Hawkins '*O*' magnitudes were calculated from his *B* and *V* values using the colour relation $O = B + 0.26\ (B - V) - 0.08$ of Hayman *et al.* The PSS magnitudes have been corrected (by ~ 0.2 mag) for differential extinction, due to the different declinations of the Plaut and Hawkins sequences, and for vignetting in the Palomar Schmidt camera.

c) PSS *E* magnitudes with spectrophotometric continuum magnitudes at 6500 Å (m_{6500}) obtained with the Anglo-Australian Telescope (AAT) for 45 stars which were, prior to spectroscopy, considered to be possible QSO identifications (White, Murdoch & Hunstead 1980).

d) PSS *E* magnitudes with magnitudes (m_{6500}) similarly obtained for 49 QSOs. One QSO, 2002-185 (labelled *v* on Fig. 2) has been reported variable (Peterson, Bolton & Shimmins (1973)) and has been omitted from this comparison.

For many purposes it is also desirable to have *V* magnitude estimates. These cannot be obtained directly from the PSS but an equivalent 'PSS *V*' magnitude may be defined as 'PSS $V' \approx (0.6m_O + m_E)/1.6$, which is based on the colour equation of Minkowski and Abell.

A further comparison has been made as follows: —

e) 'PSS *V*' magnitudes with spectroscopic continuum magnitudes at 5500 Å (m_{5500}), again obtained with the AAT, for 11 of the 14 QSOs identified from the Molonglo Deep Survey (White *et al.* 1980).

Conclusions

In the above comparisons, there is excellent agreement between the PSS and other magnitudes, with a standard deviation of ~ 0.4 mag. Any significant improvement in accuracy would require calibration of individual prints because of the 0.35 mag rms variations in plate-to-plate sensitivity of the PSS.

This work is supported by the Australian Research Grants Committee and the Science Foundation for Physics within the University of Sydney. The Author acknowledges the receipt of an Australian Commonwealth Postgraduate Research Award.

Hawkins, M. R. S., *Mon. Not. R. Astron. Soc.*, **188**, 691 (1979).
Hayman, P. G., Hazard, C., and Sanitt, N., *Mon. Not. R. Astron. Soc.*, **189**, 853 (1979).
Hazard, C., and Murdoch, H. S., *Aust. J. Phys. Astrophys. Suppl. 1*, No. 42 (1977).
Minkowski, R. L., and Abell, G. O. in *Basic Astronomical Data*, p. 481, (ed. K. Aa. Strand, Chicago University Press) (1963).
Pěkný, Zd., *Bull. Astron. Inst. Czech.*, **9**, 164 (1958).
Perek, L., *Bull. Astron. Inst. Czech.*, **9**, 39 (1958).
Peterson, B. A., Bolton, J. G., and Shimmins, A. J., *Astrophys. Lett.*, **15**, 109 (1973).
Plaut, L., *Bull. Astron. Inst. Neth.*, Suppl. 1, 105 (1966).
White, G. L., *Mon Not. R. Astron. Soc.* (1980) (in press).
White, G. L., Murdoch, H. S., and Hunstead, R. W., *Mon. Not. R. Astron. Soc.* (1980) (in press).

Infrared Studies of the Young Stellar Population of 30 Doradus

P. J. McGregor and A. R. Hyland, *Mount Stromlo and Siding Spring Observatories, Australian National University*

Introduction

The 30 Doradus region offers an excellent opportunity to study cluster formation processes and recent star formation in the Large Magellanic Cloud. The 2 μm survey of Hyland, Thomas and Robinson (1978) demonstrated that at least two star formation events have occurred in the 30 Doradus region in the last ~ 10^7 yrs. JHK infrared photometry has been obtained for 33 stars in the 2 μm survey region using the AAT and will be presented in detail elsewhere. This data, in comparison with other Magellanic Cloud infrared photometry, is used here to study these young stellar populations.

The M_{BOL} vs log T_e diagram for 24 of the stars is shown in Fig. 1. Eighteen of these stars were detected in the 2μm survey. Nebular extinction contours from Mills, Turtle and Watkinson (1978) have been used to deredden the observed photometry. For the red stars, bolometric corrections and effective temperatures were derived from the $(J\text{-}K)_o$ colours. For the blue stars this data was obtained from published spectral types. A large luminosity difference between the blue Wolf-Rayet stars and the red M supergiants is clearly seen in Fig. 1. If the Wolf-Rayet stars are single objects they lie in the region of 100 $M_\odot$ stars, implying ages of $\lesssim 3 \times 10^6$ yrs. If they are binary systems interaction between the components may cause this estimate to be increased slightly. The M supergiants, having lower luminosities and being at an advanced stage of evolution, clearly belong to an older population. If the evolutionary status of these M supergiants can be determined with some certainty a good estimate can be made of their mass and hence of the age of the population to which they belong.

Evolution in the Red Supergiant Region

Two possibilities exist for the evolutionary status of the M supergiants. Firstly, they may be high mass stars ($M/M_\odot \gtrsim 10$) in the red supergiant region for the first time and having non-degenerate carbon-burning cores (Lamb, Iben and Howard 1976; LIH). Alternatively, they may be intermediate mass stars ($3 \lesssim M/M_\odot \lesssim 9$) possessing electron degenerate carbon-oxygen cores with both outer hydrogen-burning and inner helium-burning shells. Such double shell sources evolve to exceptionally high luminosities for their mass, before carbon detonation in the degenerate core totally disrupts the star, most probably resulting in a type II supernova.

The evolution tracks of all stars in the intermediate mass range merge on the second giant branch with the luminosity being related to the core mass simply by

$$L/L_\odot = 59250\, M_c/M_\odot - 30950$$

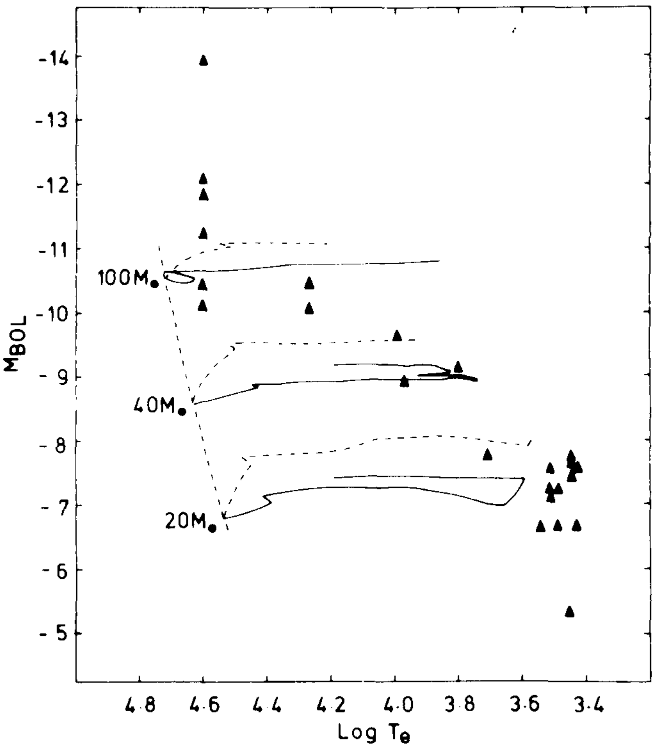

Figure 1. M_{BOL} vs log T_e diagram for stars in the central 12 arcmins of the 30 Doradus region. The Wolf-Rayet stars have an assumed log T_e = 4.6. The completeness limit of $K \sim 9.75$ mag for the 2 μm survey sets the lower limit to the observed points. Evolutionary tracks with (solid lines) and without (dashed lines) mass loss are shown (Chiosi *et al.* 1978). The central object of the 30 Doradus cluster (R136) is plotted at $M_{BOL} = -14$.

(Paczynski 1970). Evolution proceeds in equal luminosity increments in equal times, resulting in an evenly populated, narrow giant branch (Wood 1974). The sudden onset of carbon detonation when the core mass reaches the Chandrasekhar limit ($\sim$ 1.4 $M_\odot$) results in a sharp cut-off at the top of the giant branch. The theoretical cut-off luminosity, from the Paczynski relation using a core mass of 1.4 $M_\odot$, is $M_{BOL} = -7.0$ mag.

If the Doradus M supergiants are high mass objects they have masses of $\sim$15 $M_\odot$, and corresponding ages of $\sim 1.2 \times 10^7$ yrs (LIH). The ratio of blue to yellow to red supergiants of this mass is 15.9:1.0:1.6 (LIH). The eleven M supergiants should therefore be accompanied by $\sim$110 15 $M_\odot$ blue supergiants with $M_{BOL} \sim -7$ and log $T_e \gtrsim 4.0$ (11.5 $\lesssim$ V $\lesssim$ 13.5, B-V $\lesssim$ 0.0). Inspection of visual photographs shows that this number of bright stars does not exist in the region. The result is further strengthened when allowance is made for the expected number of luminous blue stars associated with the Wolf-Rayet star population. We therefore conclude that the M supergiants are intermediate mass stars. Due to the small range in luminosity over which the giant branch has been observed, the true distribution of giant branch stars is difficult to estimate. Nevertheless, the lack of any obvious unevenness above the estimated completeness limit of $M_{BOL} \sim -6.5$ and the sharp luminosity cut-off at the top of the giant branch give further support to the intermediate mass interpretation. In Fig. 2 the Doradus giant branch is compared with the giant branches of the Magellanic Cloud blue globular clusters NGC 330, NGC 2100, NGC 2004 and NGC 1850 and similar data for the brightest LMC and SMC red supergiants from Glass (1979). The Magellanic Cloud blue globulars show the predicted intermediate mass giant branch morphology with a luminosity cut-off in excellent agreement with the theoretical value (if we exclude the VV Cephei binary in NGC 2004 with $M_{BOL} = -7.5$ mag). We identify the red supergiants in these young globular clusters with *intermediate mass stars having masses in the range 3-9* $M_\odot$.

The brightest LMC stars present a different giant branch morphology. The majority of stars lie at luminosities well above the theoretical luminosity cut-off for intermediate mass stars and there is a trend towards higher temperatures at higher luminosities. This is to be expected for high mass stars ($M/M_\odot \gtrsim 10$) since the carbon-core-burning zone is approximately parallel to the hydrogen-core-burning (main sequence) and helium-core-burning zones in the H-R diagram (LIH). The brightest SMC supergiants form a similar but less populated giant branch. These brightest Magellanic Cloud stars exemplify the *high mass giant branch morphology*. Comparison of the Doradus giant branch with the above examples strengthens the interpretation of the Doradus M supergiants as intermediate mass stars, although the presence of a few bluer, more luminous stars is suggestive of higher masses for these stars.

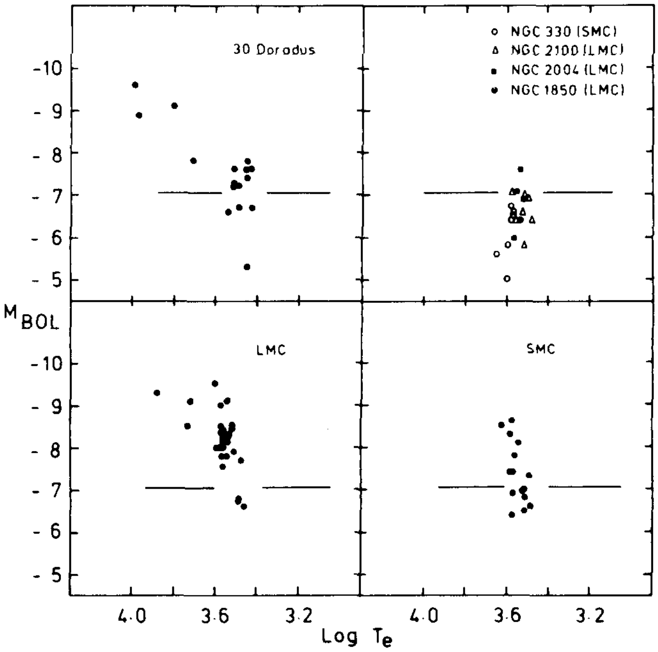

Figure 2. M_{BOL} vs log T_e diagrams for the giant branches of 30 Doradus (upper left), the blue globular clusters NGC 330, NGC 2100, NGC 2004, NGC 1850 (upper right), and the brightest red supergiants in the LMC (lower left) and SMC (lower right) from Glass (1979). The theoretical maximum luminosity for intermediate mass stars is shown in each case.

Implications for the Doradus Supergiants

Accepting the Doradus M supergiants as intermediate mass stars, we compare the observed luminosity cut-off of $M_{BOL} = -7.8$ mag with the theoretical value of $M_{BOL} = -7.0$ mag. Consideration of photometric errors for individual stars and uncertainties in the reddening and bolometric corrections leads to a probable uncertainty in the observed luminosity cut-off of 0.2 mag. The difference between the theoretical cut-off and the observed value is therefore significant. We cannot reconcile the higher Doradus luminosity cut-off with uncertainties in the theoretical luminosity-core mass relation as several workers (cf Fig. 8 of Becker and Iben 1979) have obtained essentially identical relations and our globular cluster data are in agreement with the theoretical limit. We are therefore forced to require that the core mass exceeds the Chandrasekhar limit by $\sim 0.8\ M_\odot$. Core rotation is an attractive mechanism for delaying carbon detonation until higher core masses are attained. Although no detailed calculations of rotating stellar evolution through to carbon detonation have been made, crude calculations (Sackmann and Weidemann 1972) have shown that luminosities of the required order may be achieved. In this light, we note that the low angular momentum young globular cluster systems possess non-rotating stars while the 30 Doradus population, which presumably formed from a turbulent gas cloud, may contain red supergiants which still possess some remnant of the initial nebular angular momentum.

The lower mass limit for the Doradus stars can be set by requiring that evolution terminates in carbon detonation rather than planetary nebular ejection. This limit is uncertain and may be as high as 7 $M_\odot$ (Tuchman, Sack and Barkat 1978). The Doradus stars suffer helium shell flashes, enabling a futher estimate to be made from the absence of carbon stars. No carbon stars have been found in the 30 Doradus region and only one star in our globular cluster data is a candidate. Computation (Iben 1977) suggests that only stars more massive than 8 $M_\odot$ reach the Paczynski limit before becoming carbon stars, however the large range in carbon star to M star ratios found by Blanco *et al.* (1978) indicates the dangers in using such a value. We conclude that the Doradus M supergiants most probably occupy the high mass end of the intermediate mass range and place limits on their present masses of $\sim$7-9 $M_\odot$, with corresponding ages of $\sim$2-5 $\times 10^7$ yrs (Becker, Iben and Tuggle 1977).

The same mass range must apply to the globular cluster stars since they show the same giant branch morphology and absence of carbon stars. In this case it is instructive to compare the red supergiant masses with main sequence turn-off masses for the individual clusters. The turn-off masses for NGC 330, NGC 2100 and NGC 2004 are respectively 15, 20 and 25 $M_\odot$ (Robertson, 1973). The large difference between masses in the blue and red regions of these clusters is *direct evidence for large-scale mass loss* in the late evolution of massive stars. Adopting a post-main sequence lifetime for a 9 $M_\odot$ star of $\sim 5 \times 10^6$ yrs leads to a mean mass loss rate of $\sim 2 \times 10^{-6}\ M_\odot$/yr. Detailed studies of the blue globular clusters may provide the more accurate mass loss rates required for evolution calculations. If similar mass loss has occurred in the Doradus M supergiants their initial masses will be in excess of the values determined above, with a corresponding decrease in the stellar ages. These effects are difficult to quantify at present.

Direct mass determinations for the 30 Doradus and globular cluster stars are needed to support the indirect arguments given above, however such determinations are difficult to realize. Stars with the same luminosity and temperature and differing only in mass have different surface gravities. The problem thus reduces to determining the true surface gravity of these stars, independent of the hydrodynamic motions which exist in the extended atmospheres of late-type supergiant stars. Even determining the effective surface gravity, including these mass motions, is difficult since the atmospheres are not strongly sensitive to surface gravity.

There is no doubt that at least two star formation events have taken place in the 30 Doradus region in the last $\sim 5 \times 10^7$ yrs with the latest being $\lesssim 3 \times 10^6$ yrs ago. From the data presented above we can say with some confidence that the earlier even took place $\sim$2-5 $\times 10^7$ yrs ago, perhaps slightly more recently if mass loss has been important in the evolution of the massive stars. The stars from the earlier population which now have masses of 7-9 $M_\odot$ are double shell source stars approaching the end of their evolution as supernovae. From the rate of stellar evolution up the giant branch the rate of these supernova events can be estimated to be $\sim$5 supernovae per 10^6 yrs. The red supergiants may have unusually high rotational velocities, perhaps indicating large rotational velocities in the parent gas cloud.

We are pleased to acknowledge helpful discussions had with P. R. Wood. P.J.M. is the holder of a Commonwealth Postgraduate Award.

Becker, S. A., and Iben, I., preprint, (1979).
Becker, S. A., Iben, I. Jr., and Tuggle, R. S., *Astrophys. J.*, **218**, 633 (1977).
Blanco, B. M., Blanco, V. M., and McCarthy, M. F., *Nature*, **271**, 638 (1978).
Chiosi, C., Nasi, E., and Sreenivasan, S. R., *Astron. Astrophys.*, **63**, 103 (1978).
Glass, I. S., *Mon. Not. Roy. Astron. Soc.*, **186**, 317 (1979).
Hyland, A. R., Thomas, J. A., and Robinson, G., *Astron. J.*, **83**, 20 (1978).
Iben, I. Jr., in *Advanced Stages in Stellar Evolution*, ed. P. Bouvier and A. Maeder (1977).
Lamb, S. A., Iben, I. Jr., and Howard, W. M., *Astrophys. J.*, **207**, 209 (1976).
Mills, B. Y., Turtle, A. J., and Watkinson, A., *Mon. Not. Roy. Astron. Soc.*, **185**, 263 (1978).
Paczynski, B., *Acta Astr.*, **20**, 47 (1970).
Robertson, J. W., *Astrophys. J.*, **180**, 425 (1973).
Sackmann, I. -J., and Weidemann, V., *Astrophys. J.*, **178**, 427 (1972).
Tuchman, Y., Sack, N., and Barkat, Z., *Astrophys. J. (Letters)*, **225**, L137 (1978).
Wood, P. R., *Astrophys. J.*, **190**, 609 (1974).