Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Summary talk

John E. Dyson

Department of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK

Abstract. A personal perspective of the meeting is given.

1. Introduction

It is a formidable task to try to summarise a meeting where over fifty talks and over one hundred and fifty poster papers have been presented. Perhaps I should have looked first at the programme before agreeing to give this talk! It is though even more daunting to try to follow in Peter Conti's footsteps. I will take the easy way out by attempting neither and will present my own prejudiced perspective on what by common consent has been a most successful, if demanding, meeting.

Before starting on specific scientific issues, there are a few general comments on the meeting I would like to make. The quantity and quality of the multi-wavelength data which has been presented is truly impressive. The data arguably drive the equally impressive technical advances in theory. The balance and interplay between observation and theory to me has been a highlight of the meeting. Many questions have been answered but many others have been thrown up. Apart from surely defining a successful meeting, this latter clearly justifies future meetings in equally idyllic beach resorts.

By far the most striking aspect of the meeting has been the sheer range of astronomy and astrophysics contained under the general theme of the Wolf-Rayet Phenomenon. We have heard about nucleosynthesis, stellar structure and evolution, stellar atmospheres, circumstellar and interstellar matter, galactic structure and even active galactic nuclei. *Messieurs Wolf et Rayet* little realised what they started so long ago.

I hope contributors to the meeting will excuse my not referring to them individually. This is partly because of the sheer scope of the meeting and partly because I have been so selective in my discussions.

2. Massive star formation

If I were to make one main point about the WR phenomenon it is that it cannot be de-coupled from the general question as to how massive stars form and how they influence their surroundings. So many of the areas discussed depend on this. It is pertinent therefore for me to make some general remarks about some of the problems involved, not the least because this question has really not been addressed in much detail here.

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Massive star formation is presently even less understood than low-mass star formation. The reasons are fairly obvious. Firstly, the sites of high-mass star formation are often even more deeply buried in dusty molecular clouds than are those of low-mass stars. Secondly, the accretion time onto massive stars can be appreciably longer than the Kelvin-Helmholtz time. They thus commence nuclear burning whilst still accreting and are initially surrounded by very dusty cocoons. They develop their hard radiation fields and hypersonic winds whilst in this phase and the resulting interactions of these with their surroundings are very complex. It is therefore only by the indirect means of studying such intriguing objects as the ultra-compact H II regions found associated with $\sim 10\%$ or so of Galactic OB stars that one can make inferences about the nature of the material from which the stars have definitely formed. It also has become clear over the past years that the chemical structure and chemical history of star forming regions are central to questions such as, for example, how magnetic fields couple to the gas in star forming clumps. As one last example of the problems which await resolution, a 'conventional' view of massive star formation is that the increase of the external pressure on a magnetically supercritical clump can induce collapse; however this very much depends on how the cloud temperature responds to the external pressure increase which in turn depends, amongst other things, on how physically the preasure increase occurs.

Many of the topics discussed in the meeting need the resolution of these and other issues in star formation. For example, several of the contributions have stressed that the inclusion of rotation into stellar evolution calculations is essential; the evolutionary tracks with and without rotation are very different. The rotation speed of a newly formed star depends on, for example, how the angular momentum of the star-forming material is lost by magnetic coupling to the star's surroundings. As has been noted, this can depend on the chemical history of the material and thus may be linked, in some as yet ill-understood fashion, with the metallicity of the star forming regions. Again, for example, other contributions have assessed the evolution of binary systems; yet again the formation of massive binaries is badly understood.

On a larger scale, there has been considerable interest in this meeting on the properties and evolution of groups of stars ranging from super-star clusters or SSCs, *e.g.*, R 136, to starburst and/or Wolf-Rayet galaxies. In regard to the former it is perhaps not too surprising that massive stars are formed in clusters with dimensions of typically a few parsecs. If one makes a rough estimate of the range of a supernova in a typical giant molecular cloud (such as the Rosette Molecular Cloud), it turns out that a single supernova could pressurise a significant fraction of the cloud and maybe induce a burst of star formation in this region. Of course sequential star formation might then occur over the rest of the cloud.

The propagation or induction of star formation over extended regions on almost galactic scales is clearly pertinent to an understanding of starburst and Wolf-Rayet galaxies. For example the spectral synthesis of starbursts depends strongly on whether star formation is coeval or non-coeval. Another equally important question which has surfaced is what limits the upper mass-cut off in an IMF (indeed what determines the actual IMF is also of significance). We have heard two interesting and, certainly on the surface, two conflicting pieces

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of evidence. Firstly, we have had evidence for believing that there may be very massive (in excess of 100 $M_\odot$) hydrogen burning stars with such very high mass loss rates that their spectra resemble those of more 'conventional' WN type stars. On the other hand, we have heard evidence that there may be a deficiency of very high-mass stars in starburst galaxies. It could of course be, leaving aside the implications for wind driving mechanisms, that in starburst galaxies the mass-loss rates from the very massive stars are so high that the winds are optically thick in the Lyman continuum. On the other hand it could be that different conditions in which star formation takes place produce very different upper mass cut-offs.

It may turn out to be significant that the accretion rates inferred in hot molecular cores where massive star formation seems to be occurring are far higher that previously thought and are comparable with the mass-loss rates inferred for the 'non-conventional' H burning stars of WN appearance. (Though as a caution, the final masses suggested for the stars formed in the hot cores do seem appreciably lower, perhaps $\sim$30 $M_\odot$). Simultaneous accretion and outflow with comparable accretion/mass-loss rates are becoming accepted at least in certain models of active galactic nuclei. Since nature seems to make certain general phenomena ubiquitous (*e.g.*, jets), there may be some connection between the inferred accretion and mass-loss rates.

A final point is that high-mass star formation also has important implications for low mass-star formation. For example, the now famous *HST* photographs of the cometary globules in the Orion Nebula which contain young low-mass stars clearly show that the winds and radiation fields of the nebular massive stars are interacting with these globules. There is also increasing observational evidence that the mechanical effects of low-mass stars on their surroundings may have consequences for the formation of other stars.

3. Stellar atmospheres and stellar winds

The sheer effort of the work which has gone into the calculation of stellar atmospheres of WR stars, particularly the inclusion of realistic line blanketing effects, is impressive. As was remarked in the meeting, that phase of the work is essentially complete. The real tasks now are three-fold. Firstly, to match-up properly the winds with the atmospheres. Secondly, to model clumpy winds. Finally, to continue the development of the already large and impressive body of work on the structure of and emission from regions of colliding winds in binary systems, most importantly, OB+WR binaries.

The first task is not easy. One major problem is connected with the second point; it is certainly not obvious how critical points should be defined in clumpy winds. However there has been major progress in what has until recently been a major recurring problem with WR winds, the (now apparently only historically properly named) 'momentum problem'. This now appears to be resolved by a proper treatment of the opacity sources in these radiatively driven winds. (Or, as was succinctly put, 'it's the opacity, stupid!!')

A great deal of attention has been given to the implications of clumping in winds. Of course it has been apparent for some time that wind mass-loss estimates must include clumping. The origin of this clumping is not entirely clear. However inferred density contrasts of between 4 and 16 or so might well indicate that adiabatic or not too strongly-cooling shocks are involved. It is also not clear how these density fluctuations are related to velocity fluctuations. There are some interesting problems associated with shocks in clumpy winds. Very crudely, for shocks in the velocity range defined by wind velocities, the cooling times in the post-shock gas and the associated cooling lengths will scale respectively as the cube and the fourth powers of the shock speed. Although this is likely to be of little importance for global wind termination shocks produced by their interaction with circumstellar or interstellar matter, there could be major implications for the calculation of the structure and therefore, most importantly, the soft X-ray emission produced by colliding winds in binary systems.

This latter area has been given considerable prominence at this meeting. My admiration for the calculations performed so far is considerable. It has been clearly demonstrated that 3-D calculations including a proper treatment of radiation forces and non-equilibrium radiative cooling are essential. It is true though that even the latest 3-D model grids do not well resolve the cooled gas. As noted above, the incorporation of clumping must be included at some level. From a gas dynamical perspective, there are still some intriguing technical questions. The well-known stagnation point singularity problem is still around. Of course, this may be an artefact of geometry which disappears in real systems, but since most of the soft X-ray emission comes from the subsonic zone in the post-shock region which is affected by the stagnation zone, the resolution of this question is important.

Other very interesting questions in the context of colliding winds also received attention. There has been the suggestion that the radiation from a companion O star could significantly slow down the WR wind. On the surface, this sounds very plausible, but there are again some problems. Firstly, it is not obvious how this would work in a clumpy wind. Secondly, it is very hard to see how this deceleration can operate without inducing a global shock in the WR wind. Finally, perhaps as importantly, geometry will play a role.

We have also heard that there is strong evidence for the presence of dust in the WR 140 binary and some other (WC+OB) binary system. This is particularly intriguing since at first glance, the regions where fast winds collide would seem to provide a very hostile environment for dust formation or survival. On the other hand, dust is known to form in the equally hostile environment of supernovae remnants so perhaps one should not be too surprised. There is another possibility. If the WR star reached its present stage via evolution through a red supergiant phase, there may still be dusty debris around from this phase. Either way, the problem is important.

Lastly, but by no means least, the observation of non-thermal emission in these systems suggests that our understanding of the physical processes which are occurring is still incomplete. There are several ways in which the relativistic electrons which are required may be accelerated and suggestions include acceleration in global shocks or in current sheets. Further work is clearly required on this topic.

4. Ring nebulae and bubbles

I was somewhat tempted to spend my entire talk discussing this topic, but this scientific indulgence added to the non-scientific indulgence of the past week would be hard to justify. As is well known, because the evolutionary paths to the WR phase are complex with several possible mass loss phases (*e.g.*, O, LBV, RSG, *etc.*), plus the presence of interstellar matter, the range of interactions which might take place is rather large. On the other hand, the investigation of the structure and dynamics of ring nebulae in principle can give valuable information on the evolutionary history of the associated stars and so could be linked in to the stellar evolution calculations. Since we have seen that there are many complications with these then any additional information can only be welcome. It must be stressed though that each ring nebula is an individual object and that general conclusions are hard to carry from one to another. Perhaps the initially simplest separation that can be made is to separate objects where the interaction of the WR wind is primarily with the ISM from those where the interaction is with circumstellar matter produced, for example, in the RSG phase. This separation can be made on the basis of mass and chemical composition.

In regard to the former I would like to make a fairly obvious comment. Just because WR winds are very powerful compared to the winds in say a progenitor O phase, does not necessarily mean that the WR winds have the greater effects on the ISM. This is because very roughly, the integrated mechanical energy output in the O phase, is comparable with that in the WR phase for the simple reason that the O phase lasts much longer. Bubble dynamics depend rather weakly on the mechanical luminosities of the driving winds.

The interaction of WR winds with RSG ejecta throws up many fascinating physical questions connected with problems such as the mass-loading of fast winds. The effects of this can be dramatic. For example, mass-loaded winds may globally shock at much lower mach numbers than free winds. There may also be enhanced radiative losses at ejecta-wind interfaces (*i.e.*, in boundary layers) which may have two effects. Firstly the global dynamics are significantly altered. Bubbles (or ring nebulae) could then be driven by wind momentum rather than by shocked wind pressure. However, we did hear evidence that the soft X-ray fluxes from LMC super-bubbles seem consistent with pressure driving. It may be there that the OB stars are dominating the dynamics or that if WR stars are the dominant drivers, they did not go through an RSG phase. Secondly, the emission from the boundary layers may produce spectral features which would not be predicted from purely radiatively excited nebular models. This might, for example explain the He II emission observed in nebulae excited by stars with relatively low effective temperatures.

There is clearly much scope for future work on the RSG phase and I was perhaps a little disappointed that more was not heard about it here. The mass-loss process is itself of great interest. If RSG mass-loss is somehow a scaled up version of RG mass-loss, then the study of planetary nebulae may be of relevance. The fate of RSG envelopes in the SSCs is also interesting. Studies of the Galactic Centre have given strong evidence for the ablation of the envelope of the RSG IRS 7 by the wind from IRS 16, a cluster of blue stars. A rough estimate suggests that wind ram pressures in SSCs may be comparable with that experienced by

IRS 7 and envelope ablation may take place there too. (This may also occur in active galactic nuclei). How this impacts onto the evolution of these stars is not yet known.

5. Starbursts, superwinds and AGN

I have already made some comments on star formation in starburst galaxies in Section 2. The associated superwind phenomenon is a particularly interesting one. Clearly, WR stars can input significant energy into driving such flows though their subsequent evolution to a supernovae phase probably produces the energetically most important events. It is known from X-ray studies that superwinds must be mass-loaded. Material can be picked up from cool clouds by a variety of processes including thermal conduction and hydrodynamic ablation. Of course, these clouds may also be the sites of further star formation stimulated by the pressurisation provided by the wind itself. There is a complex feed-back situation whose resolution requires an understanding of many of the points made in Section 2.

Over the past decade or so, it has been gradually realised that many of the spectral signatures (*e.g.*, the broad allowed emission lines) of AGN (including Seyfert Galaxies and QSOs) can be understood only in the context of a black hole-star cluster symbiotic model. In the case of the QSOs, supernova activity is probably dominant although there is some debate as to how exactly this activity translates into broad emission line production. In the case of Seyfert galaxies I would make special pleading for the role of WR stars. The collision of the relatively high mass-loss rate and high metallicity winds of such stars either with each other or their environment followed by cooling (probably initially Compton, then line cooling) is a tempting source of the emission line gas. Again though there is a big unknown and that is how stellar evolution is affected by the intense winds and radiation fields in AGN.

6. Final words

As I said initially, this has been a personal perspective focusing on issues which I find both interesting and, I believe, important. This is in no way to down-play the others raised in the meeting. What I am sure will find general agreement is to say that the WR phenomenon is alive, well and broadening in scope and importance and that the next meeting may need to be even longer! Thank you for listening!