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INITIAL MASSES OF WR STARS IN OPEN CLUSTERS

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RESUMEN: Se usa una muestra de 18 cúmulos abiertos que contienen estrellas WR para estimar la masa inicial.de ellas. Se discuten aspectos evolutivos que relacionan estrellas WR y estrellas O en un escenario compuesto por 52 cúmulos abiertos muy jóvenes.

ABSTRACT: A sample of 18 open clusters containing WR-type stars is used for estimating the initial masses of these stars. Evolutionary features relating WR and O-type stars in a scenery composed by 52 very young open clusters are discussed.

Key words: CLUSTERS-OPEN -- STARS-WOLF-RAYET

I. INTRODUCTION .

The initial masses of WR stars were the subject of several investigations: Massey (1981), Conti et al. (1983), Humphreys et al. (1985), Doom (1987) and more recently Van den Hutcht et al.(1988). An extensive review about related points may be also found in Conti (1988) and references therein. Conti et al. (1983) and Conti (1984) propose that WR stars evolve from O-type stars with masses greater than 40 M⊙ taken into account the spatial coincidence between O and WR-type stars in our Galaxy. Humphreys et al.(1985) have analyzed the mass distribution of initial masses of WR stars in open clusters and associations. Their analysis yielded that 80 % of WR have initial masses greater than 50 M⊙, being 20 M⊙ the lower limit to the initial mass. A mathematical analysis of the correlation of the observed distribution between WR and O-type stars was performed by Doom who describes the best correlation for =-type stars more massive than 35 M⊙. Van der Hutcht et al. discussed the Doom's analysis with a more complete sample of WR-type stars. They found the best correlations for 28-35 M⊙ in WN stars and for more than 25 M⊙ in WC stars.

The aim of this paper is to estimate the initial masses of WR-type stars in open clusters assuming to be secure members. Other related features as the constraints with evolutionary models will be examined. Our starting point is a sample of open clusters for which all intrinsic parameters were redetermined by us.

II. BASIC DATA.

A sample of 52 open clusters with ages less than 15 x 10^6 yrs was selected. The sample presents about 50 % of open clusters with this age listed in Lyngå's catalogue (1983). The data include UBV(RI) photometry and MK spectral classification for around 2700 membership stars. All these data were compiled from the literature (Vázquez 1989). The sample is assumed to be homogeneous according to:

1.- UBV(Rl) data for each upen cluster are photoelectric. A previous selection was made if more than one photometric set was available for a given cluster.
2.- We consider those clusters having the main sequences defined by, at least, 15 membership stars.
3.- A previous task was based in the re-determination of membership according to the star's position in the color-color and color-magnitude diagrams and spectral classification when it was possible.
4.- The E(U-B)/E(B-V) excess relation was checked in each cluster in order to detect possible departures from the assumed standard relation (Schmidt-Kaler 1982). Abnormal relations were detected in NGC 6611, NGC 6604 and NGC 3603.
5.- The extinction law, Av/E(B-V), was re-discussed by means of the variable extinction method (Turner 1976). In some cases, the E(V-I)/E(B-V) relation (Chini and Neckel 1981) was also used.
6.- Finally, the distance of each open cluster was derived fitting the Schmidt-Kaler's ZAMS (1982) to the de-reddened main sequence.

Table 1 displays the intrinsic distance moduli, mean color excesses, E(B-V) and ıe position on the galactic plane for 52 open clusters. .

Table 1. Intrinsic parameters for open clusters

Cluster	Vo-Mv	$\overline{E(B-V)}$	Cluster	Vo-Mv	$\overline{E(B-V)}$
NGC 6530	11.35	0.37	Tr 15	12.30	0.49
NGC 6611	11.70	0.45	Cr 228	12.40	0.33
NGC 6604	12.30	1.03	Tr 16	12.65	0.55
NGC 6823	11.90	0.71	Cr 240	11.60	0.40
NGC 6871	11.25	0.46	NGC 3603	13.50:	1.46
IC 4996	11.50	0.66	IC 2944	11.87	0.37
Be 87	10.00	1.55	Stk 14	12.20	0.29
NGC 6913	10.85	0.73	Hogg 15	13.20	1.14
Tr 37	10.10	0.56(e)	Stk 16	11.80	0.50
Ma 50	12.60	0.76(e)	NGC 6193	10.65	0.56
NGC 457	12.35	0.51(e)	NGC 6231	11.05	0.47
NGC 663	11.90:	0.84(e)	Tr 24	11.50	0.49
NGC 869	11.55	0.58(e)	NGC 6322	10.60	0.66
IC 1805	11.53	0.92(e)	C1715-387	12.80	1.83
NGC 884	11.80	0.61(e)	NGC 6334	10.90	1.17
IC 1848	11.80	0.65(e)	Tr 27	12.05	1.43
NGC 1502	10.05	0.76(e)	NGC 6383	10.60	0.35
NGC 1893	12.90	0.54(e)	Bo 14	9.74	1.55
NGC 2264	9.70	0.06(e)	Do 33	12.70	1.27
NGC 2244	11.20	0.72(e)	Bo 7	13.80	0.85(e)
Cr 121	9.10	0.04(e)	Pi 20	10.82	1.05
NGC 2362	10.80	0.11(e)	Be 86	10.60	1.01
NGC 2467	12.50	0.42(e)	NGC 3293	12.20	0.30
Ru 44	14.20	0.68(e)	NGC 3324	12.80	0.43
Bo 15a	12.40	0.55	Bo 10	12.35	0.35
IC 2395	9.90	0.22	Tr 14	12.65	0.56

Note:(e) indicates cluster placed outside the solar circle. The rest is placed inside the solar circle.

From the point of view of spectral classification, the data give: 204 O-type stars ɔf which 63 are Of-type stars), 63 blue supergiants (BI-II) stars, 57 Be-type stars, 22 WR ɴd 14 red supergiant stars. The rest includes B(V-IV-III) type stars. Only 30 % of over 2700 ɘmbership stars have spectral classification.

By other side, 18 over 52 open clusters contains WR-type stars considered as ɘcure members after the work of Lundstróm and Stenholm (1984). Only the WR star in Cr 121 is ndicated by ? in such work. This fact permit us to try the determination of initial masses of R stars as well as to describe some features related to the constraints on the evolutionary odels.

II. DETERMINATION OF INITIAL MASSES OF WR-TYPE STARS.

To estimate the WR's initial masses it shall be necessary to assume that the star ormation process is coeval for each cluster. Also, it becomes indispensable that WR stars ere evolved stars. If this is clearly valid, then one WR star had initially a mass either imilar or greater than the brightest star present in the main sequence of the parent cluster. hus, by matching a grid of evolutionary models for massive stars it is possible to econstruct the evolutionary track passing through the star, in this case, through the rightest star. The inital mass, on the ZAMS, is obtained using some mass-luminosity elationship from models.

In order to select the evolutionary model which gives the initial mass we have two ossibilities. First, to apply the models computed with moderate mass loss and Schwarszchild riterion for convection (Maeder 1981, 1984). Another way is to apply the models computed with ass loss and overshooting criterion for convection (Maeder and Meynet 1987, 1988). Those are ot the unique available models from the literature as others exist (see Chiosi and Maeder 986, for details about this topic). Here, we will use the models computed by Maeder and ollaborators. For reproducing the track outlined by the brightest star actually present in he main sequence we use the observational Mv vs $(U-B)_o$ plane because some brightest stars in oose and faint clusters have not MK spectral classification. In addition, uncertainties can rise from poor color indices but in these cases the best caution are taken. The way to derive nitial masses is similar to Humphreys et al. (1985) procedure. But some dlfferences result as e work in the observational plane and our sample is only composed by WR-type stars in open lusters.

The grids of evolutionary models were transformed to tbe observational plane by means of the relations Log L/Lo with Mv, and Log Teff with (U-B)o color index, both from Schmidt-Kaler (1982). Although the ZAMS computed with overshooting is hotter than that computed with traditional criterion (Figure 1), both give almost the same initial mass. For this reason we limit ourself to take into account those masses from models with mass loss. Due to the similarity between consecutive tracks the initial masses are computed with an error of 15 % (error from inspection) for stellar masses greater than 60 M⊙ and 10 % for smaller masses. Table 2 lists all the WR-type stars in the 18 open clusters, where the spectral classification arises from Lundstróm and Stenholm (1984) work. The initial masses estimated from models are also denoted in Table 2 but let us do some comments: in some open clusters (e.g. NGC 3603, Do 33) there is a possibility that the brightest star is coming back to the ZAMS and then it would be possible an overestimation of its initial mass. This kind of uncertainties increases for very bright and blue stars and perhaps, this is what happens for those stars with more than 100 M⊙. Figure 2 shows the distribution of initial masses of WR-type stars obtained with the procedure explained above.

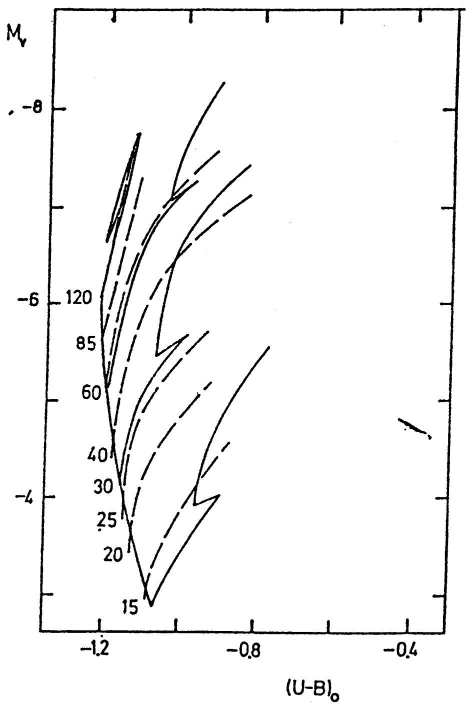

Figure 1. Grids of evolutionary models computed with mass loss (solid lines) and mass loss plus overshooting (dashed lines). Numbers indicate initial masses.

Table 2. WR stars in open clusters

Cluster		Star	Classification	Comp. Espec.or Vis.	Progenitor. a) b)
NGC 6871		HD190918	WN4.5+O9.5Ib:	*	32-30
Be 87		St 3	WO2		22
Ru 44	(e)	HD65865	WN4.5+OB	*	55
Cr 228		HD93131	WN7+a		105-97
Tr 16		HD93162	WN7+a		60
NGC 3603		HD97950	WN6+O5	*	> 60
Hogg 15		E311884	WN6+O5V	*	38
NGC 6231		HD151932	WN7		72-68
		HD152270	WC7+O5-8	*	
Tr 27		LSS 4261	WN7+WC7		62
		105	WC9		
C1715-387		LSS 4065	WN7		116-104
		LSS 4064	WN7		
Ma 50	(e)	HD218450	WN4.5+B1III	*	17-18
Cr 121	(e)	HD50896	WN5	(SB1)	24-35
Bo 10		HD92809	WC6		25
Bo 14		Ve2-45	WC9		54-51
Do 33		Vy1-3	WN7		> 108
Bo 7	(e)	CD-454482	WN7	(SB1)	22-24
Pi 20		LSS 3329	WN6		27-34
Be 86		HD193576	WN5+O6	*	18

Note:(e) indicates cluster placed outside the solar circle.
a) indicates models with moderate mass loss and b) indicates models with mass loss plus overshooting.* means binarity.

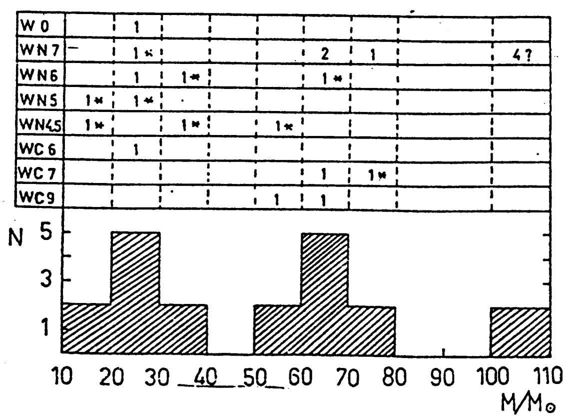

Figure 2. Distribution of initial masses for WR-type stars. The frequency of subtypes is indicated. The asterisk means binarity.

V. ANALYSIS.

The separation of the initial masses of WR-type stars into two groups: $M_p > 50$ M⊙ nd $M_p < 50$ M⊙, is completely arbitrary but also evident from Figure 2. We retain this ivision for analysing some constraints to the evolutionary models. A third group for initial asses greater than 100 M⊙ may be unrealistic as it was said above. We retain as realistic ivision for initial masses the intervals from 10 to 40 and from 50 to 80 M⊙. In this latter roup are included those stars with masses > 100 M⊙. From the figure we found that late WN and C-type stars are formed from very massive stars while early WN preferentially result from ess massive stars. Humphreys et al. (1985) point out that both types of WR stars, WN and WC, ave similar minimum initial masses. Obviously, in the present sample, WN and WC stars cover he whole range of masses (Fig. 2), but there is an unquestionable trend to concentrate in the 0-80 M⊙ interval for late WC. In fact, although a few WC-type stars ara presented in this ample, all the late WC have great initial mass and only one WC6 star posses a low mass rogenitor. Contrarily to Van der Hutcht et al. (1988) for who all WN-type stars are formed rom lower mass O-type stars we see in the figure that WN-type stars are formed from massive tars when they are of later types and from lower initial mass when they are of earlier types.

Interesting enough is the following: the binarity frequency in this sample is 36 % eing in reasonable agreement with Van der Hutcht et al. (1988). Nevertheless, Figure 2 ndicates that most of early WN-type stars in open clusters are binary stars. Their binary requency is 64 % while for late WN-type stars it falls to 23 %. We can agree with the nalysis of Van der Hutcht et al. in the sense that single WR stars come from massive stars referentially while this is not the case for the binary WR stars. But it is clear from Figure that both, late WN and WC-type stars, are formed from massive progenitors with $M_p > 50$ M⊙. he presence of two late type stars (1 WN7 * and 1 WC6) in the group from 10 to 40 M⊙ and two arly type stars (1 WN6 * and 1 WC4.5 *) in the group from 50 to 80 M⊙ indicate that binarity an be playing an important role in the production of sub-types in WR stars. (see Figure 2).

Table 3 lists the estimated WN/WC number ratio equivalent to the t(WN)/t(WC) ifetime ratio. The WN/WC number ratio is 3.2 when computed over the whole mass range of nitial masses of WR-type stars. In the case of $M_p > 50$ M⊙ the observed number ratio yields .2 and it increases those to 7 (!) for $M_p < 50$ M⊙. Models computed with mass loss plus vershooting predict stars with t(WN)/t(WC) from 1.2 to 1.34 for initial masses greater than 0 M⊙ (Maeder and Meynet 1987, 1988). No information is given by these models for lower asses. Then, the observed WN/WC number ratio is almost twice the expected from the heoretical models. As the t(WN)/t(WC) lifetime ratio is very sensitive to the metallicity radient we examine this ratio for interior and exterior clusters to the solar cirole ontaining WR stars. At first, we claim that no WC-type stars are encountered related to xterior open clusters. Secondly, for $M_p > 50$ M⊙ the observed WN/WC number ratio remains the ame that for interior clusters. It is interesting enough that WR in open clusters give issimilar results respect that obtaining using the total number of WR in the Galaxy. The bserved WN/WC number ratio according to Van der Hutcht et al. yields from 0.90 to 0.35. The ivision in shells around the galactic center where the counts are done by those authors eveals that the number of WC-type stars decreases to the galactic center. An explanation bout the lack of WC in clusters placed outside the solar circle may be the less number of ery massive stars from which WC are descendent. In Table 2, it is easy seen that late WN also void the outer clusters.

Table 3. The WN/WC number ratio

	ALL	$M_p>50M_⊙$	$M_p<50M_⊙$
	3.2	2.2	7(!)
Interior cluster		2.2	4
Exterior cluster		?	?

Table 4. The WR/O number ratio

ALL	$M_p>50M_⊙$	$M_p<50M_⊙$
0.10	0.18	0.06
0.09	0.15 #	0.06 #

number ratio computed assuming that B0-1.5 supergiants are stars in the core hydrogen burning phase.

Another constraint on the evolutionary models for massive stars is related to the R/O number ratio. This ratio is equivalent tn the t(WR)/t(O) lifetime ratio. To do this, we ill use all the O-type stars related to the 52 open clusters plus the B0-B1.5 supergiants ssumed to be stars in the core hydrogen burning phase. Table 4 indicates the observed number ratios. The division of O-type stars in more than 50 M⊙ and less than this initial mass was made counting stars in the HR diagram and using the theoretical models computed with moderate mass loss. When we calculate the WR/O number ratio for initial masses larger than 50 M⊙ it yields 0.18 and 0.15 for O-type stars plus B supergiants respectively. These numbers are in good agreement with the models of Maeder and Meynet (1987,1988) for which a star spends from 0.12 to 0.17 of its core hydrogen burning phase as a WR-type star if its initial mass is between 40 and 60 M⊙. Contrarily, in the case of less massive stars, the WR stars spend 0.06 of their hydrogen burning phase in coincidence with the prediction of current models. Without distinguishing between initial masses, the number ratio gives 0.10 and 0.09. This number is smaller than the one from Conti et al. (1983) by a factor of 3. The analysis on the evolution of stars must be done using open clusters for avoiding incompleteness arising from different magnitude scales and consequent mixtured volumes in the Galaxy.

As a final comment we observe that in those clusters with WR-type stars whose initial masses are greater than 50 M⊙, the aasociated number of O-type stars and Of-type stars are 63 and 23 respectively. All included in 8 open clusters. For initial masses lesser than 50 M⊙, there are 3 O- and 2 Of-type stars included in 3 open clusters. This is a reinforcement of the supposition that massive WR stars descend from massive O-type stars being the Of a possible transition phase.

V. CONCLUSIONS.

The picture of WR stars in open clusters permit us to draw off the following:

WR-type stars are formed over the whole mass range from approximately 20 M⊙. But initial masses of WC-type stars are preferentially 50 M⊙. Both sub-types of WR stars, late WN and late WC, have initial masses greater than 50 M⊙. Exceptionally, in the present sample, 1 WN7 and 1 WC6 are associated to progenitors with $M_p \sim$ 20-30 M⊙.

Early WN-type stars are generally found in binary systems. It is noticed an increase in binarity frequency when initial masses are smaller than 50 M⊙.

The observed WN/WC number ratio results a factor 2 greater than the expected from models with mass loss plus overshooting. Moreover, smaller the initial mass greater is the WN/WC number ratio.

There is a lack of WC stars for those clusters located outside of the solar circle.

The observed WN/O number ratio yields 0.15 to 0.18 when 52 open clusters are used. This result is in agreement wlth models with overshooting plus mass loss. This number falls for less massive stars according to current evolutionary models.

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