LARGE NUMBER OF WOLF-RAYET STARS IN EMISSION-LINE GALAXIES

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ABSTRACT. *We present synthetic populations of massive stars that constrain the properties of the star formation episodes, predict the occurence, subtype distribution and evolution of WR star populations at solar and SMC metallicities. Instantaneous burst and continuous star formation rates have been considered. Our predictions have been tested on a sample of 17 galaxies. The evolution of the WR stars is qualitatively well reproduced. The IMF slope is flatter on average than in the solar vicinity and is not correlated with the metallicity. The extinction law is in general similar to that of the SMC, independently of metallicity.*

INTRODUCTION

Evolutionary population synthesis models have been built to study the properties of the star formation episodes taking place in galaxies with starbursts. Such starbursts that occur over short periods are excellent test grounds to study the formation and evolution of massive stars. In this contribution we will show how the study of the evolution with time of a massive star cluster can be used to reproduce the output radiation of emission line galaxies at essentially all observable wavelengths from the near UV where starlight dominates down to the far infrared and the radio range. Our models will be explained in broad terms and examples will be given to illustrate the best way to reproduce the observations. A set of 17 galaxies in which starbursts are taking place have been analyzed giving some interesting clues concerning the occurence of large WR numbers, the IMF and the interstellar extinction law.

POPULATION SYNTHESIS EVOLUTIONARY MODELS

Our evolutionary population synthesis models have been explained at length in Arnault, Kunth and Schild (1989) and Mas-Hesse and Kunth (1990). We have used stellar evolutionary tracks from Maeder and Meynet (1987) including mass-loss and overshooting. For a given IMF, we can derive the number of stars per luminosity class (I, III and V) and spectral subtype (O3 to M5). Our models are improved over previous ones by including $Z_{\odot}$ and $Z_{\odot}/10$ metallicity stellar evolutionary tracks (tracks of $Z_{\odot}/10$ have been provided to us by Maeder and Meynet prior to publication) and allowing for very short time steps (≥ 0.05 Myr) to account for very rapid stellar phases such as WR. Two star formation rates (SFR) describe extreme possible situations : an instantaneous burst (IB) and a continuous regime (CSFR) lasting over 20 Myrs. The output of these models are analyzed using fundamental mean properties of standard stars. This step is performed by combining published data together with a library of theoretical model atmospheres (Kurucz, 1979 and Mihalas, 1972). We have also computed the emission of the interstellar gas ionized by massive stars and re-emitting H_{β} emission as well as the far infrared radiation (FIR) from dust particles and the radio emission from relativistic electrons and thermal gas. The mean features of the models are summarized in Table 1.

K. A. van der Hucht and B. Hidayat (eds.),
Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, 613–618.

Table 1.

Mup	120, 60 $M_\odot$
Mlow	2 $M_\odot$
α	1, 2, 3
stellar tracks	$Z_\odot$, $Z_\odot/10$
star formation rates (SFR)	instantaneous burst (IB)
	continuous star formation rate (CSFR)
time step	$\geq$ 0.05 Myr
mass loss	$\dot{M} \propto Z^{0.4}$
overshooting	included in $Z_\odot$ models

The IMF is parameterized as IMF = dN/dm proportional to $m^{-\alpha}$. Mup and Mlow are the upper and lower mass limits of the IMF.

Among the parameters we have synthesized the following deserve a particular description:

i) UV absorption lines

In the UV range the best observed absorption lines are those of SiIV and CIV. These lines are signatures of hot stars with strong driven winds. They are useful spectral type indicators and we find that the ratio of their equivalent widths W(SiIV)/W(CIV) is nearly metallicity independant. This ratio is therefore a good tracer of the massive stars that prevail in the cluster, regardless of the metallicity and can be used to estimate quite accurately the age of an instantaneous burst. Moreover the slope of the IMF is constrained by this ratio in the first million years after the onset of the burst. The ratio has also the observational advantage of beeing reddening free and independant of normalisation.

ii) The Wolf-Rayet bump at 4650 Å

Wolf-Rayet stars are detected in star-forming clusters by their characteristic bump at 4650 Å (see L. Smith, this volume). This bump appears as a blend of NIII and HeII lines from WN stars and CIII, CIV and HeII lines from WC ones. Our models predict the WR population of both types as a function of time. Progenitors at $Z_\odot$ have masses $> 35 M_\odot$ while at $Z_\odot/10$ they have masses $> 85 M_\odot$. We have estimated that the luminosity of the bump due to WN stars is 2 10^{36} ergs/sec and 6 10^{36} erg/sec for WC galactic stars. On the other hand their ionizing power compares to that of O6V-B0I type stars, i.e. around 10^{49} photons/sec. Theoretical lifetimes for WR are 0.5 Myr for galactic stars and only 0.14 Myr for WR of $Z_\odot/10$ abundances. Such short lifetimes explain why the WR bump can be seen only over a short period thus giving a strong constraint on the age of a given star formation episode. At low metallicity the detection of the feature is further constrained to a much shorter period explaining the low detection rate of WR in metal deficient galaxies. We have plotted in fig. 1 the evolution of the L(WRbump)/L(H_β) ratio for different star formation scenarios.

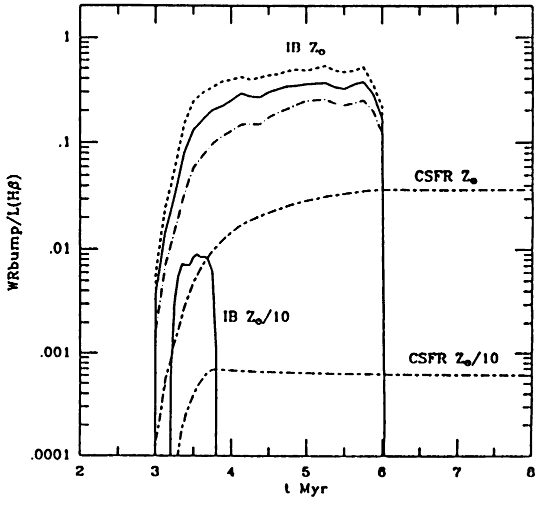

Figure 1: Predicted WR bump to H_β luminosity ratio. For $Z_\odot$ metallicity, predictions have been plotted for 3 slopes of the IMF and the IB case, α = 1:—, α = 2:—, α = 3, -.-.-, and for α = 2 in the CSFR case. Mup = 60 $M_\odot$ in all the models.

iii) The stellar continuum

The stellar energy distribution (SED) emitted by the stelllar cluster has been computed in the range 912 Å – 3.2μ using the stellar spectral energy distribution of each individual stars. Details of the procedure are given in Mas-Hesse and Kunth (1990). The ionizing flux has been obtained in a similar fashion and we also calculate the effective temperature T_{eff} of the cluster that can be easily compared with the observational effective temperature deduced from the method of Stasinska (1980) or Vilchez and Pagel (1988).

COMPARISON WITH THE OBSERVATIONS

We have analyzed a sample of 17 galaxies in which starbursts are taking place with UV, optical, FIR and radio data. All the results will be published in a forthcoming paper. These galaxies comprise 7 blue compact galaxies, 1 spiral starburst, 1 merger and 3 giant HII regions in M33 and M101. We summarize in Table 2 the most interesting observational data. The strategy adopted for the analysis of the data is the following:

- We first estimate the age, the SFR and the IMF slope using 3 diagnostic plots: W(H_β) versus W(SiIV)/W(CIV) at $Z_\odot$ and $Z_\odot/10$ and Log T_{eff} versus W(SiIV)/W(CIV) at $Z_\odot/10$. The first two plots are shown in figs. 2a and 2b.

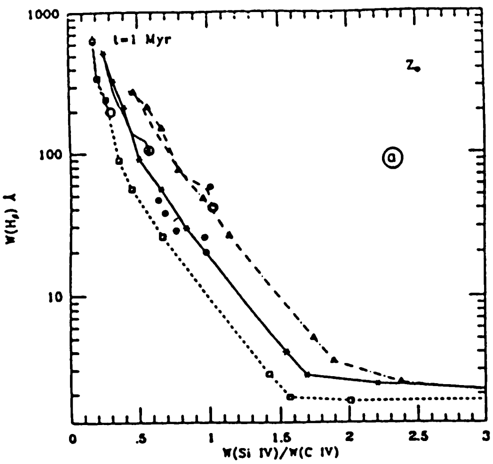

Figure 2a: Predicted W(H_β) versus W(SiIV)/W(CIV) ratio at $Z_\odot$. Filled circles represent values taken from Table 2. Symbols along the tracks are time intervals of 1 Myr.

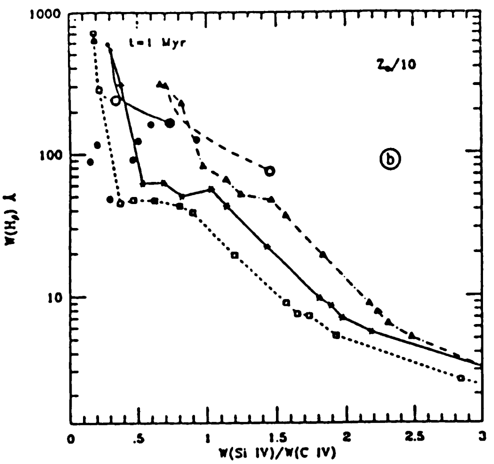

Figure 2b: Same as fig. 2a but for $Z_\odot/10$.

- The extinction law is derived and the E(B-V) is estimated by fitting the predicted SED to the observed one. We show in fig. 3 the synthesized spectrum of IZw 18 superposed on the observed one.
- Further constrains to the models are set using the L(WRbump)/L(H_β) ratio (see fig. 1a in Arnault et al., 1989) and the full set of synthesized parameters. We list in Table 2 model parameters which better reproduce the observational data.

Table 2. Observed and derived parameters of the sample.

Name	Type	O/H	WSi/WC	WH_β Å	T_{eff}	WR/H_β	LFIR erg/s	E(B-V)	k_λ	α	SFR	age Myr
NGC 588	GH	8.3	0.14	97	37500	-	≤3.7E39	0.07	M	1	IB	3.4
NGC 595	GH	8.4	0.54	-	35000	-	≤7.9E40	0.26	G	1	IB	5.5
NGC 2363	IG	7.9	-	300	47500	-	2.7E41	0.06	M	1-2	CR	4.5
IZW 18	BG	7.2	-	135	40000	-	≤6.5E41	0.08	G	1-2	IB	3.4
MRK 710	SG	8.9	0.71	35	37500	0.24	7.4E42	0.16	M	2	IB	5.5
Tol 3	BG	8.2	0.45	98	37500	0.09	5.4E42	0.09	M	2	IB	3.7
NGC 3256	ME	-	1.0	20	-	-	1.9E45	0.22	M	2	IB	7.0
Haro 2	BG	8.4	0.98	30	38500	0.15	1.5E43	0.12	M	2-3	IB	5.6
MRK 36	BG	7.8	0.20	110	45000	0.0	≤3.5E41	0.05	M	1	IB	3.0
NGC 4214	IG	8.3	0.67	49	37500	0.25	5.3E42	0.09	M	2	IB	5.0
IZW 36	BG	7.8	-	300	45000	-	≤1.2E41	0.0		1-2	CR	4.5
NGC 4670	BG	8.4	0.82	27	37500	0.1	3.1E42	0.10	M	2	IB	6.0
MRK 59	IG	8.0	0.91	135	42500	0.08	2.0E42	0.09	G	3	CR	8.5
NGC 5253	IG	8.2	0.59	160	38500	-	4.0E42	0.10	M	2-3	IB	3.3
NGC 5471	GH	8.0	0.50	129	40000	0.02	5.9E41	0.08	G	2	IB	3.5
IIZW 70	BG	8.0	0.30	49	38000	0.0	2.1E42	0.05	M	1	IB	3.8
IC 4662	IG	8.3	1.00	65	38500	-	5.6E41	0.06	M	3	CR	14

Notes:

Type: *BG: Blue compact dwarf galaxy, IG: Irregular galaxy, SG: Starburst galaxy, ME: Merger, GH: Giant HII region.*
E(B-V): *Derived from the fit of the predicted and the observed continua.*
k_λ: *Extinction law- M: SMC, G: galactic.*
α: *IMF slope.*
SFR: *Star formation rate - IB: instantaneous burst, CR: constant rate.*

The table is explained in greater detail in Mas-Hesse (1990).

The main results we have obtained are the following:

i) The WR stars

Our models satisfactorily explain the observed fact that the ratio WR/O (Kunth and Schild, 1986; Azzopardi et al., 1988) is a decreasing function of the oxygen abundance just because the WR progenitors have larger masses at smaller metallicity and a shorter lifetime. Moreover the scatter of the $L(WRbump)/L(H_\beta)$ for a given O/H also noted in Kunth and Schild is largely accounted for by the evolution of the starburst region with time. Our models however fail to generate $L(WRbump)/L(H_\beta)$ values as high as observed especially at low metallicity. Maeder's new models using higher mass loss rates (1990a,b) seem to reach better agreement but this point will be further checked in our models. The subtype distribution, i.e. the WN to WC ratio is also well reproduced. Indeed most metal poor blue compact

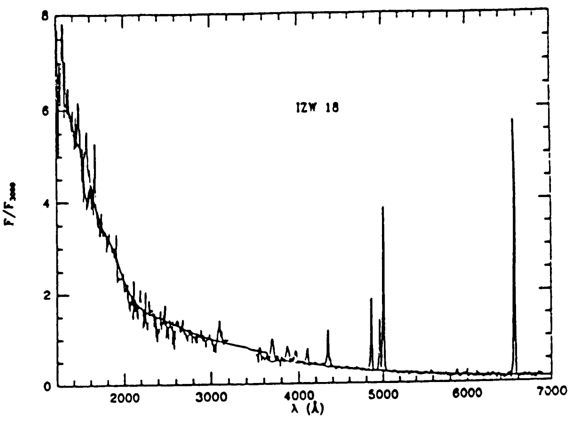

Figure 3: Observed spectrum of the BCD IZw18 from 1200 to 7000 Å. The continuous line is the synthesized spectrum normalized at 3000 Å.

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dwarf galaxies with published spectra have only WN stars because WC phases only occur when the metallicity is high (see L. Smith in this volume for a full discussion and references). The occurrence of WC stars in the Ir galaxy NGC4214 at 5808 Å has been predicted from our models and observationally confirmed afterwards with a correct WN/WC ratio as indicated by the ratio of the bumps at 4650 and 5808 Å.

ii) The interstellar extinction

The continuum (SED) of all the objects has been well reproduced in the 1200-7000 Å range using either the SMC or the Galactic extinction laws. Our method is sensitive providing the color excess is larger than 0.05. The most striking result is that the SMC extinction law generally well describe the sample independently of the metallicity. On the other hand, the color excess tends to increase with the oxygen abundance.

The color excess as derived from the continuum fitting is systematically lower than the value derived from the Balmer decrement:

a) The discrepancy can be removed by correcting from underlying stellar absorption using mean equivalent widths around 5 to 6 Å. A justification for that is that a wide slit (10") has been used giving a resolution so low as to fill in the whole stellar absorption. Equivalent widths in the range 8–13 Å have been predicted by A. Diaz (1988) for similar clusters.

b) A widely accepted possibility is that the main contribution to the UV continuum comes from windows where the extinction is relatively low, while at optical wavelengths the contribution from more obscured regions is not negligible (Fanelli et al., 1988). Nevertheless, this hypothesis can not explain why the color excess derived from the continuum is essentially the same in the whole 1200-7000 Å range.

iii) The star formation processes

Only very young bursts adequately reproduce our data. Massive stellar formation is quasi instantaneous with upper mass limits of at least 120 $M_\odot$. In few cases the star formation episodes could have lasted for about 10 Myrs.

The mean age for the star forming epoch is around 4.5 Myrs and generally in the range 3-6 Myrs, probably as a result of a selection effect since the observed emission lines that typify the sample fade drastically 6 Myrs after the onset of the burst. NGC3256 on the other hand has been selected from its strong FIR luminosity and is the most evolved object, hosting a star-forming episode having taken place around 7 Myr ago. The IMF is not universal in the sense that its slope is in the range 1 to 3 with a mean value of 2, i.e. richer in massive stars than the solar neighbourhood. Our results do not support the correlation found by Terlevich and Melnick (1981) between the IMF slope and the oxygen abundance. Such a correlation is postulated by the authors to account for the increase of T_{eff} as O/H decreases and the observational evidence that $W(H_\beta)$ appear to be systematically lower as O/H increases. In fact we find that T_{eff} is only affected by the IMF slope at the very beginning of the burst (2 Myrs). On the other hand, the slower evolution at low metallicity implies a longer lifetime of massive stars and therefore a higher effective temperature in the cluster. Furthermore, the evolution of red supergiants is strongly metal dependent, and their contribution to the luminosity at 5000 Å changes by up to a factor 2 from $Z_\odot$ to $Z_\odot/10$, originating lower $W(H_\beta)$ at solar metallicity.

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DISCUSSION

Walborn: I want to qualify the remark I made after Lindsey's paper, I think may be relevant to this last point you were making, I think I momentarily forgot my own review on 30 Dor at the Starburst Meetings in Baltimore and Sydney. The point is that if you are isolating the population of the giant *HII* region, then it will be dominated by the evolutionary products of the most massive stars, I think that is why you see predominately WN. But, 30 Dor has emerged in a ten times larger young region which contains many WC stars and undoubtedly mass transfer binaries. At these very large distances, you will be integrating over those different populations, and as Lindsey very nicely showed, one early type WC can equal 20 late type WN's. So, I think the point is that the interpretation of the stellar population and the relationship to the ionized nebulosity becomes extremely complicated and difficult the further you go in distance.