Massive Stars Across Redshifts in the Era of JWST and Large Surveys
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Concluding remarks

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Abstract. The International Astronomical Union Symposium Number 402 focused on massive stars across redshifts in the era of JWST and large-scale surveys, and brought together specialists from a broad range of topics. I briefly summarize a few of the highlights from the excellent presentations and rich discussions and, because recent observations suggest that binary interactions dominated star formation and evolution during the early universe, I venture a few personal reflections on this topic.

Keywords. IAU Symposium #402, massive stars, binary star interactions

1. Introduction

The International Astronomical Union Symposium Number 402 focused on massive stars across redshifts in the era of JWST and large-scale surveys, and brought together specialists studying intermediate mass, massive and very massive stars, the interstellar medium, integrated stellar populations, and objects in the early universe. The meeting was organized into eight sessions which addressed topics touching on most aspects of modern astrophysics. It would be a daunting task to summarize the work presented at this meeting, and it would be unnecessary as each paper in this Proceedings volume will speak for itself. The best I can do here is to gloss over some of the highlights from each of the sessions, colored by my expertise and lack thereof, and encourage readers to discover for themselves the richness of the results presented. This brief summary is presented in Section 2.

In Section 3, I present a few reflections on binary interactions, now considered a fundamental ingredient for understanding massive stars at all redshifts, but the one that suffers from the greatest uncertainties. Finally, in Section 4, I summarize my conclusions.

2. The sessions

Session 1, Large Surveys and Key Observations gave an overview of new data being acquired and analyzed, highlighting their extraordinary quality and quantity. Fundamental properties, as derived by comparing these data to standard single-star model predictions were shown to compare favorably in many cases, but in many others some form of binary interaction effects were thought to be needed.

The large quantity of data makes the use of automated methods necessary. Attention was drawn to machine learning tools being developed and some of the spectacular results being obtained from using, for example, neural networks. However, it was pointed out that at least in the case of spectroscopic surveys of stellar objects, fitting theoretical models to the observations is far from straightforward. Spectral fitting routines using machine learning methods need to account for binarity, micro-turbulence and line-profile variability associated with pulsations, surface convective regions and wind clumping.

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It was emphasized that a careful one-by-one analysis of sub-samples and peculiar objects cannot be neglected. Surveys alone can not solve all problems and need to be supported by detailed assessments of individual stars.

In *Session 2* we heard results on *High-z stars: observed and synthetic*. One of the many highlighted results is the discovery of very highly redshifted spectra displaying a strong FUV rest-wavelength spectral energy distribution and prominent emission lines of nuclear processed material such as nitrogen, carbon and oxygen. These properties at such high redshifts are not predicted by population synthesis models based on standard stellar evolutionary tracks. An extraordinary example of these discoveries is a JADES NIRSpec object at a z=11 and believed to have formed ∼430 Myr after the Big Bang (Bunker et al. 2023). It exemplifies the tension between current theoretical models and observations of early universe objects as it implies that a lot of the light we see at high redshift must originate in massive stars. These stars must have very efficient mixing processes, such as in chemically homogeneous evolutionary models, a top-heavy initial mass function, and very efficient star formation rates.

Sessions 3 and 4 dealt with *Stellar evolution and atmosphere models and observations*. Recent results on the interior structure and evolution of massive stars were presented, several making use of Kippenhahn-diagrams to illustrate the results because they provide a useful birds-eye view of the physical location of nuclear burning, convective, and radiative zones over time from the ZAMS to the pre-SN phases. The primary takeaway of these presentations is that there is a lot of Physics involved in constructing the theoretical models! The processes involved include: nuclear reaction networks and rates, equations of state, opacity, neutrino losses, convection, mass-loss, and magnetic fields. Most of these have a dependence on metallicity and they are not all independent of each other. Tweaking only one of these processes can significantly affect the fate of massive stars and their products.

The metallicity dependence that is found in large 1D stellar structure grids was discussed, and it was noted that the emerging 3D simulations can be used to improve the prescriptions used in 1D models, especially important for parameters such as the convective overshoot. A striking novel result of multi-dimensional calculations is that late-phase nuclear-burning shells suffer instabilities that can lead them to merge (Rizzuti et al. 2024). This effectively replaces the idealized onion-ring picture of the pre-SN internal structure.

Observational constraints on the interior structure depend on another layer (both literally and figuratively!) of models. Specifically, once the internal structure has been modeled, stellar atmosphere models are required to deal with the large temperature and density gradients in the atmosphere, as well as with large scale mass motions such as winds. Important new developments include results from multi-dimensional models showing the presence of a turbulent atmospheric region below the photosphere, and a highly structured developing wind region above it (see N. Moens, these Proceedings). Comparison with observations requires detailed radiative transfer calculations which, however, are challenging in multi-dimensions even for isotropic, smooth flows.

Quantitative spectroscopy is a powerful tool for obtaining strong constraints on fundamental parameters (effective temperature, surface gravity, metallicity and projected rotation velocity). Full advantage of this technique requires observations obtained with sufficiently high signal-to-noise (S/N $\geq$200) and spectral resolution (R∼100,000). Such observations are extremely challenging to obtain for even relatively nearby objects (due to limited availability of telescope time) but are important for ascertaining the uncertainties of results derived only from lower quality data.

All of the above comments refer stellar properties viewed through the lense of single-star models. Incorporating the manner in which internal and surface physical processes respond to binary-induced perturbations during the main sequence is mostly unchartered

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territory. The focus of presentations in this Symposium, with only a few exceptions, was on mass-transfer and orbital angular momentum processes leading to stripped stars, all within scenarios that assume the binary system to be in equilibrium. I will comment on this assumption and possible implications for non-equilibrium systems in Section 3.

Session 5 focused on *Asteroseismology, Spectropolarimetry, and Interferometry*. We heared how these methods can be used to significantly constrain the properties of massive stars. For example, the internal rotation and mixing characteristics can be gleaned through asteroseismology, while interferometry allows spatially resolving binary companions and circumstellar material, and spectropolarimetry yields information on magnetic fields and large scale departures from symmetry. The talks in this session were highly informative and were delivered in such a way that the the general methodolgy was easy to understand and the impact of the results clearly evident. Detailed results were also found in the posters.

In *Session 6, Final products of massive stars*, it was pointed out how critically important for the final stages of massive star evolution are the processes that preceded them, particularly the interior mixing efficiency and mass-loss. The uncertainties in main sequence models propagate to later phases and are amplified as a star reaches the pre-supernova phase. Thus, connecting final products with progenitors is far from straightforward. The uncertainties are even greater when trying to relate the properties of mergers deduced from gravitational wave sources with their progenitors because of the long timescale between the final stellar evolutionary phase and the occurence of the merger. In this context, the caption of the *xkcd* cartoon† shown by F. Broekgaarden is quite relevant:

I don't know how to propagate error correctly, so I just put error bars on all my error bars.

Session 7 dealt with Population Synthesis models and feedback. Population synthesis models are key to gleaning the physical properties and evolutionary histories of distant galaxies. They use an assumed initial mass function and stellar structure, evolution and atmosphere models. They include feedback processes and, in some cases, products of binary evolution. The models constructed with all these ingredients are used to predict observables, such as spectral energy distributions, which are compared with observations (Bruzual this Symposium; Walcher et al. 2011; Stanway 2020).

It was noted during the discussions that the inherent uncertainties in the individual input models are compounded when dealing with very distant galaxies. In particular, the unknowns in late stage massive star evolution introduce significant uncertainties. Despite all the uncertainties, it is interesting to note that population synthesis models successfully match spectral energy distribution of even the most distant galaxies and provide insight on the total mass and ages (Chevallard & Charlot 2016). However, models still face challenges regarding both feedback predictions (specially ionizing fluxes) and being able to reproduce all strong stellar UV features seen in integrated spectra simultaneously.

Nearby, low-metallicity populations are useful testing grounds for the models, particularly because they allow for high signal-to-noise and high spectral resolution observations (see, for example, Asa'd et al. 2025). Thus, the importance of studying local low-metallicity analogues, such as NGC 346 and POX 186, and producing integrated properties to compare with population synthesis models of high-redshift objects was highlighted several times during the meeting. It was also pointed out that, in addition to the feedback processes due to winds and SN ejecta, wind-wind collisions in binaries

† https://www.explainxkcd.com/wiki/index.php/2110:_Error_Bars

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and clusters also inject material into the ISM with potentially different properties from those contemplated as standard feedback processes (see A. Kashi, this Symposium).

Finally, in *Session 8*, *Looking to the future*, we got a glimpse of what the future may hold in terms of observational facilities which are currently in different phases of development. We heard about new and powerful MOS and other instruments for the very large telescopes; new spectropolarimeters; new initiatives for large baseline interferomenters; CubeSpec, a dedicated space mission for asteroseismology and others being considered for launch in the 2040s; and Hubble Space Telescope's health and outlook into the 2030s. There was ample agreement that the POLSTAR project is essential for bridging the gap between Hubble's UV capabilities and the next UV space-based facility. The importance of the UV spectropolarimetric data sets it will provide for understanding massive stars was even highlighted by the lyrics of a delightful song that closed J. Drake's presentation.

3. Reflections on binary interactions

The daunting complexity of binary evolution has caused some people to decide that this problem is simply a cleverly disguised opportunity for theorists (and enterprising observers) to ascend into free-parameter heaven. (J. Gallagher 1989).

A recurring theme throughout the Symposium was the importance of binary stars for understanding the integrated light from distant objects. Binary interactions were invoked as a possible source of very large inferred heavy element abundances in high redshift objects and their strong UV continua, both of these anomalous compared to current predictions. In this section, I would like to reflect on the assumptions adopted by most binary interaction models, and comment on some of the physical processes that are often omitted, including some that are not yet well understood and require significant advances before they can be included in grids of models.

It is first important to clarify that the term *binary interactions* encompasses a wide range of different and sometimes unrelated physical processes: dynamical ejection of a star during a supernova event or as a consequence of a third-body encounter; periodic variability in spectra and light curves; mass-transfer which strips away the hydrogen-rich external layer exposing the nuclear processed region below; and processes involving very efficient internal mixing.

I focus on the latter connotation because mixing not only transports nuclear processed material toward surface layers but also produces larger nuclear-processed stellar cores that live longer and can produce more massive end products (de Mink et al. 2009). In the limit of very large mixing efficiency, the transition from H-burning to He-burning in the core does not involve the expansion of outer layers and thus, when in a binary system, does not lead to the extensively invoked Roche Lobe Overflow mass transfer process. Instead, the star remains compact and evolves blueward on the Hertzprung-Russell Diagram. Thus, very efficient mixing leads to properties that could explain recent observations of early-universe objects.

According to current scenarios, efficient mixing is achieved by maintaining a star in rapid rotation over a significant portion of its main sequence lifetime (Heger et al. 2000; Meynet & Maeder 2000). These theoretical models predict an increase in surface abundances of nuclear processed materials with increasing stellar rotation speed (Brott *et al.* 2011). As summarized below, this expectation is not always met.

3.1. *A dichotomy in mixing efficiency?*

Massive stars cannot sustain rapid rotation very long because their powerful stellar winds carry away angular momentum, reducing the rotation rate before significant

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mixing can be achieved. In order to keep them rapidly rotating, models are constructed in which they form part of very short-period, tidally locked binary systems (Mandel & de Mink 2016; Marchant et al. 2016). This way, tidal forces keep the star rotating at the (fast) orbital speed, with angular momentum from the orbit replacing that which is being carried away by the wind. Thus, in essence, the star is assumed to evolve on the main sequence as a rapidly rotating single star without a net loss of rotation angular momentum. Accordingly, observations should show a correlation between orbital period and nitrogen abundance, the element typically used to quantify heavy element abundance enhancements in massive stars.

However, such a correlation is not clearly present in observations. In fact, observations show an apparent dichotomy in the ability of binary stars to mix. For example, Pavlovski et al. (2018) find that the photospheric chemical composition in a large sample of close binaries appears unaffected by evolution on the main sequence, suggesting that existing transport processes may in fact be inhibited. At the same time, Mahy et al. (2020) find that components on longer-period orbits show higher nitrogen enrichment at their surface than those on shorter-period orbits.

The above suggests that there may be missing ingredients, or mixing processes whose efficiency is either enhanced or inhibited by the presence of a binary companion. An example of the latter is illustrated by Hastings et al. (2020) who noted that the standard calculation of Eddington-Sweet currents neglects the effect of a companion. Although a theoretical framework for the inclusion of the binary interaction in the form of tidal flows has long been known (Tassoul & Tassoul 1982), it wasn't until recently that the effect was incorporated into the models, showing that it leads to an increase in the mixing efficiency (Hastings et al. 2020). This raises the question as to what other processes intrinsic to binary interactions are currently either being neglected or underestimated.

3.2. *Induced differential rotation*

The simplest configuration of a binary system is the equilibrium state, which is defined as one in which the orbit is circular and the rotation rate of the nucleus and all layers above it is the same as the orbital angular velocity. This means the star is in uniform rotation and tidally locked throughout the orbital cycle. Of course, Nature is not that simple. Many binary stars have an asynchronous rotation, be it because they are in eccentric orbits or because their internal regions have not yet synchronized. In an asynchronous state (faster or slower than the orbital motion), the star will be forced into an induced differential rotation structure, and as noted by Maeder & Meynet (2015):

The tides accelerate the external layers, this increases the shear throughout the star and thus the N-enrichments at the surface. The opposite case may also occur (Song 2013): the tides may produce a spin-down of initially fast rotators, the resulting shears also contribute to N-enrichments.

The long-term effect of the tides is to drive the star toward the equilibrium state, but their action is such that corrotation is first achieved by the outer layers (Goldreich & Nicholson 1989; Koenigsberger *et al.* 2021). The efficiency with which angular momentum is transferred between outer and inner layers depends on a parameter commonly referred to as *turbulent viscosity*, ν_{turb}, whose values lie within a range of many orders of magnitude depending on the hydrodynamics of the system (Penev et al. 2007; Zahn 2008; Garaud 2020; Mathis et al. 2016). Assuming even very large ν_{turb} values, synchronization timescales for the inner layers can significantly exceed the lifetime of massive stars (see Maranan et al. these Proceedings). The non-uniform rotation is associated with shearing flows (Park et al. 2021) which have the potential of enhancing mixing efficiency.

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Observational evidence for a shearing layer within stellar envelopes comes from asteroseismology, as for example, in the β Cep star HD 192575 (Burssens et al. 2023). One can hypothesize that the extent and depth of the shearing layer will depend on the age of the binary system.

In addition to the overall differential rotation induced by the tides, there is an additional superposed perturbation which takes the form of periodic oscillations. The observational manifestation of such perturbations is found in photospheric line-profile variations and in the light curves of the so-called Heartbeat stars (Guo 2021). The non-uniform relative flows have been hypothesized to enhance mixing even further (Koenigsberger *et al.* 2021), assuming of course that the tidal perturbations are active in deep layers containing nuclear processed material.

3.3. *The rotation dichotomy*

I pointed out above that samples of observed binaries do not show the surface chemical abundance enhancements expected from their rotation velocity. Particularly noteworthy are those in close, tidally locked systems which depite rapid rotation seem to inhibit efficient mixing, while those in eccentric orbits seem to favor efficient mixing.

Considerations of the previous sections suggest that this diversity is likely related to the internal rotational profile and, specifically, whether uniform or differential rotation prevails. A possible scenario is that in binaries born in the equilibrium state and that undergo rigid-body rotation during most of the main sequence lifetime, the standard mixing processes are suppressed (see L. Sciarini, this Symposium). In contrast, systems born out of equilibrium, such as eccentric binaries, have non-uniform rotation profiles which allow for the triggering of efficient mixing processes. Binaries in circular orbits that are not synchronized would also fall in this category.

Clearly, there are other factors, such as subsurface convective regions, magenetic fields and gravity waves (Eggenberger 2024), which also intervene in the mixing processes, and one of the important challenges ahead is to study the manner in which these other processes that are active in single stars can be affected by the tidal perturbations.

4. Conclusions

The first conclusion after hearing all of the fine presentations and reading the posters is that we are living in exciting times. Extraordinary data sets are being acquired, new discoveries are being made, important new data reduction and analysis pipelines are being developed, and many of the theoretical models are successful in helping us interpret the observational results. The second conclusion is that a great deal of work still needs to be done, particularly in the area of stellar structure and binary interactions. There is a lot of Physics in the current stellar structure models, but the sensitivity of existing processes to a companion's perturbations requires careful assessment, as well as the possible need of processes thus far overlooked, particularly those that may dominate in very low-metallicity environments. It is good to see that many young researchers are, indeed, involved in exploring these challenging topics.

It is also good to see that several of the new and proposed observing facilities are focused on the powerful astroseismology, spectropolarimetry and interferometry techniques which, combined with traditional methods and advanced theoretical models will likely lead to important breakthroughs. Particularly important is extending UV capabilities.

A final conclusion is the importance of careful one-by-one analyses of a few objects, both the kind deemed "normal" and those seen as peculiar. Surveys alone can not solve all problems and need to be supported by detailed assessments of individual stars.

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This is particularly important as new spectral fitting routines using machine learning methods are implemented and ever more distant stars are studied.

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References

Abdul-Masih M. et al. 2019, ApJ, 880, 115.
Almeida, L.-A. et al. 2015, ApJ, 812, 102.
Asa'd, R. et al. 2025, AJ, 170, 85.
Astoul, A. et al. 2021, A&A, 647, 144.
Barker, A.J. et al. 2021, MNRAS, 506, 69.
Brott, I., et al. 2011, A&A, 530, A115.
Bunker, A.J. et al. 2023, A&A, 677, A88.
Burssens, S. et al. 2023, NatAs, 7, 913.
Chevallard, J. & Charlot, S. 2016, MNRAS, 462, 1415.
de Mink et al. 2009, A&A, 497, 243.
Eggenberger, P. 2024, 2024arXiv240911354E.
Gallagher, J. 1989, in *Physics of luminous blue variables*, proceedings of the 113th Colloquium of the International Astronomical Union, 1989 ASSL, 157, 185.
Garaud, P. 2020, ApJ, 901, 146.
Goldreich, P. & Nicholson, P.D. 1989, ApJ, 342, 1079.
Guo, Z. 2021, Frontiers in Astronomy and Space Sciences, Volume 8, id.67.
Hastings, B., Langer, N. & Koenigsberger, G. 2020, A&A, 641, A86.
Heger, A.,Langer, N. & Woosley, S.-E. 2000, ApJ, 528, 368. EAS, 64, 339.
Koenigsberger, G., Moreno, E. & Langer, N. 2021, A&A, 653, A127.
Maeder, A. & Meynet, G. 2015, in *Physics of rotation: problems and challenges*, IAU Symposium 307, p. 9.
Mahy, L. et al. 2020, A&A, 634, A118.
Mandel I. & de Mink, S.E. 2016, MNRAS, 458, 2634.
Marchant P. et al. 2016, A&A, 588, A50.
Meynet, G. & Maeder, A. 2000, A&A, 361, 101.
Mathis et al. 2016, A&A, 592, 33.
Park et al. 2021, A&A, 646, 64.
Pavlovski, K., Southworth, J., & Tamajo, E. 2018, 2018, MNRAS, 481, 3129.
Penev K. et al. 2007, ApJ, 655, 1166.
Rizzuti, F. et al. 2024, MNRAS, 533, 687.
Song, H.F. 2013, A&A, 556, A100.
Stanway, E. R 2020, Galax, 8,6.
Tassoul, J.L. & Tassoul, M. 1982, ApJ, 261, 265.
Walcher, J. et al. 2011, Astrophysics and Space Science, 331, 1.
Zahn, J.-P. 2008, EAS Publication Series, 29, 67.

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