Evolutionary Links Between Ofpe/WN9 Stars and Other Massive Stars in Clusters

N. St-Louis, A.F.J. Moffat, L. Turbide, and J.-F. Bertrand

Département de Physique, Université de Montréal and Observatoire du Mont Mégantic, C.P. 6128, Succ. Centre Ville, Montréal (Québec), H3C 3J7, Canada

Abstract. We present photometric and spectroscopic observations of hot, massive stars in five LMC clusters each containing an Ofpe/WN9 star. We find that two out of the five Ofpe/WN9 stars we have studied are located in clusters populated mainly by early B stars. For another cluster there appears to be an age gradient accross the field we have observed with the Ofpe/WN9 star located near late-type O and early-type B stars. However, that cluster is not very populated and therefore we are dealing with small number statistics. This result seems to indicate that some Ofpe/WN9 stars are quite old and come from relatively low-mass O stars. The other two cases are ambiguous, as the clusters seem to consist of a mixture of mid-early O-type dwarf stars together with more evolved late-type O and early-type B stars. The confusion might arise because of errors in the luminosity classes which are sometimes difficult to assign, or because there are two distinct populations in the line of sight. The possibility remains that some Ofpe/WN9 stars might be associated with groups of early-type O stars and that in consequence they are younger with very massive progenitors.

1. Introduction

Although it is clear that most O stars at solar metallicities evolve to become Wolf-Rayet (WR) stars, the detailed manner in which they do so is still not perfectly well understood. Therefore, finding transition objects between these two phases of massive-star evolution could provide new clues to help us understand this process. Walborn (1977) discovered a class of hot stars which display spectral caracteristics of both O stars with emission lines and late-type WR stars, which he appropriately named Ofpe/WN9 stars. Later, Stahl et al. (1983) found that the LMC Ofpe/WN9 star R127 (HDE 269858, BE397, S128) underwent an S Doradus-type eruption, thereby establishing a link between Ofpe/WN9 stars and Luminous Blue Variables (LBVs). Bohannan & Walborn (1989) suggested that all Ofpe/WN9 stars are in fact *quiescent* LBVs. On the other hand, one of the stars in the SMC O+WN binary HD 5980 *erupted* in 1994 to Ofpe/WN9=WN11 (Barba et al. 1995)! More recently, Crowther et al. (1995) and Crowther & Smith (1997) reclassified all Ofpe/WN9 stars to

WN9–WN11, therefore suggesting that these objects constitute an extension of the WNL sequence to lower excitations.

In order to gain more insight into the evolutionary status of Ofpe/WN9 (WN9–WN11) stars, we have obtained photometry and spectroscopy of the most luminous stars in 5 LMC clusters containing such an object. These clusters were first studied with photographic techniques by Westerlund (1961). Assuming all the stars are coeval, such an analysis should give an estimate of their age and initial mass. Note that for an environment with a metallicity of one third solar, the initial mass of single stars that produce WR stars are expected to be higher in the LMC than in the solar neighbourhood. (e.g., Maeder & Conti 1994). We have already published some results for part of our dataset (St-Louis et al. 1997). In this paper, we present preliminary results of the analysis of the complete dataset.

2. Observations

We have secured B and V photometry of 5 LMC clusters containing Ofpe/WN9 stars by using the 1.54-m Dutch telescope of the European Southern Observatory (ESO) in Chile in January 1993. We also have UBV photometry of two of our clusters, which was kindly provided by Phil Massey, who used the CTIO 0.9-m telescope on Cerro Tololo, Chile in October 1996.

We have also obtained spectroscopy of the brightest members of the 5 clusters during two different observing runs. The first was in January 1993 using the 1.5-m ESO telescope in Chile and the second was in October 1996 using the Victor Blanco 4-m telescope on Cerro Tololo in Chile with the ARGUS multi-fibre spectrograph. The dispersions were 2.8 Å/pixel and 1.0 Å/pixel respectively.

For all these observations we have applied the standard data reduction procedures using the DAOPHOT and IRAF software packages, respectively, for the photometric and spectroscopic observations.

3. Results

In Figures 1 to 5 we present B-band images of the 5 clusters we have studied. We indicate the position of the Ofpe/WN9 star as well as the spectral types and luminosity classes of the stars for which we have obtained spectra. The errors on the classifications are of the order of half a spectral sub-class and one or two luminosity sub-classes. Below we discuss each cluster in turn.

3.1. NGC 2074: HDE 269927

NGC 2074 is the tightest of the 5 clusters we have studied and includes the Ofpe/WN9 star HDE 269927 (see Fig. 1). We do not have three-colour photometry for this cluster so we cannot plot a dereddened colour-magnitude diagram, but we have presented our uncorrected V versus $(B-V)$ diagram for a region of approximately $3'$ in diameter centred on the cluster, in St-Louis et al. (1997). The sequence delineated by the stars is slightly broad. This can either be caused by differential reddening in a coeval group or/and to a mixture or superposition in the line of sight of two different populations of stars. The latter interpretation

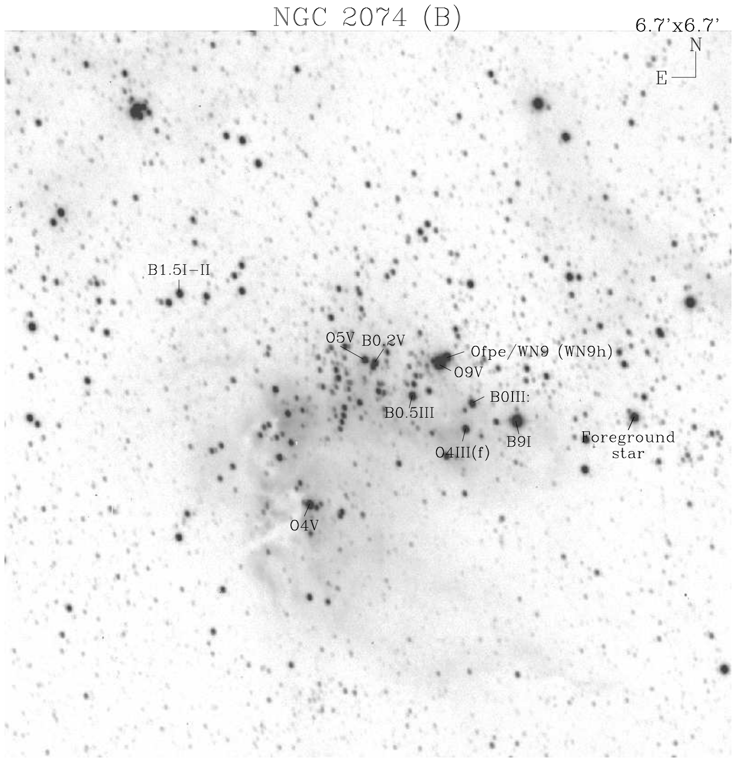

Figure 1. *B*-band image of NGC 2074. The estimated spectral types and luminosity classes of individual stars are indicated (in brackets we have added the new spectral types of Crowther et al. 1995 and Crowther & Smith 1997). The intensity scale is logarithmic.

seems to be supported by the spectral types of the stars we have observed. It is indeed strange for a coeval group to be populated by B0 III, B0.5 III, B9 I, and B1.5 I–II stars, together with O4 III(f), O4 V, and O5 V stars. If there are two distinct populations in this cluster, one young (the early O stars) and the other much older (the evolved B stars), it is not clear with which the Ofpe/WN9 star is associated. It is possible that the star is quite young (3–4 Myr) with a very massive progenitor ($60 M_{\odot}$) but equally possible that it is more similar to its immediate neighbour (an O9 V star) and that it is older with a much less massive progenitor.

3.2. Region D: BE381

As can be seen from Fig. 2, Region D is an elongated association (oriented in the northeast-southwest direction) containing a large number of luminous stars. In order to increase the chances of finding a coeval group associated with the Ofpe/WN9 star, we have concentrated mainly on a sub-region of approximately $3'$ in diameter close to the Ofpe/WN9 star. The membership of two early-type

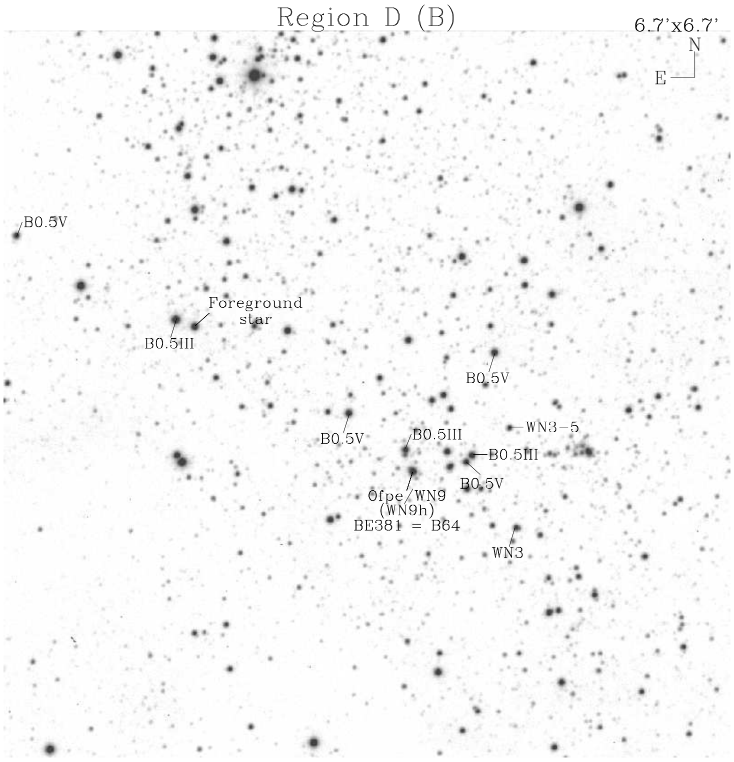

Figure 2. *B*-band image of Region D; details as in Fig. 1.

WN stars (Br 60 and Br 61) was already known from previous studies and their position is indicated on Fig. 2. As for NGC 2074, we only have photometry in two filters (B and V) for this sub-cluster of the association. The uncorrected colour–magnitude diagram is presented in St-Louis et al. (1997). Once again, we find a broadened sequence, but the uniformity of spectral types suggests that these stars were born at the same time: all seven associated stars (the brightest) we have observed are of spectral type B0.5. This seems to indicate that the southern part of Region D has an age of 6–10 Myr and that the progenitor of BE381 had a relatively small initial mass (20–25$M_{\odot}$).

3.3. NGC 1983: HDE 269582

HDE 269582=BE294 is an Ofpe/WN9 star which was shown to be an S-Doradus variable by Stahl (1986). It is located about $1'$ east of a very tight group of stars on which we have concentrated our study (see Fig. 3). There is also another tight group located about $4'$ to the east. In this case we do have three-colour photometry and therefore we can plot a dereddened colour–magnitude diagram which we present in Fig. 6. In constructing this diagram we have restricted ourselves to a region of about $2'$ in diameter centred on the Ofpe/WN9 star. It can readily be seen that the sequence delineated by the relatively large number

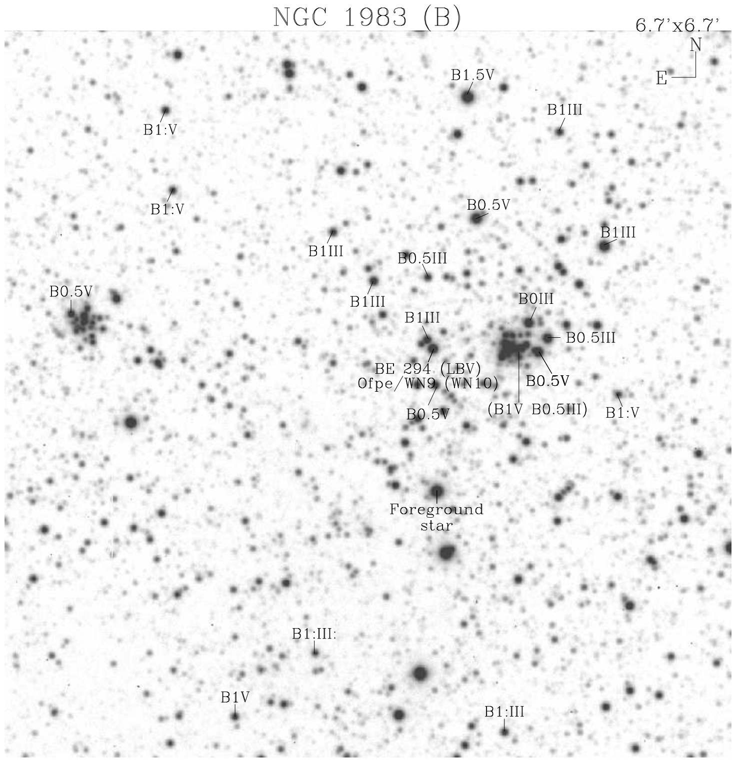

Figure 3. *B*-band image of NGC 1983; details as in Fig. 1. The object indicated '(B1V B0.5III)' refers to means from integrated light at two adjacent east-west positions in the dense cluster core.

of stars for which we have spectra is quite narrow, indicating clearly a coeval group (compare with the uncorrected diagram in St-Louis et al. 1997). Just as for Region D, we find that the spectral distribution of stars in NGC 1983 is extremely uniform. The 21 brightest stars in Fig. 3 are all of early B0.5 or B1 spectral type. These results seem to suggest that once again the cluster has an age of 6–10 Myr and that the progenitor initial mass of BE294 is rather low (20–25$M_{\odot}$).

3.4. IC2128: HDE 269445

This cluster is relatively loose and less populated than the three discussed above (see Fig. 4). The Ofpe/WN9 star HDE 269445=R99 is also quite isolated, with no immediate bright neighbours. In St-Louis et al. (1997) we present the uncorrected colour–magnitude diagram for a region of about 3$'$ in diameter with R99 sitting near its north-eastern boundary. Because of the smaller number of stars, the sequence is not so well delineated but can still be distinguished. Of the ten stars we have observed that are not foreground objects, two are early-type O supergiants, one is an O6.5 V star, two are late-type O V stars, and five are

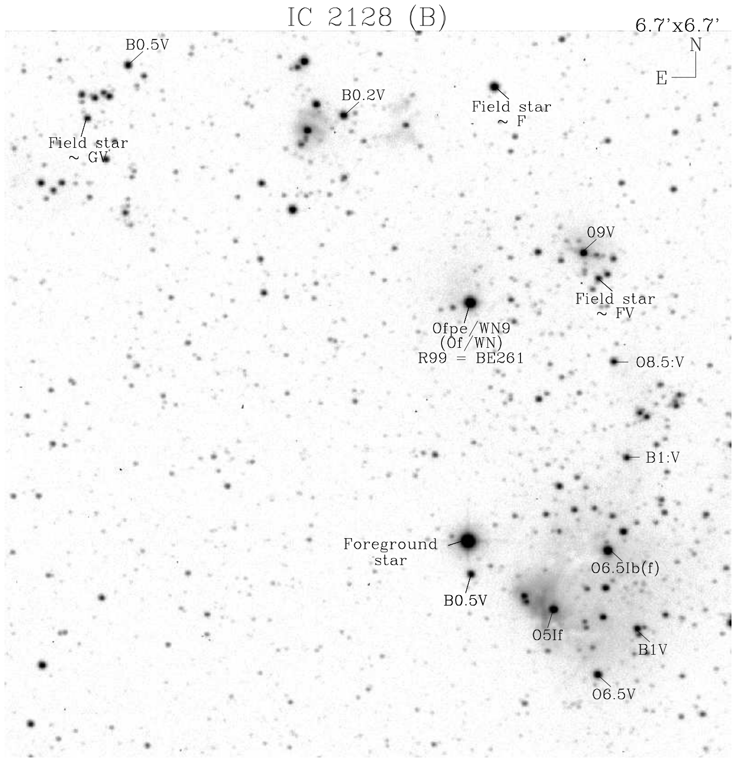

Figure 4. B-band image of IC2128; details as in Fig. 1.

early B stars. The early–mid O stars are concentrated in the southwestern corner while the late-type O stars are located closer to the Ofpe/WN9 star in the centre of the field. Although based on small number statistics, we are tempted to conclude that there is an age gradient from the northeast to the southwest. More observations are needed to confirm this but if it is real, we can conclude that the age of HDE 269445 would be no less than that of an O8 star (4–6 Myr) and that its progenitor would have been of $\sim$25–30$M_\odot$.

3.5. NGC 2055: HDE 269858

NGC 2055, the cluster containing R127, is shown in Fig. 5. Walborn et al. (1991) have presented spectra for 4 stars in this region for which they claim that only two are likely to be generically linked to R127 (the O7 Iaf and the ON9 Ib stars). The others (the B2 Ia and the BN0.5 Ib stars) have a lower $E(B-V)$. We have observed a few more stars located futher away from R127 and find three late-type O and two early-type B dwarfs plus one O6.5 III(f) star. There are two possible interpretations for these observations. We can assume, as Walborn et al. (1991) did, that the B2 Ia and the BN0.5 Ib stars are not associated with the Ofpe/WN9 star and conclude, based on the presence of the O7 Iaf and the ON9Ib stars, that the cluster is young (2–3 Myr) and that the progenitor is

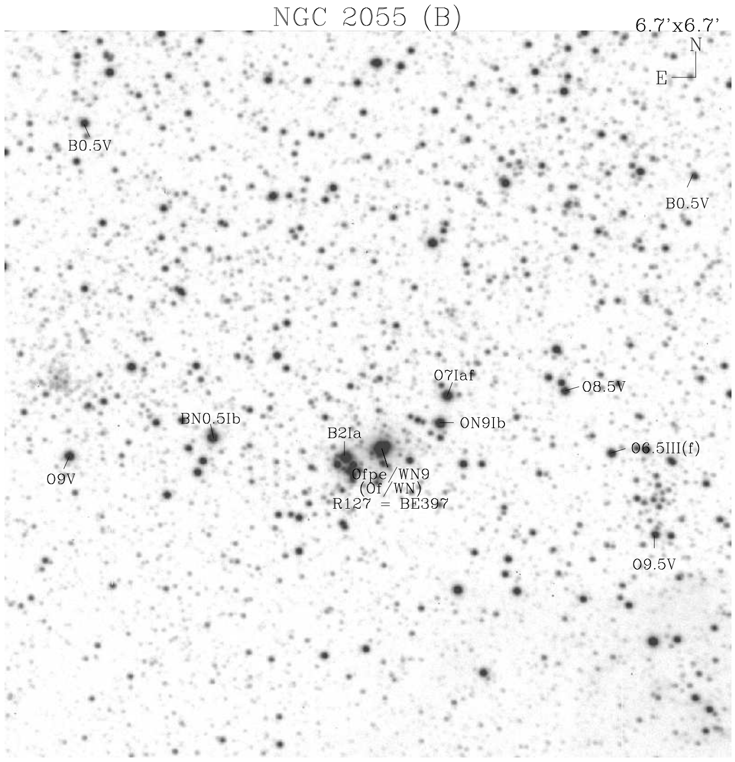

Figure 5. B-band image of NGC 2055. Details as in Fig. 1.

massive ($> 60M_\odot$). Alternatively, we can assume that the difference in $E(B-V)$ is due to differential redening within the cluster. In this case, we would have a mixture of two populations namely evolved O supergiants suggesting a very young cluster, and B supergiants suggesting an older cluster. In this case, it is not clear which population the Ofpe/WN9 star would be associated with. More spectroscopy would help to disentangle this cluster, since there are still several bright stars for which we lack spectral types. The dereddened colour–magnitude diagram shown in Fig. 6 seems to give some support to the first interpretation since the sequence delineated by the stars in a very small region centred on R127 is very narrow, strongly suggesting that it consists of only one coeval population (admittedly this can only be correct if cases of anomalous $E(B-V)$ as for the B2 Ia and the BN0.5 Ib stars are few).

4. Summary and Conclusions

We have observed five LMC clusters photometrically and spectroscopically in order to try to shed more light on the evolutionary status of Ofpe/WN9 (WN9–11) stars which are thought to be transition objects between massive O and WR

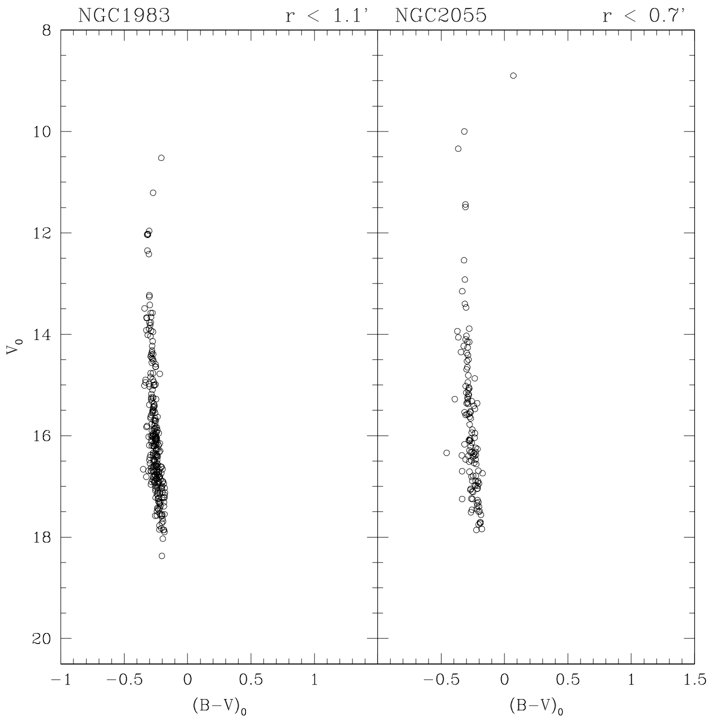

Figure 6. Dereddened colour–magnitude diagrams for NGC 1983 and NGC 2055.

stars. In three cases we conclude that the Ofpe/WN9 star is associated with a rather old environment and that consequently its progenitor mass must have been quite low ($\sim$20–25$M_{\odot}$). The best example is BE294 in NGC 1983, which seems to be a rather old cluster. Indeed, we have obtained spectra for 21 of the brightest stars in this cluster and find that they are all of spectral type B0.5 to B1, indicating an age of $\sim$6–10 Myr and therefore a low mass for the progenitor O star. For NGC 2074 and NGC 2055 the situation is more ambiguous. In both cases we seem to have a mixture of two distinct populations either superimposed on the line of sight or two bursts of star formation arising at different times. It is therefore impossible with the data in hand to conclude in these two cases if the Ofpe/WN9 star is associated with the young or old population. In one case we obtain the surprising result that all Ofpe/WN9 stars we have studied are rather old objects with low progenitor mass while in the other case we obtain the equally surprising result that Ofpe/WN9 stars can be found in very different environments (young or old) which suggests that perhaps there is not a unique path by which to reach the Ofpe/WNE evolutionary stage.

Acknowledgments. We thank Phil Massey for generously supplying us with *UBV* photometry of NGC 1983 and NGC 2055.

References

Barba, R. H., Niemela, V. S., Baume, G., Vasquez, R. A., 1995, ApJ, 446, L23

Bohannan, B., Walborn, N. R., 1989, PASP, 101, 520

Crowther, P. A., Hillier, D. J., Smith, L. J., 1995, A&A, 293, 172

Crowther, P. A., Smith, L. J., 1997, A&A, 320, 500

Maeder, A., Conti, P. S., 1994, ARA&A, 32, 227

Stahl, O., Wolf, B., Klare, G., Cassatella, A., Krautter, J., Persi, P., Ferrari-Toniolo, M., 1983, A&A, 127, 49

Stahl, O., 1986, A&A, 164, 321 (erratum, A&A, 170, 197)

St-Louis, N., Turbide, L., Moffat, A. F. J., 1997, in Luminous Blue Variables: Massive Stars in Transition (ASP Conf. Series, Vol. 120) eds. A. Nota & H. J. G. L. M. Lamers (ASP, San Francisco), p. 187

Walborn, N. R., 1977, ApJ, 215, 53

Walborn, N. R., Evans, I. E., Fitzpatrick, E. L., Phillips, M. M., 1991, in Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies (IAU Symp. 143), eds. K. A. van der Hucht & B. Hidayat (Kluwer, Dordrecht), p. 505

Westerlund, B., 1961, Uppsala Astron. Obs. Ann., 5, No. 1

Discussion

Walborn: R127, or HDE 269858, is two stars. The Radcliffe people called the LBV 'HDE 269858f', for 'following'; when they observed, it was of comparable brightness to the preceding star, but the LBV now dominates.

Was one of your stars HDE 269227? R84?

St-Louis: Ah... possibly... all these numbers... [laughter].

Walborn: That one was studied by Schild some years ago, and he found it also to be in a cluster with B stars.

Crowther: In Kona you mentioned initial masses of these things [St-Louis et al. 1997], and now you're not...?

St-Louis: Well, I did say *rough* initial masses. So for the clusters with O4 stars, probably the initial mass is higher, but for these B-star clusters you can't have $80 M_{\odot}$ progenitors or anything like that.

Walborn: Bruce [Bohannan] and I, and also others, subdivided these slash stars, and it would be interesting to see if there was any sort of correlation between the different types of cluster and these subdivisions.

Conti: The Magellanic Clouds are good for spotting stars very easily, but, because they're all at the same distance, when you say there's a cluster there what you're really saying is that there are a number of stars at the same magnitude; but that doesn't really mean they were born at the same time. In some cases it's pretty clear there's a real cluster, in the sense that there's a clumping of stars, but in other cases, if you were pressed to the wall, and asked do you *really* believe there's a cluster there, well, I might be a little dubious about some of those.

St-Louis: In some cases, yes. We do have radial velocities for these things, but I'm not sure that with the accuracy we have we'll be able to do anything useful with the dynamics. In the last two cases I showed we do have a really nice, narrow sequence, however; that's true even for R127, which has very sparse distribution of stars. But I agree, that's always a problem: do we have a cluster or not?

Nota: Did you take any spectra in the region around S119? With our high-resolution spectra we found it has a very peculiar velocity, and seems to be located in the LMC foreground; so it would be interesting to see the velocities of nearby objects.

St-Louis: Well, apart from a few obvious foreground stars, all our objects are at the LMC distance, but I haven't done the analysis yet to answer your question.

Conti: I noticed there were two WN3 stars associated with B-star clusters.

St-Louis: Yes, that's strange. We have a lot of spectra in that region, so I think we'd know if there were very massive (O-type) stars there too.