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A personal perspective on the history of massive OB stellar spectroscopy

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Abstract. I present a personal view of some of the advances in stellar spectroscopy of massive OB stars that have occurred in the last century, a human time scale. Together with always more realistic models, the improvements in data quality, wavelength coverage and multiplexing capabilities of the observations have revealed the strong links to other fields of Astrophysics and the high impact of these objects in our interpretation of the Universe, from our neighborhood to the early epochs: a cosmic time scale.

Key words. Stars: massive, early-type, mass-loss, atmospheres, fundamental parameters – Galaxies: Local Group

1. An acknowledgement and a disclaimer

Although adknowledgements are usually at the end of the corresponding contribution, I want to begin with a special thanks to Margeritha Hack. As a young student beginning with Physics I serendipitiously read one of her classical outreach books: *The Universe*. It had a strong influence on my final decission to study Astrophysics, which I never regretted[1].

A disclaimer is also needed. The extension, quality and impact of the many contributions to the field of massive OB-types stellar spectroscopy renders the presentation in a short article an impossible task. The narration presented here will therefore be incomplete and personally biased. It will focus on the optical and (to a lesser extent) UV ranges of O-type stars, with some notes on related ranges and stars. Nevertheless, I hope it will retain some of the flavour of the story and allow the interested readers to complete by themselves the many facts and names that will be omited here.

2. Introduction: the early days of massive OB stellar spectroscopy

Massive stars are rare. That's the reason why since the groundbreaking observation by Fraunhofer of the solar spectral lines (Fraunhofer , 1815, p. 202) and the seminal classification scheme by Secchi (see Hentschel , 2021), there is so little information about them at early times. For example, the *Spectra of Bright Stars* catalog from the Harvard

[1] whether this was positive for the discipline is a different question

Observatory (Maury & Pickering , 1897) lists a small number of massive hot stars: from 681 stars distributed in 22 different spectral types, from I to XXII, only 23 belong to the types I and II, where O stars are common, whilst early B stars dominate the types III and IV (that contain 69 objects). We can compare the photographic plate reproduced in Cannon (1916) with much later ones (for example, in Walborn (1982), already in the epoch when Charge Coupled Devices were starting to replace photographic plates) to realize the difficulty of those pioneering observations. Not only their quality was extremely modest, but also the lack of an accurate wavelength scale and of information about the spectra of the individual atoms and ions were limiting the advances in the classification of such stars, as reflected in the first chapter of the PhD work by Cecilia Payne (Payne , 1925) presenting the state-of-the-art of the atomic information at that time.

Margherita Hack contributed strongly to the classification, theory and analysis of massive stars in a series of articles (for example Hack , 1953; Botto & Hack , 1962) and books (Hack & Struve , 1969, 1970) in the fifties and sixties, shortly after the works by W.W. Morgan and collaborators (Morgan, Keenan & Kellman , 1943) improved the former Harvard classification by A.J. Cannon by including the luminosity class into the scheme. The classification of massive hot stars was later boosted by the work of N.R. Walborn in an extensive series of papers along more than fifty years (f.e., Walborn (1972); Walborn & Fitzpatrick (1990); Walborn et al. (2002)) that extended also to other wavelength ranges and metallicities (e.g. Walborn et al. , 1985, 1995). He stablished, together with other authors (particularly P.S. Conti, like f.e. in Conti & Alschuler, 1971; Conti & Leep , 1974) the nearly final scheme of present-day classification of OB type stars. Extensions of these works prompted the building of catalogs of OB massive stars (Cruz-González et al. , 1974), the exploration of OB clusters and associations in the Milky Way (like Humphreys , 1978; Massey & Thomson , 1991; Massey et al., 1995) and other galaxies (f.e. Massey et al. , 1985; Conti et al. , 1986), the study of abundance anomalies of different elements (mainly, but not only, CNO, see Walborn , 1976; Mathys , 1988, 1989), or the extension to other spectral types (e.g. Lennon et al. , 1992, 1993, for B-type supergiants) or wavelength regions (f.e., Hanson et al. , 1996, 1998, in the near infrared).

3. Theory and analyses of massive OB stars

Due to their high temperature and luminosity, OB stars present special difficulties to modeling of their spectra. The interplay between the intense radiation field and the relatively low density matter produces strong deviations from Local Thermodynamic Equilibrium (Non-LTE). The problems encountered when using LTE models (following f.e. Unsöld , 1955), particularly the high abundances needed to reproduce the observed spectral lines of many elements (including He), were summarized by Underhill (1968). The calculation of NLTE model atmospheres was possible only after the development of computer capabilities and the corresponding numerical methods. Groundbreaking steps were done by Auer & Mihalas (1969, 1972) that allowed stablishing the link between the morphological spectral classification and the stellar parameters (e.g., Conti , 1973a,b, 1975; Kudritzki , 1980; Kudritzki et al. , 1983). Further developments in computer efficieny and numerical methods (f.e., Scharmer , 1981; Herrero , 1986; Puls & Herrero , 1988; Anderson , 1989; Rybicki & Hummer , 1992) allowed more sophisticated calculations with more and more detailed model atoms, with unprecedented results in the understanding of multilevel effects and UV spectral synthesis (f.e. Pauldrach , 1987; Pauldrach et al. , 1994). The work by Herrero et al. (1992) showed the improvements due to the developments in model atmospheres in the 80's, but also the need of more realistic ones including at least winds, detailed atomic models and line blanketing (see Hubeny & Lanz, 1995; Hillier & Miller, 1998; Santolaya-Rey et al., 1997; Puls et al., 2005). As an example of the changes, Fig. 1 gives a comparison of the Conti scale with the more recent one by

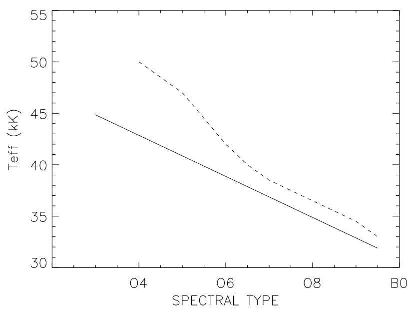

Fig. 1. The temperature scale for luminosity class V O-type stars by Conti (1973b) (dashed line) and the more recent one by Martins et al. (2005) (solid line; the so-called observational scale was chosen).

Martins et al. (2005), where we see the important changes for the early spectral types.

The hard radiation also produces an intense stellar wind. In the late sixties, a crucial point was the realization of strong mass-loss phenomena in early massive stars[2] (Morton , 1967a,b). The launch of the Copernicus satellite in 1972 (a.k.a. OAO-3) showed that the phenomenon of stellar winds was ubiquotus in OB stars (Snow & Morton , 1976). This stellar wind extends the atmosphere, modifies the observed spectrum, affects the evolution and changes the energy, momentum and chemical feedback of the star. The seminal works by Castor, Abbott & Klein (1975); Pauldrach, Puls & Kudritzki (1986) opened the way to include the effects of radiatively driven winds in the model atmospheres.

Evolution is also altered in advanced phases by the appearance of pulsations, mass ejections and mass outburst (for example, the so-called Luminous Blue Variables, LBV), and extreme mass-loss (as in the Wolf-Rayet phase). None of these phases will be reviewed here, but we note that they may even alter the final destiny of the stellar remnant after the Supernova explosion (Maeder & Meynet , 2000; Heger et al. , 2003; Langer, 2012). The situation is further complicated by the fact that massive stars are usually found in binary or multiple systems whose components often interact in different moments of their lifes (see Sana et al. , 2012). Not to mention effects introduced by pulsations, subsurface convection or magnetic fields (Aerts & Rogers , 2015; Grassitelli et al. , 2015; Wade et al. , 2015). Therefore, in spite of their small number, massive stars present a significant diversity in spectral appearance and many possible evolutionary ways that can only be adequately explored with extensive surveys in the Milky Way (for a detailed physical study) and nearby galaxies (to study the metallicity dependence). This latter aspect is crucial if we want to extend our knowledge to the observations of the early Universe (see Garcia et al. , 2021)

Thus the study of massive stars has continously changed its focus: in the early years of last century the effort was dedicated to the characterization of the stellar spectra, to later focus on the classification and interpretation of those observations. This interpretation has become more and more sophisticated, as the interplay between the different physical processes mentioned above has become apparent. Advances in modelling have allowed a consistent treatment of the UV and optical spectra (e.g. Bouret et al. , 2012; Bestenlehner et al., 2014) and those in observational techniques and facilities have led to a change fom the study of individual stars or relatively small samples to large surveys that try to catch up on this complexity by collecting larger and larger numbers of massive OB star spectra (and related spectral types) of increasingly quality and wavelength coverage. Examples of these surveys, among others, appear in Table 1. It gives an idea of the effort that has been and is still being dedicated to massive stars research in the form of large surveys, whose results shifted the focus to the effects of mass-loss, rotation, metallicity, magnetic fields, and multiepoch observations to study pulsations and mutiplicity effects. In the next sections we review some of the questions that have been mentioned.

[2] Margherita Hack also played an important role in the first years of UV satellite observations (see f.e. Hack et al. , 1974; Hack & Selvelli , 1978)

Table 1. Some of the large modern ground-based spectroscopic surveys (except for the HST-ULLYSES UV contribution). The number of targets is sometimes an estimation (the survey is continously collecting data), sometimes an expectation (the survey hasn't started yet) and may include different stellar types, not only OB stars. For each survey, a reference for more details is given. (1) Evans et al., 2005, A&A, 437, 467; (2) Evans et al.,2011, A&A, 530, A108; (3) Almeida et al., 2017, A&A, 598, 84; (4) Wade et al., 2016, MNRAS, 456, 2; (5) Morel et al., 2014, The Messenger, 157, 27; (6) Alecian et al., 2015, IAUS 307, 330; (7) Maíz Apellániz et al., 2017, Highlights of SA IX, 509; (8) Simón-Díaz et al., 2020, Highlights of SA XIV, id. 187; (9) Barbá et al., 2017, IAUS 329, 89; (10) Negueruela et al., 2015, Highlights of SA VIII, 524; (11) Blomme et al., 2022, A&A, 661, A120; (12) https://massivestars.org/xshootu/ ; (13) Jin et al., 2023, MNRAS, in press; (14) Cioni et al., 2019, The Messenger, 175, 54

Survey	Targets	Main Objective	Main Instrument & Telescope	Resolution	# stars	Principal Investigator	Ref.
VSMS	MW, MCs	Winds	FLAMES@VLT	20k	803	S.J. Smartt	1
VFTS	30 Dor	Multiplicity	FLAMES@VLT	7+8.5k	1037	C.J. Evans	2
				16k			
TMBM	30 Dor	binaries follow-up	VLT	6400	102	H. Sana	3
MiMeS	MW	magnetic stars	ESPaDOnS@ CFHT	65k	221	G.A. Wade	4
			HARPSpol@ESO 3.6m	110k			
BOB	MW	magnetic stars	FORS2@VLT	2000	69	T. Morel	5
			HARPSpol@ESO 3.6m	110k			
BinaMIcs	MW	mag. stars, binaries	ESPaDOnS@CFHT	65k	150	E. Alecian	6
GOSSS	MW	complete census	Several	2500	3000	J. Maíz Apellániz	7
IACOB	MW	high res., multiepoch	FIES@NOT	25+46k	1200	S. Simón-Díaz	8
			HERMES@MERCATOR	80k			
OWN	MW	high res., multiepoch	REOSC@CASLEO 2.15m	15k	205	R. Barbá	9
			FEROS@ESO 2.2m	48k			
CAFE-BEANS	MW	binaries follow-up	CAFE@CAHA 2.2m	70k	100	I. Negueruela	10
Gaia-ESO- hot stars	MW	increase census	FLAMES@VLT	20k	1300	R. Blomme	11
XShootU/ULLYSES	MCs	massive stars legacy	COS@HST	3-20k	250	J.S. Vink	12
			STIS@HST	30-46k			
			XShooter@VLT	5.6-8.9k			
WEAVE-SCIP	MW	Galactic Plane	WEAVE@WHT			J. Drew	13
	MW	Map OB stars	WEAVE@WHT	5000	20000	S. Simón-Díaz	
	Cygnus	high res., multiepoch	WEAVE@WHT	20k	2000	A. Herrero	
4MOST-1001MC massive stars	MCs	Map OB stars	4MOST@VISTA	6000	15000	J. Bestenlehner	14

4. Winds and mass-loss

The realization of the universality of mass-loss in massive hot stars triggered the efforts to characterize their winds, particularly after the launch of the International Ultraviolet Explorer (IUE) in 1978 (see f.e. Lucy & Solomon , 1970; Lamers & Morton , 1976; Lamers et al. , 1980; Howarth & Prinja , 1989, ; see also the recent review by Hillier (2020) on UV spectroscopy). The dependency of the mass-loss rate with the stellar luminosity was clear from the beginning, as shown in Fig. 2. Here we compare the values given by Lamers et al. (1980) and those by Mokiem et al. (2007). It is amazing how consistent are their values, after nearly 30 years and many theoretical and observational advances. However the latest developments modify this picture, as described below.

Therefore, the radiatively driven wind theory (RDWT, (Castor, Abbott & Klein, 1975; Pauldrach, Puls & Kudritzki, 1986; Kudritzki & Puls , 2000)) became a key aspect of modern research in massive stars. It plays a fundamental role in understanding the behaviour of massive stars (their feedback and evolution) not only in the Milky Way, but also in metal-poor galaxies, like those expected in the early Universe, due to its predicted wind metallicity dependence. Theory predicts a tight relationship between the stellar luminosity, the metallicity and the mass-loss rate, the so-called Modified Wind Momentum – Luminosty Relationship (WLR, Kudritzki et al. (1995)):

$$log D_{mom} = x \, log(L/L_\odot) + D_0 \tag{1}$$

with

$$D_{mom} = \dot{M} v_\infty R^{3/2} \tag{2}$$

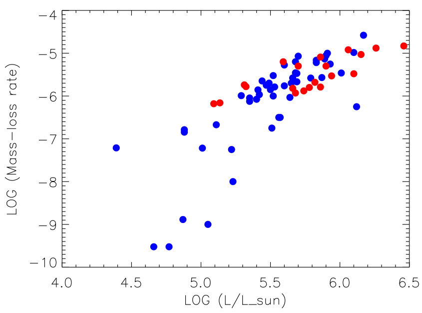

Fig. 2. A comparison of the mass-loss rates derived for Galactic stars by Lamers et al. (1980) (red dots) and Mokiem et al. (2007) (blue dots). Mass-loss rates are given in units of solar masses per years.

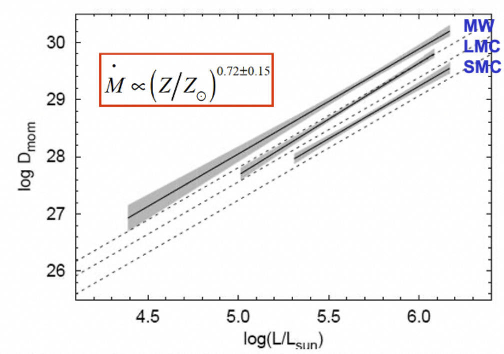

Fig. 3. The Modified Wind Momentum – Luminosity Relationship (WLR) in the Galaxy and the Magellanic Clouds according to Mokiem et al. (2007). The dashed lines represent the theoretical predictions, whereas thick lines are the fit to the observed points in the different galaxies. The shaded areas represent the 1-σ error regions. The derived metallicity dependence of the mass-loss rate can be seen in the box, and agrees well with the theoretical prediction.

where D_{mom} is the wind momentum modified because of the effect of gravity, R is the stellar radius, v_∞ the wind terminal velocity, L the stellar luminosity and $\dot{M}$ the mass-loss rate. The coefficients x and D_0 are a function of spectral type and metallicity (Kudritzki & Puls , 2000).

Confirmation of this theoretical prediction was the prime objective of the VLT-Survey of Massive Stars (VSMS, PI S.J. Smartt), where OB stars in the Milky Way and the Magellanic Clouds were observed and their mass-loss rates and modified wind momenta derived using H_α as main diagnostic (Puls et al., 1996). The key result of the VSMS can be seen in Fig. 3, adapted from Mokiem et al. (2007). The figure shows the logarithm of the Modified Wind Momentum (log D_{mom}) versus the stellar luminosity for the Milky Way, the Large Magellanic Cloud and the Small Magellanic Cloud. The agreement between theory and observation is excellent and confirms the validity of the RDWT for OB stars up to the SMC metallicity.

This result is extremely important, as it opens the way to the population synthesis in far galaxies and to the interpretation of the observations in the early Universe. Nevertheless, we see that some details differ: (a) there is a vertical shift, indicating that the derived mass-loss rates are larger than predicted, and (b) the observed luminosities of the wind onset are higher for lower metallicities.

The first problem points to the wind structure: when the wind is not homogeneous, the mass loss rates derived from lines like H_α (as was the case in Mokiem et al. (2007)) are too large. The problem was already indicated in previous articles. For example, Fullerton et al. (2006) compared the mass-loss rates derived from optical (H_α) and radio observations with those derived from the P v line profiles obtained with FUSE, ORFEUS and Copernicus, all three satellites with access to the far UV. The discrepancies between the different diagnostics could be explained if the winds of OB stars are clumped (the presence of overdensities in the wind together with regions of low or zero-density, see Rubio-Díez et al. (2022); Brands et al. (2022) for recent presentations). Inclusion of optically thin clumps (a.k.a. *micro-clumping*, where the light emitted within the clump in recombination lines like H_α escapes and the interclump medium is void) decreases the amount of material needed to reach a given emission in H_α. Thus, an observed profile can be reproduced with a lower mass-loss rate. This reduces the mass ejected by the stars, which is the parameter affecting the stellar evolution. In fact, in spite of the confirmation of the validity of the RDWT and the good agreement seen in Fig. 2, the *actual* mass-loss rate is subject to debate. For example, Rubio-Díez et al. (2022)[3], and Brands et al. (2022) present determinations including clumping that imply a reduction of a 2-5.5 factor in the mass-loss rate of O-type stars. In addition to the reduction implied by the wind inhomogeneities (clumping), new formulations of the theory may also reduce the mass-loss rate that alter stellar evolution (Vink et al. , 2001; Krtička et al. , 2021; Björklund et al. , 2022). For example, the evolution of a 60 $M_{\odot}$ star becomes a 23 $M_{\odot}$ Wolf-Rayet star with the Vink et al. (2001) mass-loss prescription, whereas with the Björklund et al. (2022) prescription it becomes a 47 $M_{\odot}$ blue supergiant. Including *macro-clumping* (optically thick clumps where light is trapped by resonance lines and the interclump medium has a lower than average density and allows light to escape) can reconcile the predictions for P v and H_{α} (Hawcroft et al. , 2021). Clumping alone, however, cannot fully explain the differences found between the far-UV and H_{α} calculations. X-rays caused by the wind structure as a results of inestabilities in the driving lines (Line Driven Instabilities) can also ionize P beyond the predicted populations, (see Owocki et al. , 1988; Feldmeier et al. , 1997; Oskinova et al. , 2006; Bouret et al. , 2012). Moreover, X-rays can also explain the so-called super-ionization showed by other ions, like O vi and N v (Snow & Morton , 1976; Lamers & Snow , 1978) that cannot be explained only with clumping. The combination of multiwavelength observations, from far-UV to radio, has thus revealed the structure of the stellar winds (for the role of the infrared wavelengths we may consider here Najarro, Hanson & Puls (2011)).

[3] These authors also find that the mass-loss rate used in evolutionary calculations for the B supergiant phase is much too large, by factors of 6-200

The second problem is related to the triggering of winds and to the dependency of wind strengths with metallicity. It seems that higher and higher luminosities are required to initiate the wind as metallicity decreases. This is important, as other processes may appear when luminosity is not able to support the stellar wind at a given metallicity. Alternatively, we note that there are also some stars that show wind strengths weaker than predicted by theory at their luminosity and chemical composition (Bouret et al. (2005); Martins et al. (2005); they can also be seen at luminosities of $\log(L/L_{\odot})$= 4.5-5.0 in Fig. 2. These so-called *weak wind stars* also represent a challenge for the theory. Thus, extrapolation of the RDWT to metallicities below that of the SMC has to be done with caution until new observations confirm its validity.

5. Binaries and rotation

Stellar winds not only remove mass, but they also carry away angular momentum, affecting the stellar rotation with time, which can effect the stellar evolution and have consequences on the inner structure and the surface abundances (see Maeder & Meynet , 2000). Thus the determination of rotational velocities in massive stars is a primary tool to understand their evolution. Pioneering studies revealing the main properties of such distribution were presented by Slettebak (1956) and Conti & Ebbets (1977) (for example, the decrease of the average rotational velocity with luminosity class, or the presence of a secondary frequency peak at high velocities; in addition, both emphasize the need of considering some kind of additional broadening in the early type stars)[4].

Modern surveys have provided us with large samples of high-quality spectra to study the rotational velocity distribution. It is interesting to compare the results of Ramírez-Agudelo et al. (2013) and Simón-Díaz & Herrero (2014). The former authors have studied the distribution of rotational velocities of

[4] Although not restricted to OB stars, we mention here the seminal works by Struve (1930) and Carroll (1933) on the methods that were later applied to the determination of rotational velocities

LMC O stars in 30 Dor in the frame of the VLT-FLAMES Tarantula Survey (VFTS), whereas the latter have studied Galactic stars within the IAC OB stars (IACOB) survey. Thus, the first study refers to an homogeneous sample of stars born in the same environment and with similar ages (although Schneider et al. (2018) identify a number of star-forming bursts in 30 Dor), whereas the second one refers to stars born and located in different places of the Milky Way.

In spite of these and other differences (f.e., those related to the observations or details of the technique used for the determination of rotational velocities), both distributions share several characteristics. They have a bimodal character, with two distinct peaks. The first one appears at projected rotational velocities of $\approx$60 kms^{-1}. The second peak appears at $\approx$400 kms^{-1}and extends up to $\approx$600 kms^{-1}for the LMC stars, whilst in the MW the corresponding values are $\approx$300 and 450 kms^{-1}. The similar shape of the distribution in two samples with very different characteristics raises the question whether the distribution of rotational velocities of O stars is a universal function, although sometimes small differences appear[5]. The origin of the second peak, already noted by Conti & Ebbets (1977) and confirmed by other works (Penny, 1996; Howarth et al., 1997), has been the subject of different hypothesis. The presently preferred one is that the tail of fast rotating stars producing the second peak is the result of interaction in massive binaries.

Spectroscopic surveys show that most massive OB stars are born in binary or multiple systems. According to Sana et al. (2012) only 29% of those stars will be born as single or in wide binaries whose components will not interact, whereas 71% will interact in the course of their evolution, giving raise to different products: stripped stars, i.e., stars that have lost their outer layers because of mass transfer (33%); stars following chemically homogeneous evolution (CHE) because of high rotational velocities and efficient rotational mixing after accreting mass and angular momentum and thus being spun up (14%); or even stellar mergers (24%). The majority of OB stars will thus suffer from binary interaction. Population synthesis by de Mink et al. (2013) indicate that the observed tail of fast rotators may be formed by products of binary interaction after a phase of Roche-lobe overflow: the initially more massive primary transfers mass and angular momentum to the initial secondary, that is then spun up and appears as the brightest component in the system. While this scenario is consistent with recent interpretations of the observations (Holgado et al. , 2022) caution is required, as it is based on still not well constrained physics (see Schneider et al. , 2016; Wang et al. , 2020).

Particularly interesting is the way how binarity modifies the evolutionary paths followed by the stars. In the late phases of the evolution the initial primary (often the fainter component after mass transfer) may be a stripped star that has lost its outer layers and is now a comparatively faint and hot star; or it may even be presently a compact object, remnant of a Supernova explosion that did not disrupt the system (see Langer, 2012). The Tarantula Massive Binary Monitoring (TMBM) survey has studied SB1 systems to try to determine the nature of the secondary object and thus put constrains on the different evolutionary channels. Shenar et al. (2022a) have found that while most of the SB1 systems in TMBM have a non-degenerate companion (43 objects, 84%), a small fraction (8 objects, 16%) have a companion that could not be detected. Two of the latter are candidate OB+BH systems (VFTS 514 and 779) while one is confirmed (VFTS 243 Shenar et al. , 2022b). In recent times, systems candidates to host an undetected compact companion have proliferated (f.e., Casares et al. , 2014; Liu et al. , 2019; Lennon et al. , 2022; Herrero et al. , 2022), although the works by Shenar et al. (2022a) and others (f.e. Simón-Díaz et al., 2020; El-Badry et al. , 2022) show the difficulties of a confirmation. Nevertheless, these systems are extremely interesting, as they could be used to investigate the progenitors of gravitational wave systems (Abbott et al. (2016), LIGO collaboration) and their frequency.

[5] f.ex., the distribution in the OB association Cyg OB2 shows a lack of very fast rotators, making the second peak less clear (see Berlanas et al. , 2020)

The relevance of rotational velocities for the studies of massive stars at sub-SMC metallicities relies on the possibility of new (or more frequent) alternative evolutionary scenarios. At very low metallicities we expect stellar winds to be weaker (see previous section) and thus to carry out less angular momentum. Stars could then originally rotate faster or, to be more precise, keep the rotational velocity with which they were born (although the expectation of high initial rotational velocities in the Milky Way has decreased after works like Holgado et al. (2022)). The possible acceleration after mass transfer could then spin up the star even further. Such large rotational velocities would have important effects in the evolution of single and binary stars, including the possibility of CHE that would result in bluewards evolution in the Hertzsprung-Russell Diagram, with CNO-processed material at the surface and enhanced UV flux (also because of a lower opacity in the UV). Such effects could alter the population synthesis in low-Z (high z) galaxies and our interpretation of their emitted light.

6. Towards the early ages

The maximum of the cosmic star formation rate is found at a redshift of z≈2, when the average metallicity of the Universe was $Z/Z_{\odot} \leq 0.1$ (Madau & Dickinson , 2014). Thus we need to confirm our knowledge of the processes dominating the physics of massive stars by studying objects at these metallicities, at least a factor of 2 below that of the SMC. Present-day facilities allow us a deep study of stars and stellar systems up to SMC metallicities, and the efforts to expand our present knowledge continue (f.e., XShootU in the MCs, WEAVE in the MW and 4MOST in both), but they barely allow us to scratch the surface of sub-SMC systems.

Spectroscopy of OB-type stars[6] at metallicities below that of the Magellanic Clouds demands careful preparatory work. Of course, we need an idea of the metallicity of the host galaxy. From the ground, photometric catalogs including the U-band are mandatory (Massey et al. , 2007; Garcia et al. , 2009) because of the colour degeneracy of hot stars in the blue and visible. But in addition, the spatial resolution decreases rapidly, local extinction is poorly known and crowding becomes soon a problem. Therefore, the role of UV-satellites, like GALEX (for a better detection of hot stars) or specially HST (improving both the detection capabilities and the spatial resolution, e.g. Bianchi et al. (2012); Calzetti et al. (2015)) has been fundamental to built up the catalogs from which to select the most promising candidates for the expensive spectroscopy of extragalactic stars (whose precious metal spectral lines become weaker and weaker with the decreasing metallicity, requiring increasingly higher signal-to-noise spectra[7]). Table 2 gives a brief overview of the opportunities offered by Local Group and nearby galaxies.

IC 1613 was the obvious choice to extend the research towards lower metallicities and got a lot of attention. Bresolin et al. (2007) presented a spectroscopic catalog of massive young stars in this galaxy (including six O-type stars and one WO). Garcia et al. (2009) presented a photometric census of massive star candidates and Herrero et al. (2010, 2012) carried out the analysis of an LBV and an Of star, finding winds somewhat more intense than expected. Garcia & Herrero (2013) presented the first temperature scale at sub-SMC metallicities, whilst Tramper et al. (2011, 2014) analyzed 5 stars in this galaxy (plus other 5 in WLM and NGC 3109) and even a WO in IC 1613 (Tramper et al. , 2013). However, a bit later Garcia et al. (2014) showed that the UV spectra of massive stars in this galaxy present a similar Fe forest as stars in the SMC, a result that is consistent with the abundance analyses of Red Supergiants in this galaxy[8]

[6] Although the brighter B and A-type supergiants could be individually analyzed at $Z \leq 0.2 Z_{\odot}$ even beyond the Local Group (e.g. Evans et al., 2007; Urbaneja et al., 2008) this was not possible for the fainter O-type stars

[7] in addition, Evans et al. (2019) et al. estimate that massive O-stars in low-Z galaxies will have absolute visual magnitudes 0.5 mag. fainter than in the MW at the same stellar luminosity

[8] and also with a somewhat surprising Fe abundance of 0.2 solar derived by Herrero et al. (2010) in the LBV mentioned above

(Tautvaišienė et al. , 2007) and that has been confirmed by other authors (see Bouret et al., 2015). IC 1613 has thus a metallicity based on the O abundance of H II regions of only 0.13 $Z_{\odot}$, but its Fe abundance is similar to that of the SMC. Therefore, it was mandatory to extend the observational efforts to other galaxies, as it is the abundance of Fe group elements that determines the wind strength. Although there have been some works in other galaxies (like Hosek et al. (2014) in NGC 3109, Garcia (2018) in Sag DIG, Evans et al. (2019) in Leo P or Gull et al. (2022) in Leo A), the most promising next target is Sex A, with a consistent low O abundance according to H II regions and blue supergiants (Skillman et al. , 1989; Kaufer et al. , 2004), a low Fe content from HST-UV spectra (Garcia et al. , 2017) and a solar α/Fe ratio (Kaufer et al. , 2004). However at the price of a factor of 2 in the distance compared to IC 1613.

Camacho et al. (2016) presented the first obervations of individual stars in Sex A, including a temperature scale at this even lower metallicity. However, this work also confirms something suspected in the former IC 1613 ones: the lack of evidence for CHE stars in these galaxies. Whether this points to the need of more and higher quality observations or is a consequence of the dominant evolutionary channels in these galaxies (or has any other origin) is still unclear. Nevertheless, the question whether CHE stars are common or not in low-Z galaxies is a crucial one.

Our team has carried out a programme of massive hot stars in Sex A during several years. Based on observations with the multiobject spectrograph OSIRIS attached to the Gran Telecopio Canarias (GTC), we have recently compiled the first catalog of OB stars in SexA, with more than 150 objects from which more than 100 have spectral types between O3 and B3 (Lorenzo et al. , 2022). An example is shown in Fig. 4.18 stars in the catalog show very blue colors, suggesting 9 of them being possibly stripped and/or to CHE stars, while for the other 9 their possible nature remains undetermined. Also Telford et al. (2021) have reported two fast rotating stars in Leo P and Sex A. These stars will constitute a first step in our effort to unveil the physical processes dominating the stellar evolution below SMC metallicities. Future analyses will require better quality observations, but its pioneering character opens the way for the studies of individual stars at sub-SMC metallicities, that the new generation of telescopes like the ELT, TMT or GMT will make possible.

Table 2. List of possible target galaxies for a ladder to the early Universe. Distance moduli and abundances have been taken from the corresponding references cited in text, except for the distance of IZw 18 (from Lelli et al. , 2014).

Galaxy	distance modulus	$Z/Z_{\odot}$
Milky Way	0	1.0
LMC	18.48	0.25
SMC	18.98	0.20
IC 1613	24.27	0.13 (O)
		0.20 (Fe)
Sag DIG	25.10	0.05 (O)
Sex A	25.63	0.10
Leo P	26.05	0.03
IZw 18	31.30	0.03 (O)

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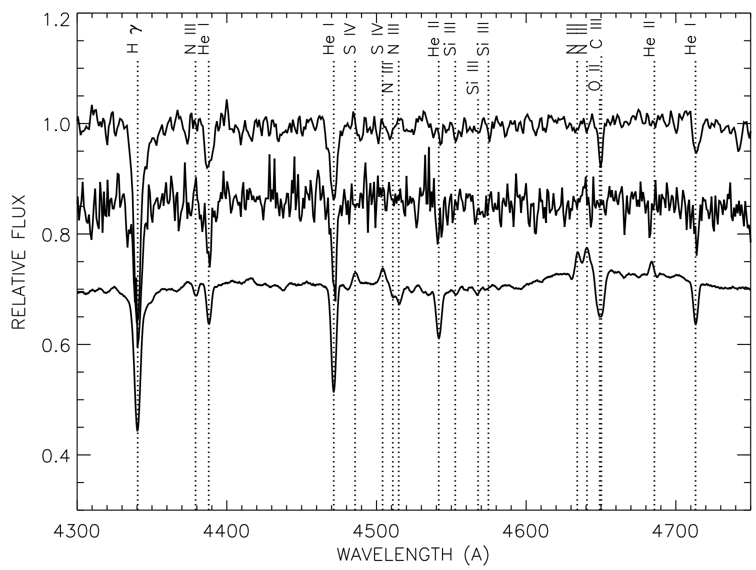

Fig. 4. Spectra of O9 supergiants in Sex A (upper spectrum: s036, middle spectrum: s038 , observed with GTC, from the Lorenzo et al. (2022) catalog) and the SMC star Sk-66 171 (lower spectrum, from the XShootU observations with VLT; here degraded to the resolution of the GTC observations). The position of some H , He and metal lines have been overplotted to reveal the lower metal abundance in Sex A.

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