Session 6: Conference Summary

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The Lives and Death-Throes of Massive Stars
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Symposium Summary

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Abstract. This proceeding summarizes the highlights of IAU 329, "The Lives and Death-Throes of Massive Stars", held in Auckland, NZ from 28 Nov - 2 Dec. I consider the progress that has been made in the field over the course of these "beach symposia", outline the overall content of the conference, and discuss how the current subfields in massive stellar astrophysics have evolved in recent years. I summarize some of the new results and innovative approaches that were presented during the symposium, and conclude with a discussion of how current and future resources in astronomy can serve as valuable tools for studying massive stars in the coming years.

Keywords. stars: atmospheres, binaries: general, stars: evolution, stars: fundamental parameters (classification, colors, luminosities, masses, radii, temperatures, etc.), stars: interiors, stars: magnetic fields, stars: mass loss; supernovae: general, galaxies: stellar content, sociology of astronomy

1. Introduction

IAU 329 was the eleventh meeting in the "beach symposium" series focused on massive stars. As noted by Claus Leitherer in his conference summary of IAU 250, the topics covered at these symposia have shifted noticeably since IAU 49, held in Boulder, CO in 1968. The "median distance" of the objects at each meeting has increased, and the power and scope of computational tools has evolved drastically, allowing our picture of massive stars and the questions we are able to pose about their physical properties and evolution to grow remarkably in complexity.

When preparing the closing summary for this conference, I began by looking over the conference program to try and identify a simple outline or a straightforward progression of topics. At first glance the conference talks could be split into four basic categories: supernovae, stellar evolution, stellar properties, and stellar populations. The organization of the topics was sensible and is typical of how work on massive stars has traditionally been classified.

That said, these topics are related cyclically rather that linearly, and as the field of massive stellar astrophysics has progressed research spanning one of more of these broad areas has become the rule rather than exception. Much of the current work at the forefront of this field is taking place "in the gaps", considering, for example, how detections of core-collapse supernovae (CCSNe) sample star-forming galaxies or how computationally-rigorous treatments of key stellar properties impact evolutionary predictions.

During the opening summary of the conference Georges Meynet laid out the key challenges facing massive stellar astrophysics along with some of the most powerful new observational and computational tools we have at our disposal for addressing these challenges. Following his comments and the conference program, this proceedings summary of my closing talk will offer a brief overview of the new results presented in these four "main" areas of stellar astrophysics while also highlighting cross-disciplinary work and

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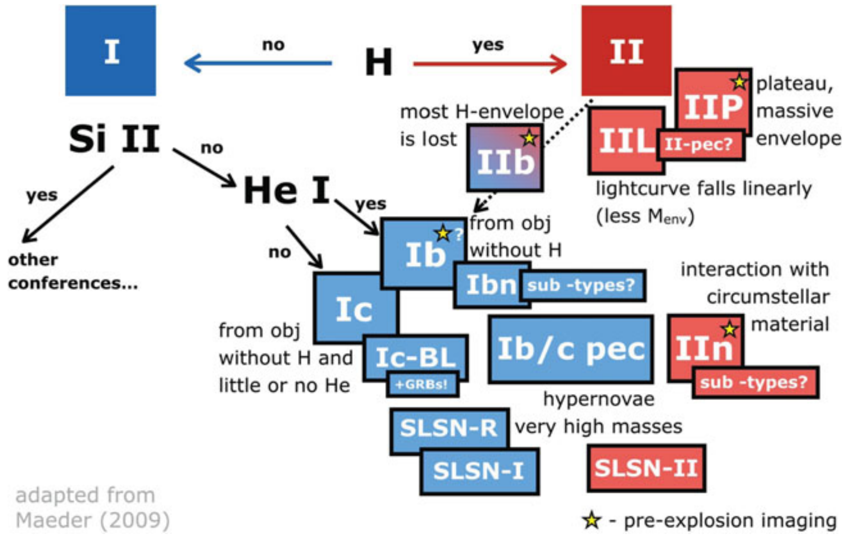

Figure 1. Illustration of current core-collapse supernova classification scheme and subtypes.

emphasizing ways in which we can continue the remarkable progress that has been made in the massive star field in the coming years.

2. Supernovae

The classification of CCSNe and the association of these various subclasses with progenitors has become increasingly complex in recent years (Fig. 1). Despite the increasing diversity of supernova sub-types, based largely on lightcurve evolution and spectroscopic properties, only a handful of definitive subtype+progenitor associations exist, and reproducing the lightcurves and spectra of supernovae from existing massive star models is still a challenge.

That said, much progress has been made in recently years on bringing theoretical models of CCSNe into agreement with their observed properties. Recently, 3D simulations have demonstrated the viability of the neutrino-driven mechanism of supernova explosions, and further work on these simulations should improve our ability to produce actual explosions from core-collapse models (*Muller*). These improvements have also extended to work on the relatively new subclass of superluminous supernovae (SLSNe), with models capable of reproducing lightcurves for Type I (hydrogen-free) SLSNe (*Nomoto*). Work is also underway to better reproduce the spectra of CCSNe based on models of their ejecta (*Hillier*). The ultimate goal of this work is the pursuit of a complete initial mass - metallicity parameter space that associates massive star progenitors with their counterpart CCSN subtypes; unfortunately, at the moment much of this landscape is still theoretical with only a tiny region of the plot ($\sim$11-17$M_{\odot}$ and $\sim Z_{\odot}$) supported by robust observations (*Fraser*).

It is now clear that achieving this goal will demand a much better understanding of not only how massive stars explode, but *which* phases of massive stellar evolution directly precede core-collapse and how their prior evolution affects their terminal explosion. Theoretical work has explored this question in detail, trying to directly reproduce a path from different classes of evolved massive stars to their eventual supernovae based on initial mass (*Groh*) and modeling the predicted lightcurves of different progenitor models to compare with observations (*Bersten*). One good observation-based approach was

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effectively summarized with the following question: "If [Star] X exploded tomorrow, how would we interpret it?" (*Beasor*). Given that, when studying the supernovae themselves, we often find ourselves working only with pre-explosion imaging (if we're lucky), this represents a practical and rigorous means of approaching this question from the stellar side: considering how known evolved massive stars might appear as supernovae and combining different treatments of available pre-explosion observations to better understand the limits of our current interpretations. Such an approach also leaves room for the growing sample of ambiguous events produced by evolved massive stars, such as luminous transients that cannot always immediately be classified as terminal supernovae or eruptive mass loss events; right now our best means of interpreting these is through studying their host environments and potential parent populations (*Drout, Thöne*). Very massive stars, and their role in producing pair-instability supernovae (particularly at low metallicity), also represent an important region of this relation between initial mass, metallicity, progenitor, and supernova type (*Yusof*).

3. Stellar Evolution

The massive star community now has access to multiple complete grids of stellar evolutionary models with varying treatments of key parameters such as metalliicty, rotation, and binary interaction. In recent years it has become abundantly clear that stellar evolution must be considered within the context of key stellar properties such as multiplicity, mass loss, magnetic fields, and rotation (see also Section 4). As a result, much of the current body of theoretical work on massive stars is focused on how stellar properties impact stellar evolution, and how observations and models can be combined to start placing massive stars into an evolutionary context.

The location of evolved massive stars such as luminous blue variables on the Hertzsprung-Russell diagram can be used to test both single-star and binary evolution models, and to potentially backsolve in the hopes of determining these enigmatic stars' evolutionary histories (*Smith*). Invoking massive binary evolution also opens up a broader range of potential terminal core-collapse products (e.g., the role that mass transfer plays in produced stripped-envelope supernovae produced by mass transfer, direct collapse of very massive stars to black holes, and even the eventual coalescence and gravitational wave signal of binary compact remnants; *Hamann, Podsiadlowski*). Strong surface magnetic fields also appear to decrease the mass loss rates of massive stars during their main sequence evolution, thus impacting the CCSN subtype and compact object that is ultimately produced (*Keszthelyi*). These critical evolutionary effects are not restricted to "external" physical properties such as mass loss and binary interactions; wave energy transport in the interior of a massive star can have a dramatic impact on its evolutionary track during the final years of its life, strongly influencing the question of how we can effectively backtrack from pre-explosion imaging to a progenitor's evolutionary history and initial mass (*Fuller*).

4. Stellar Properties

Much of the research presented at this symposium touched on at least one of the five phenomena in massive stars that currently pose the greatest challenge to models of stellar interiors and evolution: rotation, winds and mass loss, multiplicity, convection, and magnetic fields (Fig. 2).

The evolution of massive stars in binary or multiple systems offers a rich variety of possibilities for observable physical properties and core-collapse outcomes. Models that simulate phenomena such as post-main-sequence mergers and common envelope evolution

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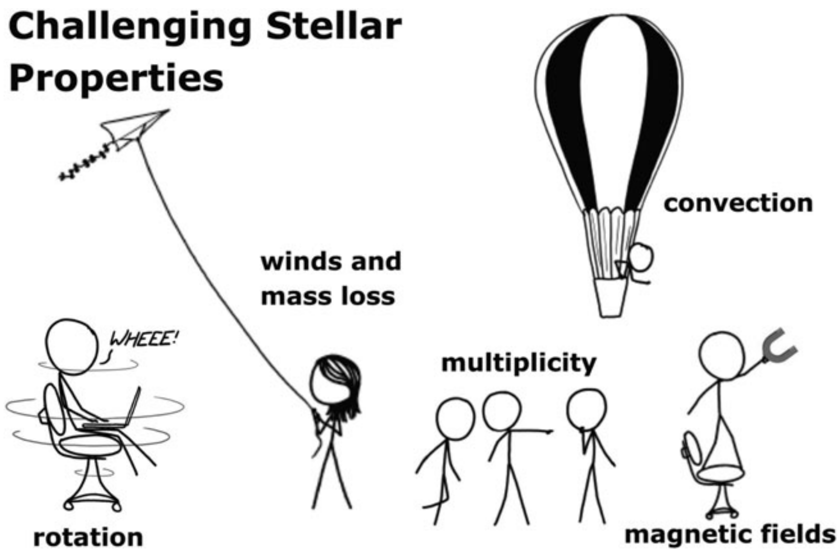

Figure 2. Pictorial summary of the physical properties and phenomena that currently pose the greatest challenge to stellar models. Adapted from illustrations by Randall Munroe available at `xkcd.com`.

are capable of producing stars such as yellow supergiant SN progenitors, close black hole binaries, and collapsar models for long-duration gamma-ray burst progenitors that agree with observed host environment metallicity effects (*Justham, Ivanova*). Binaries consisting of two massive stars were a particularly compelling topic at this conference given the announcement in February of 2016 of the discovery of gravitational waves from massive black hole binaries: the masses, merger rates, and spins determined from this tremendous discovery all offer new constraints on massive binary evolution (*Postnov*).

Stellar winds and mass loss have long been identified as key physical phenomena in the evolution of massive stars, impacting their observational signatures, angular momentum evolution, and the eventual properties of their core-collapse products. Work on this area in recent years has included high angular resolution imaging observations, using long-baseline interferometry or coronagraphic imaging, that are capable of spatially resolving circumstellar environments and offer us a new means of studying mass loss and dust production in large nearby massive stars (*Ohnaka*). As has been seen at previous massive star symposia, new treatments of phenomena such as clumping and porosity also continue to impact the theoretically-inferred rates of wind-driven mass loss in massive stars, highlighting the importance of incorporating these effects into existing codes (*Gräfener*).

Great progress has also been made in recent years on the effects of magnetic fields, with treatments of both interior and surface magnetic fields now included in models of massive stars. While magnetic field effects can be extremely complex (including orientation-dependent effects on the stars' observed spectra and the effect of stellar properties such as luminosity and changing rotation rates on the dynamo), they are a critical phenomenon to consider given that magnetic massive stars comprise $\sim$10% of the total population (*Erba, Augustson*). It is also worth noting that, while discussions of magnetic massive stars are traditionally focused on main-sequence O- and B-type stars, magnetic fields in massive stars continue to impact their observed spectra and evolution well beyond the main sequence; this highlights the importance of understanding magnetic activity in these stars from formation through death (*Oksala*).

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Finally, while each of these phenomena is complex and compelling on its own, a common theme that arose at this symposium was work that has started to combine their effects. Unsurprisingly, a complete stellar model must be able to reproduce how all of these phenomena interact. To take just one example, modeling a dipole magnetic field in a rotating star leads to a decrease in the effective stellar mass loss rate (*Bard*). Interactions (and, from an observational perspective, degeneracies) between effects arising from mass loss, interacting multiple systems, changing rotation rates, and the impact of magnetic fields and convection treatments on interior evolution must all eventually be taken into account when trying to model the realistic evolution of a massive star.

5. Stellar Populations

While individual massive stars still serve as excellent test cases for our models of stellar properties and evolution, it is becoming increasingly common to study these objects on a population-wide scale. Large surveys of massive stars have already proven invaluable for characterizing the typical physical properties of various evolutionary stages.

Spectroscopy of hundreds of O stars in our own galaxy (*Maiz Apellaniz*) and 30 Doradus (*Vink, Sabin-Sanjulian*) has made it possible to determine the positions, parallaxes, proper motions, radial velocities, effective temperature, rotation rate, and evolutionary state. Hundreds of red supergiants in and beyond the Local Group have also been studied both photometrically and spectroscopically. While identifying these populations can be challenging due to contamination from foreground stars or misclassification, determining their physical properties and placing them on the H-R diagram allows them to be used as an extremely effective "magnifying glass" for studying and testing stellar evolutionary theory in the post-main-sequence regime and across a broad range of metallicities (*Dorn-Wallenstein, Massey, Georgy*). Wolf-Rayet stars represent a critical late-time evolutionary stage for massive stars due to their strong mass loss and their presumed (and potentially observationally confirmed) role as the direct progenitors of core-collapse supernovae. Studies of Wolf-Rayet populations in other galaxies have made it possible to calculate an empirical $\dot{\mathrm{M}}$-Z relation for these stars (*Hainich*); such a relation is critical in understanding, for example, the role that single or binary Wolf-Rayet stars can play as the progenitors of long-duration gamma-ray bursts and stripped-envelope supernovae. A new population of Wolf-Rayet stars, WN3/O3 stars, has also been discovered in the Magellanic Clouds and appears to be specific to metal-poor environments, highlighting the many questions that still remain regarding post-main-sequence massive stellar evolution and the effects of metallicity (*Neugent*). Finally, population-scale studies of massive stars have also proven invaluable for measuring the binary (and, with increasing frequency, the multiple) fraction of both main-sequence and post-main-sequence massive stars, and for determining the typical angular separations and interactions of these systems (*Barba, Sana*). In all of these cases, new data from Gaia in the next few years will prove invaluable for this work, identifying young clusters of massive stars and making it easier to separate foreground and background populations using exceptionally precise astrometry.

Considering massive stars as a population in their own right also offers an extremely effective means of testing stellar evolutionary models. Massive stars in nearby regions like the Galactic center or nearby clusters in the Milky Way and Magellanic Clouds can be studied in detail and treated as young single-age systems (*Najarro*). Comparing the properties of these clusters with the predictions of simulated massive star samples from stellar population synthesis models serves as a powerful test of evolutionary theory on a large scale (*Vink, Crowther*). At greater distances, individual massive stars can no longer be resolved and we instead observe individual HII regions or starburst galaxies

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with very young coeval stellar populations such as II Zw 40; however, massive stars still dominate the radiative signature of these regions and galaxies, serving as the main source of ionizing photons and dominating the continuum signature in the blue and ultraviolet regimes. We can therefore use these sites of young active star formation as excellent tests of massive star atmosphere and evolutionary models, comparing observations to synthetic stellar population and examining how different treatments of key properties such as multiplicity and rotation agree with observations of the composite massive star sample (*Stanway, Leitherer*).

This large-scale work - using stellar population synthesis models to simulate large samples of stars in young galaxies and HII regions - brings the study of massive stars, and the summary of this symposium, full circle. Stellar population synthesis and photoionization models, which depend on accurate models of stellar atmospheres and evolution, are the key theoretical tools used for interpreting observations of star-forming galaxies. They are often used as the foundation for developing observational diagnostics used to determine fundamental galaxy properties such as metallicity and star formation rate. Those same properties are in turn the key (indeed, sometimes the only) data points available to observers studying the core-collapse deaths of massive stars in distant galaxies, determining whether supernova and gamma-ray burst subtypes occur preferentially in host environments with a specific metallicity or age profile (*Xiao*).

6. The Next Beach Symposium?

One overarching theme throughout the week of the symposium was the impressive diversity of scientific tools and approaches currently being applied to the study of massive stars. The research presented spanned the entire electromagnetic spectrum, ranging from radio mapping of massive stars' circumstellar environments and winds to observations of high-mass X-ray binaries and the detection of high-energy X-rays and gamma rays from eta Carinae. Imaging studies in stellar astrophysics now operate on massive scales, including a number of different transient surveys and immense missions such as Gaia. The reach of spectroscopic work on massive stars has continued to increase, with observations reaching out to tremendous distances (*Davies*). Challenging observational techniques such as interferometry (*Gies*) and spectropolarimetry (*Hoffmann, Agliozzo*) are offering a new perspective on nearby massive stars, allowing us to spatially resolve our nearest massive neighbors and probe the circumstellar environments of Galactic and even extragalactic massive stars in unprecedented detail. We are also pursuing asteroseismological studies of massive stars and should be able to conduct these on a larger scale in the coming years (*Buysschaert, Fuller*). The study of massive stars has also extended fully into the realm of three-dimensional models and simulations, sometimes literally - practical demonstrations during this symposium included an immersive simulation of the Galactic center based on Chandra data that could be viewed with 3D goggles (*Russell*), and a 3D-printed model of the Homunculus Nebula and interacting winds in eta Carinae (*Daminelli*). Finally, IAU 329 was also held at the dawn of a new era in astrophysics, one particularly pertinent to the study of massive stars: detections of gravitational waves offers us the chance to move beyond the electromagnetic spectrum and conduct multi-messenger explorations of massive stars' evolution, death, and the compact objects they leave behind.

The coming decade of observational facilities is going to continue this incredible rate of progress in the field of massive stellar astrophysics. The James Webb Space Telescope (JWST) is due to launch in October of 2018 and will lead the way in shifting the majority of space-based observational astronomy in the nearby universe into the infrared regime. JWST will also be capable of acquiring spectra of massive star-forming galaxies

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at $z \sim$9-10, sampling the rest-frame ultraviolet and capturing the composite spectrum of young massive stars in the early universe. The Large Synoptic Survey Telescope (LSST) will achieve first science light in 2021; with a 9.6 square degree field of view and a rapid cadence, LSST will usher in a new era of transient astronomy, demanding new and rigorously-tested models of stellar evolution and supernova properties in order to match the influx of newly-detected massive star transients with their potential progenitors.

Further down the road, the Extremely Large Telescope (ELTs) will be coming online in the next 5-10 years. Multi-object spectrographs on these facilities, supported by multi-conjugate or laser tomography adaptive optics, will open up an astonishing new volume of observable massive stars, capable of acquiring spectrophotometry of individual stars out to tens of Mpc. Future plans for ground- and space-based gravitational wave detectors will significantly expand the detectable strain and frequency parameter space (allowing us to detect gravitational waves from new phenomena such as pre-merger binaries) and improve our ability to localize gravitational wave sources (making it faster and easier to confidently associate these sources with their electromagnetic counterparts). Finally, the Wide-Field Infrared Space Telescope (WFIRST) is scheduled to launch in 2025, with a 0.281 square degree field of view and a 0.11 arcsec/pixel resolution. While the specifications of the WFIRST instrument suite are still being discussed, its incredible resolution will be a valuable tool for expanding the local volume of star-forming galaxies in which stellar populations can be resolved and studied in unprecedented detail. Looking at the potential discoveries that could come from combining these new facilities with the impressive theoretical and observational work that was presented in Auckland, I look forward to learning about more exciting results in massive stellar astrophysics at future "beach symposia" in the coming years.

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