Walking along Cosmic History: Metal-poor Massive Stars

A White Paper Submitted to the Decadal Survey Committee A2020

Thematic Areas:
Stars and Stellar Evolution (primary)
Resolved Stellar Populations and their Environments (secondary)

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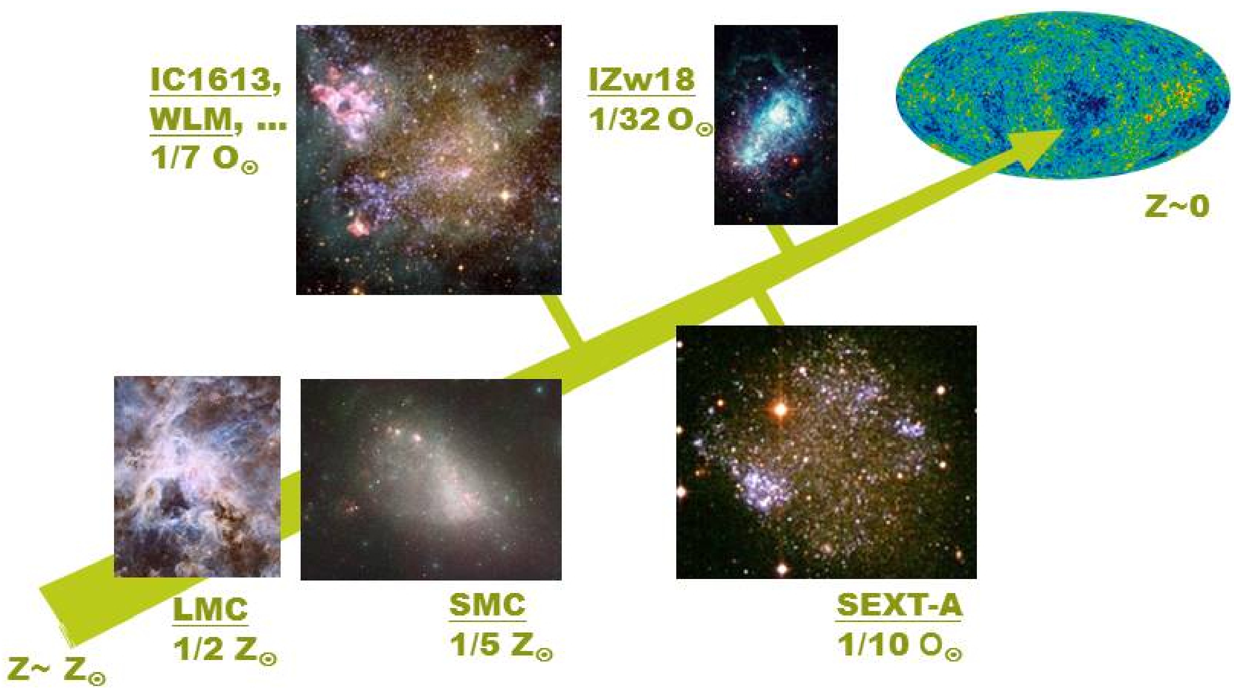
Abstract: Multiple generations of massive stars have lived and died during Cosmic History, invigorating host galaxies with ionizing photons, kinetic energy, fresh material and stellar-size black holes. At present, massive stars in the Small Magellanic Cloud (SMC) serve as templates for low-metallicity objects in the early Universe. However, recent results have highlighted important differences in the evolution, death and feedback of massive stars with poorer metal content that better matches the extremely low metallicity of previous Cosmic epochs. This paper proposes to supersede the SMC standard with a new metallicity ladder built from very metal-poor galaxies, and provides a brief overview of the technological facilities needed to this aim.



1 Introduction: sub-SMC metallicity massive stars

Massive stars are major agents of the Universe, deeply interwoven with other fields of Astrophysics. Born with M>9 $M_\odot$ they live fast and die spectacularly, making an excellent source of fast chemical enrichment. During their evolution they experience stages with very high effective temperature ($T_{\rm eff}$≥20,000 K, sometimes up to 200,000 K) that results in an extreme ionizing ultraviolet (UV) field. This field can power supersonic winds that inject kinetic energy and turbulence into the interstellar medium (ISM) and creates the ionized bubbles and complex HII structures often detected around massive stars. The deaths of massive stars are counted among the most disrupting events ever registered: type Ib,c,II supernovae (SNe), super-luminous supernovae (SLSNe) and long γ-ray bursts (LGRB). The surviving end-products, neutron-stars and stellar-size black holes, are sites of extreme physics.

Hence massive star feedback enters many small and large-scale processes spanning the age of the Universe. Since Cosmic chemical complexity is ever-growing after the Big Bang, the simulation and interpretation of these phenomena as we look back in time demand robust predictions for massive stars at ever-decreasing metallicity. Ultimately we need tested models for nearly metal-free very massive stars that can be extrapolated to describe the First Stars of the Universe.

The massive stars of the Small Magellanic Cloud (SMC) constitute the current standard of the metal-poor regime, with an extensive battery of observations from ground- and space-based telescopes[88,59,23,51] providing constraints to inform theory. This is well integrated into population synthesis codes used to interpret observations of star-forming galaxies along Cosmic History.

However, the 1/5 $Z_\odot$ metallicity of the SMC is not representative of the Universe past redshift z=1[55]. The theoretical framework for lower metallicities predicts substantial differences in the evolutionary pathways[60,77,58,22] with impact in life-overall feedback and end-products. One of the proposed mechanisms to reproduce the first gravitational wave ever detected involves the binary evolution of two metal-poor massive stars[1,56] (Sect.3).

Teams around the world are working to build a representative sample of massive stars with sub-SMC metallicity: a complete spectral atlas that will allow us to draw the evolutionary pathways of massive stars, and constrain their stellar properties ($T_{\rm eff}$, stellar mass M_*, luminosity $L_{\rm bol}$, and mass loss rate $Mdot$). Unfortunately the SMC marks not only a metallicity but also a distance frontier, and a sizeable leap down in metallicity requires reaching distances of at least 1 Mpc (outer Local Group and surroundings). Very promising galaxies with 1/10 $Z_\odot$ (Sextans A, 1.3 Mpc away)[12], 1/20 $Z_\odot$ (SagDIG, 1.1 Mpc)[35] and 1/30 $Z_\odot$ (Leo P, 1.6 Mpc)[26] are subject to close scrutiny with VLT, Keck and GTC[9,24,12,26,36], with the *holy-grail* 1/32 $Z_\odot$ starburst galaxy I Zw18 (18.2 Mpc)[85,4] always in mind. However, the world's largest ground-based telescopes only reach the brightest, un-reddened members after long integration times, and even for these spectral quality is sometimes too poor to yield stellar parameters. The result is a biased and sorely incomplete view of sub-SMC massive stars. *We have hit the limit of current observational facilities.*

This paper deals with metal-poor, sub-SMC metallicity massive stars. In the following pages we will summarize the state-of-the-art on the topic of metal-poor massive stars, the exciting new scenarios that we may expect from the theoretical predictions, how far we have reached with current observatories and prospects for future missions in the planning.

2 Stellar winds at low metallicity

The evolution of massive stars is strongly conditioned by metallicity via stellar winds. The extreme UV-field of the hot stages exchanges energy and momentum with metal ions in the atmosphere, resulting in an outflow that we know as radiation-driven wind RDWs[53,13]. The ensuing removal of mass $\sim 10^{-8} M_{\odot}/yr - 10^{-4} M_{\odot}/yr$[50] is significant to peel off the outer stellar layers (explaining the flavors of Wolf-Rayet stars -WR-), but also to alter the conditions at the stellar core and the rate of nuclear reactions. It is because of the wind, which inherits a strong dependence on metal content, that two massive stars born with the same initial mass but different metallicity can follow very distinct evolutionary pathways[17].

The winds of hot massive stas are weaker as their metallicity decreases. The theoretical dependence of mass loss rate on metallicity $Mdot \propto Z^{0.7-0.8}$ [86] has been verified observationally down to the metallicity of the SMC[61]. The winds of metal-poorer hot stars require a special formalism[49] and the consideration that the driving ions shift from Fe to CNO at $Z \leq 0.1\,Z_{\odot}$, and therefore the wind may evolve as processed material is brought to the surface by internal mixing. The expectation is that at $Z < 10^{-2}\,Z_{\odot}$ winds are negligible, unless the star is very luminous, and consequently will have very little impact on evolution.

Multi-object spectrographs at 8-10m telescopes finally enabled the first studies of RDWs at sub-SMC metallicity. The first efforts focused on IC 1613 (715 Kpc), the closest star-forming Local Group galaxy whose $\sim 1/7\,O_{\odot}$ nebular abundances marked a significant decrease in metallicity from the SMC. They soon were followed by studies in NGC3109 and WLM, ~1 Mpc away. The results were unanticipated: the finding of an LBV with strong optical P Cygni profiles[41], an extreme oxygen WR[79], and the optical analysis of O-stars[42,80] all indicated that winds were stronger than predicted by theory at that metallicty.

Hubble Space Telescope (HST) played a crucial role deciphering the *strong wind problem*. The detailed analysis of UV spectral lines, more sensitive to the wind than the optical range, yielded lower mass loss rates for O-stars[7]. In parallel, UV spectroscopy showed that IC1613's content of iron was similar or even larger than the $\sim 1/5\,Fe_{\odot}$ content of the SMC, superseding the $1/7\,Fe_{\odot}$ value scaled from oxygen[32]. SMC-like Fe-abundances were also reported for WLM and NGC3109[44,7]. These findings alleviated the *strong wind problem* since the expected mass loss rate is larger at the updated iron content[86].

New efforts are being directed to Sextans A that has nebular abundances as low as $1/10$-$1/15\,O_{\odot}$ [47] and similarly low stellar $1/10\,Fe_{\odot}$ abundances[45,34]. The first spectroscopic surveys have reported 16 OB stars[12], but being located 1.32 Mpc away, only 5 of them have been observed in the UV with HST-COS[34]. The metal-poor component of the recently announced *ULLYSES DD program* will provide a priceless extension to such studies. Only two other extremely metal-poor star-forming galaxies with resolved stellar population, have been surveyed: SagDIG ($1/20\,Z_{\odot}$, 1.1 Mpc), and Leo P ($1/30\,Z_{\odot}$, 1.6 Mpc) but they are either very far away or the foreground extinction severely hampers optical and UV observations.

Consequently, sub-SMC metallicity RDWs remain unexplored, and additional processes also need to be studied: pulsation- and rotation-driven outflows, interaction/mass exchange in binary systems, or eruptions[72]. In fact, the concept that super-Eddington stars like Eta Car may experience continuum-driven winds, provides an interesting metallicity-independent mass loss mechanism[83]. However, *we simply lack evidence to assess what is the dominant mass loss mechanism ruling the life of metal-poor massive stars.*

3 Evolution, explosions and feedback

The close interaction between massive stars and the Universe began with the first generation of stars, since at least a fraction of them were sufficiently massive and hot to commence re-ionization[43,10,29]. Ever since, signature of their copious ionizing flux can be seen in highly-ionized UV emission lines (CIV1548,1551, OIII]1661,1666, [CIII] 1907 + C III] 1909)[67], and in a few interesting cases in the shape of $Ly\alpha$ emission -LAEs-, that allows us to detect galaxies out to redshift $z \sim 10$ (see e.g. introduction by[89]).

Hence, understanding massive stars with decreasing metal content, matching the composition of the Universe as we look back in time, is crucial to interpret star-forming galaxies in all their flavors: LAEs, LBGs, ULIRGs, Blue compact dwarfs, etc. A proper characterization of the properties and sequence of their evolutionary stages will enter population synthesis and radiative transfer codes such as Starburst99[52] and CLOUDY[27], to subsequently interpret observations of the integrated light from massive star populations[91]. Armed with these tools we can tackle outstanding questions such as the average ionizing photon escape fraction of galaxies, a crucial parameter to establish the end of the re-ionization epoch[84,28].

Evolutionary tracks that properly deal with rotation, RDW mass loss, and mass exchange in binary systems have been calculated for Population III stars[57,20,94], $1/50\,Z_\odot$ [77] and extensively for the Milky Way, LMC and SMC[11,21]. Significant changes are expected in the evolution of metal-poor massive stars, the most notable example being the incidence of chemically homogeneous evolution (CHE) in which fresh He produced in the core is brought to the surface by rotation-induced mixing. A $1/5\,Z_\odot$, M_{ini}=25 $M_\odot$ SMC star will usually reach the red supergiant -RSG- stage, but if the initial rotational velocity ($v\sin i$) is extremely high it will evolve into a CHE-induced WR stage with $T_{\rm eff}$~100,000 K[11]. This effect is magnified at lower metallicities, where very massive stars can either evolve into an envelope-inflated RSG, or become Transparent Wind Ultraviolet INtense stars (TWUIN)[77]. TWUINs double the HI ionizing luminosity and quadruple the HeII luminosity with respect to lower $v\sin i$ counterparts, and could be responsible for the extreme HeII emission detected in I Zw18 and the $z \sim 6.5$ galaxy CR7, currently attributed to population III stars[46,73].

Another fundamental aspect of the life of massive stars is the end of their evolution, associated with a plethora of very energetic events: core-collapse SNe, pair instability SNe, electron-capture SNe, hypernovae, kilonovae, SLSNe and LGRBs. Evolutionary models can predict the ending mechanism and remnant of single and binary systems[92,93,38,63], but observations are decisive to inform theory. For instance, the preference of LGRBs and SLSNe for metal-poor galaxies[54,16] is a clue on the specific evolution of metal-poor massive stars. Armed with a sound *map of progenitors*[30,69,82] were the variation with metallicity is understood, the most energentic LGRBs and SLSNe can be used to constrain star-formation rates at high redshift[64] or even to detect the signatures of the First Stars[10].

The LIGO and Virgo experiments have also revolutionized our view of massive star evolution during their short period of operations[3]. The detection of GW170817, associated with a collapsing double neutron star and kilonova[2], linked short-GRBs with massive stars[81]. The very first gravitational wave event detected, GW150914, unveiled two in-spiraling black-holes whose 36 $M_\odot$ and 29 $M_\odot$ masses were significantly larger than those that models can form at solar metallicity ($\sim 20\,M_\odot$)[76]. This system has inspired the development of new scenarios, the most successful being the CHE evolution of two metal-poor massive stars that evolve within their Roche Lobes avoiding mass exchange and the common-envelope phase[56].

Constraining massive stars evolution is a multi-dimensional problem, even if focusing on metal-poor environments only. The high incidence of massive star in multiple systems, and the fraction that will interact with their companions[65], complicates the problem exponentially. The way to proceed is to assemble large, multi-epoch samples of massive stars to fully cover the parameter space, reconstruct the evolutionary pathways, and constrain their physical properties with advanced stellar atmosphere models. Such ensembles have been built over the years in the Milky Way[68], and in the Magellanic Clouds[25,15]. However, only a handful of massive stars have been confirmed by spectroscopy in sub-SMC metallicity galaxies[34]. At this stage no signature of CHE has been reported in these galaxies, and very few massive binaries have been detected.

4 Massive star formation in metal-poor environments

How massive stars form remains a matter of intense investigation. Our understanding of this topic has significant gaps ranging from the formation of individuals, to how the upper initial mass function (IMF) builds, and whether there is a dependency on environment. Two principal issues make the process markedly different from lower-mass sibblings: the star-forming clumps must be prevented from breaking into smaller pieces, and radiation pressure from the forming star may halt accretion.

Two theories of star formation are emerging, competitive accretion[6] and monolithic collapse[48]. At solar metallicity, they both struggle to form stars more massive than 20-40 $\mathbf{M}_{\odot}$ [95,40,78] in stark contrast with the number of known ≥60 $\mathbf{M}_{\odot}$ stars in Milky Way clusters (e.g. Westerlund 1[18], Carina[71], Cygnus OB2[5] or the Galactic Center[62]) and evidence of a top-heavy initial mass function in resolved, bursty star forming regions[66].

The situation should be alleviated in environments of decreasing metallicity, since the paucity of metals would both prevent gas from cooling and breaking down, and make pre-stellar radiation-driven outflows weaker[87]. The former argument is fundamental to support the widely-accepted concept that the *first, metal-free, stars of the Universe were very massive*. In fact, the record holder ∼150 $\mathbf{M}_{\odot}$ massive stars have been found at the heart of the *Tarantula Nebula* in the LMC[19] and have 0.4 $\mathbf{Z}_{\odot}$ metallicity. Evidence of over 100 $\mathbf{M}_{\odot}$ stars has also been found in the integrated light of unresolved, metal-poor starburst[90,70]

The sequence drawn by Local Group dIrr's enables us to investigate whether the upper mass limit is set to higher values as metallicity decreases: IC1613, WLM and NGC3109 (1/7 $\mathbf{O}_{\odot}$), Sextans A (1/10 $\mathbf{O}_{\odot}$), SagDIG (1/20 $\mathbf{O}_{\odot}$) and Leo P (1/30 $\mathbf{O}_{\odot}$). Some of these galaxies host spectacular HII shells equivalent in size to the 30 Dor region, but no analog to the LMC's *monster stars* has been found yet. The most massive star reported has an initial mass of only 60 $\mathbf{M}_{\odot}$, and only a handful of them have masses in the 40-60 $\mathbf{M}_{\odot}$ range[34].

It may be argued that other factors outweigh the paucity of metals such as infalling gas, the local gas density or the star-formation rate[39], expecting higher mass stars in denser, more active regions. This hypothesis was challenged by the spectroscopic detection of OB-stars at the low stellar and gas density outskirts of Sextans A, 2 of them being the youngest and most massive stars known so far in the galaxy[36]. Previous indications of young massive stars in low gas-density environments existed, like extreme UV-disk galaxies[31], but O-stars identified spectroscopically enable us to date the young populations.

The joint study of resolved massive stars and detailed maps of neutral and molecular gas, will help to unravel the role of star-formation rate and gas density in star formation, and whether they translate into different mechanisms that populate the IMF and the distribution of $v\sin i$ and binaries distinctly. Ideally, untargeted, unbiased spectroscopic censuses of massive stars in clusters and galaxies would enable reconstructing these distributions that are so important to understand the star formation, establishing the local upper mass limit in particular, and checking for any dependence on metallicity and gas content. However, observations of the required spectral quality are out of reach to current technology.

5 Technological needs for a significant break-through

Our partial understanding of metal-poor massive stars jeopardizes the interpretation of SNe and LGRBs, star-forming galaxies along Cosmic History, and the re-ionization epoch. Four questions summarize the next great challenges faced by the field:

- Is the IMF universal? What is the upper mass limit? Does it depend on metallicity?
- What kind of outflows do metal-poor massive stars experience?
- How do they evolve? What is the frequency of CHE?
- What are the evolutionary channels that lead to binary stellar mass black holes?

Answering these questions requires a phenomenal observational ensemble in sub-SMC metallicity galaxies enabling an equivalent level of detailed work as achieved in the Milky Way and the Magellanic Clouds[68,25,15], unfeasible with current facilities. The wavelength coverage, sensitivity and spatial resolution of a 10m-class telescope in space, such as the LUVOIR-A (15m) and LUVOIR-B (8m) mission concepts, is needed[33]. In particular:

- The outstanding spatial resolution of a nearly diffraction-limited $\sim$ 10m telescope in space to disentangle 30 Dor-like concentrations of massive stars out to 1 Mpc. Coupled to integral-field spectrographs (optimized after lessons learnt from JWST), they will provide unprecedented constraints on the IMF of both dense, and starburst regions.
- High resolution (R=$\lambda/\Delta/\lambda$ $\geq$10,000) multi-object optical and near-IR spectroscopy to constrain stellar parameters. The Extremely Large Telescope will have superior sensitivity and reach the faintest objects, but continuous UV-optical-NIR coverage in the nearly background-free space environment is still highly desirable for reliable flux calibration.
- Ultraviolet multi-object spectroscopy with medium resolution (R=$\lambda/\Delta/\lambda$ $\geq$5,000) to confirm the presence of winds, and to constrain mass loss rates and velocity fields. In this respect the multi-object capabilities of LUMOS coupled with on-going improvements on UV detectors, will revolutionize the field, by enabling the first extensive characterization of the outflows of massive stars beyond the SMC.

The selection of the most ambitious design LUMOS-A would enable studies of individual stars in the sparse regions of I Zw18 which currently stands the reference of extremely metal-poor, starburst dwarf galaxies. However, both LUMOS-A and LUMOS-B will comfortably reach out to few Mpc distances, opening great discovery opportunities of even metal-poorer massive stars in the Sculptor, Centaurus and M81 Groups. On the whole, both designs will provide definitive answers to the most pressing questions in our understanding of the properties and evolution of high-mass stars in very metal poor environments.

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