun to be had out there.

We're grateful to the conference organizers for giving us a chance to come together like this, and exchange all of these ideas and thoughts—this really was a swell meeting. The sadness we all feel at losing our dear friend so soon afterwards cannot be alleviated by that, but we're glad we did all get to be together with her one last time.

The LOC trying to figure out how are they going to cancel the hotel balance.