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OBSERVATIONAL EVIDENCE FOR EVOLUTIONARY CONNECTIONS BETWEEN WOLF-RAYET STARS AND RED SUPERGIANTS

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RESUMEN

Se examina la influencia de la metalicidad en la formación de estrellas Wolf-Rayet en la galaxia M33. Se obtiene el límite de luminosidad de las supergigantes rojas, que pueden evolucionar a estrellas WR. Sobre la base de este límite, se confirma la existencia de un gradiente con la distancia galactocéntrica del cociente de estrellas WR a supergigantes rojas (Maeder et al. 1980).

ABSTRACT

The influence of metallicity on the formation of WR stars is examined for the M33 galaxy. The luminosity limit of red supergiants, which can evolve to WR stars, is obtained. On the basis of this limit, the existence of a gradient of the WR stars-to-red supergiants ratio with galactocentric distance (Maeder et al. 1980) is confirmed.

Key words: **GALAXIES – STELLAR CONTENT — STARS – SUPERGIANTS — STARS – WOLF-RAYET**

1. INTRODUCTION

Wolf-Rayet stars are believed to be evolved objects that reveal products of CNO or triple α processes, whose progenitors are massive stars $M \geq 20\ M_{\odot}$ (Humphreys, Nicholis, & Massey 1985). Current evolutionary scenarios suggest two main modes for WR star production. The more massive progenitors ($M \geq 60\ M_{\odot}$) evolve directly toward WR stars. The lower mass stars ($20\ M_{\odot} \leq M \leq 60\ M_{\odot}$) evolve first to red supergiants (RSG) and then, losing their envelopes, become WR stars. Maeder, Lequeux, & Azzopardi (1980) (hereafter MLA), and Maeder (1981a,b) have shown that the lifetime of each of these evolutionary phases depends on the initial metallicity: stars with higher metallicity have higher mass loss rate and therefore, they evolve faster to the WR phase. Therefore, in the regions where the metallicity Z is higher, the relative number of WR stars (N_{WR}) with respect to the number of RSG (N_{RSG}) – N_{WR}/N_{RSG} will be larger than in the regions with smaller Z. The observed gradient of N_{WR}/N_{RSG} in the solar neighbourhood is used as an argument in favour of this conclusion. MLA explained this gradient as a consequence of a similar gradient of the chemical composition in this region and as a confirmation of their theory.

This result was reexamined by Bertelli & Chiosi (1982). They argued that MLA's conclusions had been influenced by selection effects due to the specific choice of the region. They argued that the observed gradient could be simply explained by a similar gradient in the WR progenitors, concluding that, although the effects of metallicity cannot be excluded, their influence is insignificant. On the other hand, Humphreys et al. (1985) (hereafter HNM) have determined the masses of WR progenitors; these authors estimated that the lower limit of the initial masses is $\geq 20\ M_{\odot}$. Based on this limit, they concluded that only the brightest M type supergiants ($M_b = -9.0^m$ to -9.5^m) had enough mass to become WR stars. Therefore, the results of MLA are sensitive to the choice of the lower limit of the luminosity of RSG also. Repeating the calculation of Maeder et al. (1980), but with the new sample of RSG, Humphreys et al. (1985) found little or no evidence for a gradient of N_{WR}/N_{RSG} with galactocentric distance.

As a result, there are two open questions: (1) Does the spatial distribution of the WR stars simply follow the distribution of their possible progenitors? (2) Is

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there any influence of the metallicity on the number of WR stars and RSG?

In order to answer these questions we have to compare the spatial distributions of classes of objects of different numbers of members. In this paper we suggest a method which permits this comparison. The method is almost independent of the choice of regions and is less sensitive to the incompleteness of the samples. We applied it to the M33 galaxy, because good data for blue and red supergiants for that galaxy are available and because it has a large number of WR stars.

2. OBSERVATIONAL DATA

We have collected data from the literature for WR stars. Conti & Massey (1983) have published coordinates for 79 stars. We added to them the data from Massey et al. (1987) and Armandroff & Massey (1985). The stars from these sources with coincident coordinates (3" error box) and with the same spectral index are excluded. As a result, we have a list of 133 WR stars. The stars discovered by Drissen, Moffat, & Shara (1993) are only in 3 H II regions and do not influence the global distribution of the WR stars (see below). The new stars from Johnson & Massey (1995) are not included due to the absence of published coördinates. Johnson & Massey (1995) showed that the incompleteness of the photographic data, used here, is no more than 50%. Later on, we will discuss its influence of that incompleteness on our results.

The data for red and blue supergiants are taken from the catalogue of Ivanov, Freedman, & Madore (1993). We have accepted as blue supergiants the stars with $U - V < -0.3^m$. In order to minimize the effects of background dwarfs, only the stars with $B - V > 1.9^m$ were included as RSG (Humphreys et al. 1985). This catalog is complete up to 19.5^m (Ivanov et al. 1993). If we assume an apparent distance modulus of $\cong 25.0^m$ to M33 (Wilson, Freedman, & Madore 1990), then the blue supergiants in our data are more luminous than -5.5^m. These are stars with masses not less than 30 $M_\odot$ (Massey 1985) and following HNM, these are the progenitors of Wolf-Rayet stars. Having that in mind, we could assume that the sample of BSG is less influenced by the selection effects than the sample of RSG.

3. RADIAL DISTRIBUTION

The ratio $P(r)$ is defined as

$$P(r) = N(r)/N_{tot} \quad , \tag{1}$$

where $N(r)$ is the number of objects of a given class with galactocentric distance less than r, and N_{tot} is the number of class members. Hence, $P(r)$ is the probability of finding a member of a class in a circle of radius r. This is a smooth function, monotonically increasing from 0.0 for $r = 0.0$ to 1.0 for r equal to the radius of the galaxy and it is a characteristic of a given class of objects. We will call $P(r)$ the *distribution* of the class. Note the difference between $P(r)$ and the statistical meaning of a distribution. Obviously, $P(r)$ can be determined from the observed sample, by dividing the galaxy into concentric circles with increasing radii and counting the objects inside the circle with current radius. But, since it is a characteristic of the class itself, its shape does not depend on the particular set of radii selected. Any given set gives an approximation of the same function. For example, suppose that an association exists in some region, and let us have a set of radii so that all members of the association are included between the radii r_i and r_o ($r_i < r_o$). In that case, the surface density (SD) of the OB stars would have a peak. Let us add a new radius r_a; $r_i < r_a < r_o$. It divides the association, and the surface density peak would be smaller or it may even disappear. The behaviour of P is different. For the first mesh, we would calculate $P(r_i)$ and $P(r_o)$, where $P(r_i) < P(r_o)$. Adding a new point r_a, we obtain another value $P(r_a)$ which is between $P(r_i)$ and $P(r_o)$ ($P(r_i) < P(r_a) < P(r_o)$). This would make the transition from $P(r_i)$ to $P(r_o)$ smoother, but the shape of P would remain the same. *Therefore, using $P(r)$ instead of the surface density we avoid the problems mentioned by Bertelli & Chiosi (1982).*

The incompleteness of the samples also has much smaller effects on P than on the surface density. For example, if 10 new objects are discovered in a region, where before only one was known, this would increase by a factor of 10 the SD. Suppose that the sample contained 100 objects before the discovery, and 50 of them were inside the radius r_1 including the region with the new objects, then $P(r_1) = 0.5$. After the discovery, the number of objects inside r_1 would be 60, but $N_{tot} = 110$ and $P(r_1) = 0.55$, which is only 9% difference from the previous one. The figures are even better, if the discovery is made not only in a single region (association) but along all radii. In that case the shape of $P(r)$ would not change. We can conclude that even though the sample is incomplete, if the number of objects is sufficient to represent the general shape of $P(r)$, the results based on that representation should be valid for the future improvement of the samples.

4. DISCUSSION

Now, we are ready to test the hypothesis that the distribution of WR stars is the same as that of their progenitors. The *distributions* of WR stars and BSG are shown on Figure 1. The Kolmogorov-Smirnov two-samples test *rejects* the null hypothesis that the two distributions are identical at the 98 per cent level of significance. Therefore, we cannot conclude that

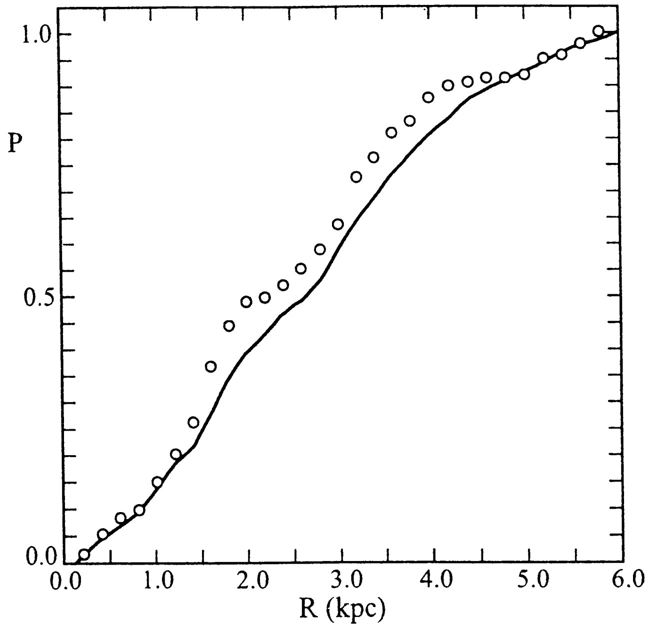

Fig. 1. Distributions of the blue supergiants (solid line) and WR stars (marked by circles) as functions of galactocentric distance R.

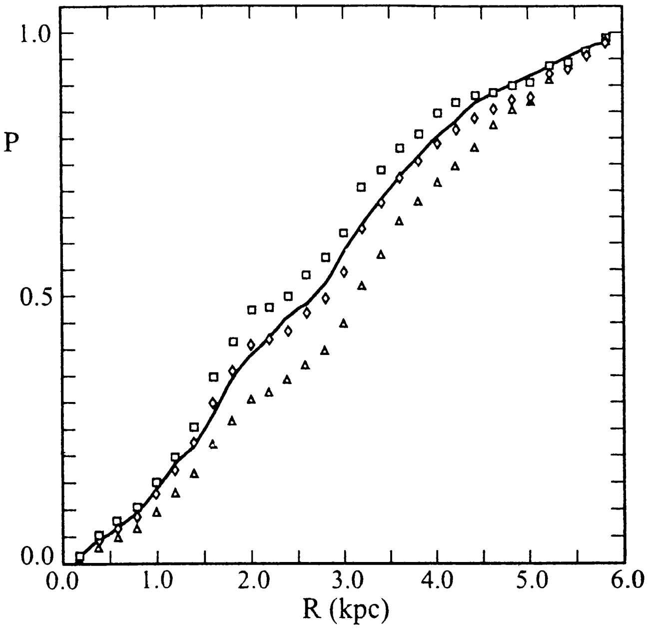

Fig. 2. Comparison between distribution of blue supergiants (solid line) and distribution of (WR + RSG), for RSG brighter than: 18.0^m - squares; 18.5^m - diamants; 19.0^m - triangles, respectively.

the galactic distribution of WR stars simply follows the distribution of blue supergiants.

The obvious question is: if in the future there are more and more discoveries of WR stars, even the effect on the $P(r)$ is small, at the end we could obtain the same distribution of WR stars as that of the BSG, hence the above conclusion would be wrong. In order to answer it, let us see what is the behaviour of P_{WR}. One can see on Fig. 1 that the distribution of WR stars is above the distribution of BSG. To lower it, any new objects must be added on the outer part of the galaxy, but not close to the core. But, first, the number of WR stars are less on the outer regions of the galaxy, and second these regions are less crowded. Therefore, it is more probable that any new WR stars will be discovered in the inner regions, and P_{WR} would be raised even further away from P_{BSG} which would make the conclusion even stronger.

Let us assume an initial distribution of the stars with masses higher than 30 $M_{\odot}$. As it was mentioned above, the most massive of them would evolve to WR stars, whereas the less massive should spend some part of their lives as RSG. If we were able to get samples of the descendants of those stars at different epochs, first we would see the appearance of the RSG in all regions of the galaxy. Then, in the metal rich regions, some of the RSG would evolve to WR and eventually disappear. But in a less metal rich region, even the mass of the progenitors is high enough to evolve to WR phase, they will be still in a RSG stage, due to the longer lifetime in of RSG in that conditions. *Therefore, any sample of progenitors, would have to be compared with the sample of all their descendants.* So, the distribution of the BSG should be compared with the distribution of the combined class of WR and RSG stars. If the assumption is correct, then we can obtain the sample of RSG, which have the same progenitors as the WR stars and therefore, they will evolve to WR phase. This is actually the sample of RSG needed to check the existing of a gradient in N_{WR}/N_{RSG}.

Since the number of WR stars is fixed, and we have more or less a good criteria to select the BSG, then the only uncertain value is the brightness of the RSG with the corresponding mass. We constructed a combined class of the descendants, including all WR stars, and RSG with $V \leq V_{lim}$. Increasing V_{lim}, we include less massive red stars. The value of V_{lim} at which the distribution of the classes of the progenitors and of the descendants coincide (in the context of the χ^2 test), is the limiting brightness for the RSG. The brighter stars can evolve to WR stars whereas the less bright stars cannot. On Figure 2, we show the distribution of WR+RSG for $V_{lim} = 18.0, 18.5, 19.0$. The best fit is obtained for $V_{lim} = 18.5^m$. Thus we can conclude that the RSG stars in M33 that are brighter than 18.5^m evolve to WR stars.

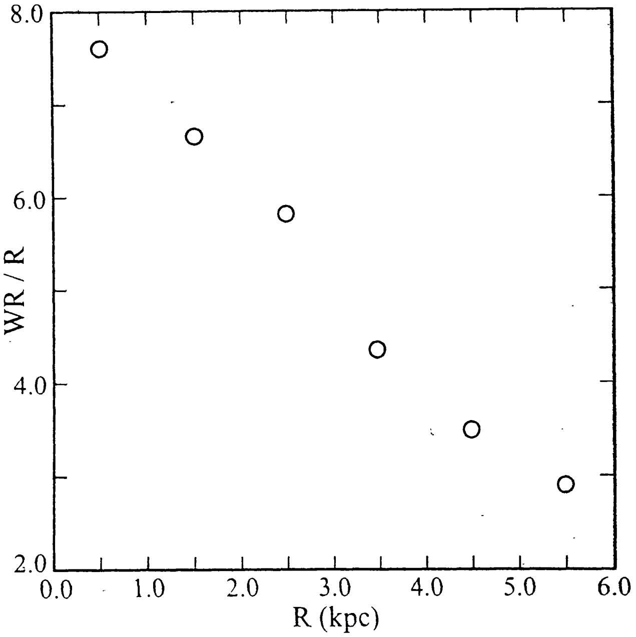

Fig. 3. Gradient of the relative number of WR stars and red supergiants (WR/RSG) as function of galactocentric distance R.

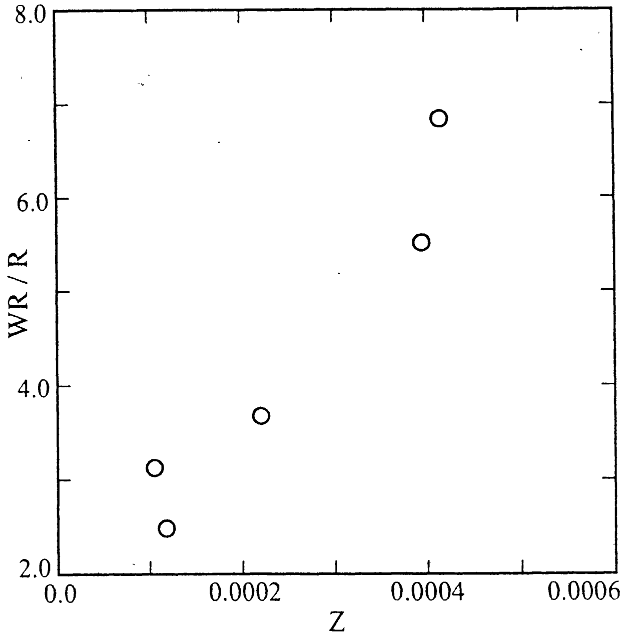

Fig. 4. Correlation between WR stars to red supergiants ratio (WR/R) and abundance of CNO (Z).

Having this new sample of RSG, we can test the next question: how large is the influence of the chemical composition on the lifetime of the stars? Figure 3 shows clearly a gradient of N_{WR}/N_{RSG} with the galoctocentric distance. We check the dependence of N_{WR}/N_{RSG} on the abundance of heavy elements with the aid of the data of Kwitter & Aller (1981). We separate the galaxy into 5 regions. The abundances of C, N, and O in each region is added and their sum, Z, is plotted against N_{WR}/N_{RSG} (Figure 4). The correlation between N_{WR}/N_{RSG} and Z is obvious.

As a result, we conclude that the Maeder et al. (1980) predictions for the influence of metallicity over the star's lifetime are confirmed by observations. It is worth noting that M33 is a bit peculiar. The gradient of the chemical composition in that galaxy is better defined than in all other galaxies (Henry & Howard 1995; Vila-Costa & Edmunds 1992) and the average over the circles with the same galactocentric distances, but including different regions, is correct. In other cases, one should take the local inhomogenities into account and to plot the local values of the ratio N_{WR}/N_{RSG}. Due to the small number of objects would be much more noisy and will not give the same definite result.

Our main assumption was that the present day distributions of the progenitors and descendants are the same. This means that the IMF and the star formation rate (averaged in the circles) are the same over the galaxy and are constant in time. Massey et al. (1987) demonstrated that IMF is the same for different parts of the Milky Way and it is the same as in the Magellanic Clouds, which supports our assumption.

Finally we should mention that the number of RSG, predicted by the evolutionary models, is very sensitive to the assumed mixing mechanism, but the number of WR stars are not (Langer & Maeder 1995). Our method allows to get a sample of RSG corresponding to the given interval of BSG masses, and therefore, to obtain less biased calculation of B/R. The other question is: what is the origin of the chemical gradient? It is not clear if the chemical composition produces the differences in the stellar population, or whether the evolution of the stars with pronounced galactocentric gradients create the present day gradient of the composition (Henry & Howard 1995). The combination of a better RSG sampling with population synthesis could give a clue for the origin —the stellar population or the chemical gradient.

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