THE H-R DIAGRAMS OF THE LMC AND SMC

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ABSTRACT. We present new determinations of the H-R diagrams for luminous, hot stars in the LMC and the SMC. Using all available photometric and spectroscopic data, we discuss the conversion of the observed measurements to temperature and luminosity. The resulting H-R diagrams for normal stars confirm the upper luminosity limit, and also show an interesting "ridge" not noted before.

1. INTRODUCTION

It was first noted by Hutchings (1976) that the maximum luminosity observed for early-type stars decreases with decreasing effective temperature. Humphreys and Davidson (1979) further demonstrated that this decrease stops at an effective temperature of about 10^4 K and that the maximum luminosity is essentially constant for cooler temperatures. More recent estimates of this luminosity limit, often referred to as the "HD limit," are found in Humphreys (1987), Garmany, Conti and Massey (1987), and Humphreys (this volume). It is generally assumed that these observations indicate that stellar evolution tracks reverse their direction, i.e., from rightward evolution in the H-R diagram (HRD) to leftward evolution, at effective temperatures which depend on the initial masses of the stars. Lamers and Fitzpatrick (1988) showed that there is a very good correspondence between the observed upper luminosity limit and the locus of very low stellar effective gravities, as deduced from line blanketed, LTE, plane parallel model atmospheres calculated using Kurucz's (1979) atmosphere program.

In order to understand the physical processes which control the evolution of massive stars, it is necessary that the distribution of stars in the HRD be well-determined. This includes accurate measurements of the location of the HD limit, as well as of the ratio of red-to-blue supergiants, and of the metallicity dependence of the HRD. As has been pointed out frequently, the Large and Small Magellanic Clouds (LMC and SMC) are excellent candidate galaxies for such studies, providing the opportunity to study nearly complete samples of early-

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type stars. The uniform and relatively well known distances of the stars in these galaxies, and their generally low interstellar reddening offer obvious advantages over their Galactic counterparts. In addition, LMC and SMC studies, when combined with Galactic studies, allow the effects of stellar metallicity differences of up to a factor of 10 or more to be investigated.

In this paper, we present new determinations of the HRD's for the LMC and SMC, emphasizing the M_{bol} vs. T_{eff} distributions of the normal stars, for which the effective temperatures and reddenings can be determined accurately (i.e., we exclude the LBV's and the WR stars). The obvious extension of our work will be to compare our results with the M_{bol} vs. T_{eff} distributions of the more exotic objects, which may lead to some insight into the evolutionary relationships between the various classes of stars. The data for this project have been compiled from numerous sources, including catalogs of UBV photometry, spectral types, and reddenings. The sheer number of stars for which published data exist now allows for a better definition of the upper luminosity limit for normal stars than available previously and brings out other features of the upper HRD.

2. THE LARGE MAGELLANIC CLOUD

The data we have for the LMC stars usually include UBV photometry and spectral types of widely varying accuracy. In compiling these data, we began with a copy of the Rousseau et al. (1978) catalog of 1822 members of the LMC, which contains both new and previously published spectral types and UBV photometry. We added additional photometry from Isserstedt (1982) and slit spectral types determined by Walborn (1983), Crampton (1979), Conti, Garmany, and Massey (1986) and Fitzpatrick (1988). All known WR stars (Breysacher 1981) and H-alpha emitters later than type O (Henize 1956; Bohannan and Epps 1974) were removed from the dataset. Also removed were stars lacking UBV photometry and objects noted by Rousseau et al. as being non-stellar, multiple, or having composite spectra. The final dataset consisted of 1334 "normal" stars with spectral types in the range early-O to late-G and visual brightnesses in the range V = 10-15 mag.

In order to construct an HRD, we first determine T_{eff} (from which we determine the bolometric correction) and E(B-V) (from which we determine the absolute magnitude) for each star. Our sample includes 114 O-type stars which have well-determined spectral types derived from slit spectra. For these stars, we determined T_{eff} from a calibration of T_{eff} vs. spectral type derived from recent non-LTE spectral line analyses of O stars by Simon et al. (1983), Bohannan et al. (1986), and Voels et al. (1989). To derive E(B-V) for the O stars we assumed their intrinsic B-V colors to be -0.30. A LMC distance modulus of 18.3 mag was adopted.

For the rest of the stars, we pieced together a calibration of spectral class (temperature type) vs. effective temperature, bolometric correction, and intrinsic color. At a given spectral type, the intrinsic colors were tabulated for luminosity classes Ia, Ib, and II.

The adopted T_{eff} calibration is independent of the luminosity class. These calibrations were taken from various published sources and are reasonably well-determined and noncontroversial. In a more detailed version of this paper being prepared for publication, we will list all the sources and the final adopted calibrations.

E(B-V) was derived independently of the available spectral type information using the Johnson Q-method and the intrinsic color relations between B-V and U-B. The choice between the Ia, Ib, and II intrinsic colors depended on the absolute magnitudes of the stars. For the stars which have slit spectral types, the effective temperatures were taken from the calibration of spectral type vs. T_{eff}. For the majority of the stars, only poorly determined objective prism spectral types exist. For these, the temperature was derived from a calibration between T_{eff} and intrinsic U-B color.

The final result of all these calibrations is shown in Figure 1, where we plot T_{eff} vs. M_{bol} for the LMC stars. The open circles represent stars for which the photometry indicates E(B-V) > 0.4. These stars are highlighted because we feel that the reddening estimates may be incorrect. In most cases they are located in regions where such high reddening is not expected. Photometry errors may be responsible for the large E(B-V)'s, which result in erroneously large M_V and M_{bol} values. At the cool end of Figure 1 (log T_{eff} < 3.6) we have included about 40 M-type supergiants from Humphreys (1979). It should be realized that the sample of cool stars shown in the figure is by no means complete. We show the M stars to indicate the maximum luminosity observed for such stars in the LMC, NOT to indicate their numbers relative to the hotter stars. The x's indicate the locations of some

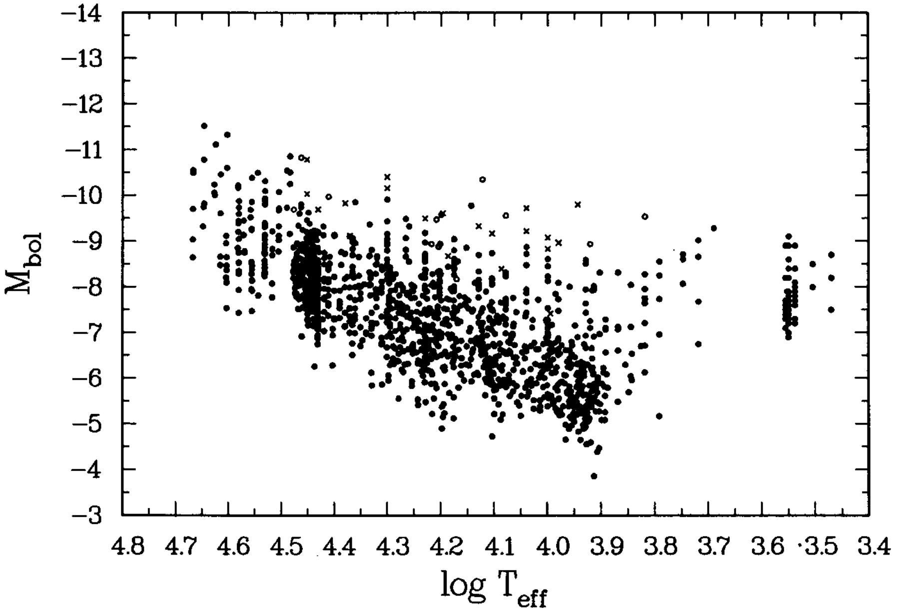

Figure 1. HRD for the LMC. Symbols are described in the text.

of the brightest "semi-normal" emission line stars. These stars exhibit emission only in the Balmer lines and have otherwise normal optical spectra. Note the pileup of stars between log T_{eff} values of 4.43 and 4.48 (i.e., T_{eff} = 27000-30000 K). These are stars for which no slit spectral types exist and which have UBV colors bluer than our calibration for type B0. Using their U-B values, we interpolated these stars onto a temperature grid ranging from 27000 K (the temperature adopted for B0) to 30000 K (the temperature adopted for O9.5). This group undoubtedly contains a large number of O stars which cannot be identified photometrically because of the well-known degeneracy of UBV colors for the O and early B stars. Slit spectral types are required to correctly assign their temperatures. The vertical strings of stars seen at several temperatures in Figure 1 result from T_{eff} being determined from a slit spectral type. These stars are forced into discrete bins in the figure, while the rest of the stars are spread more uniformly because their T_{eff}'s were determined from their UBV photometry.

There are two astrophysically interesting features in this diagram. The first is the upper luminosity limit of the normal supergiants. Figure 2 shows the same HRD with the inclusion of several previous estimates of the upper limit, as well as recent evolutionary tracks by Maeder and Meynet (1987). The distribution of the normal supergiants is consistent with the existing measurements of the limit

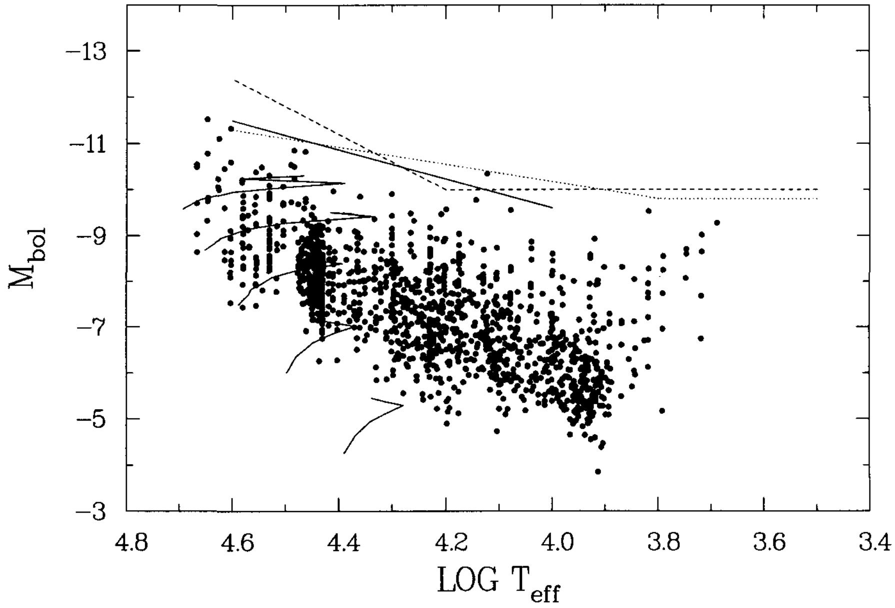

Figure 2. Same as Fig. 1, with the inclusion of evolutionary tracks by Maeder and Meynet for 60, 40, 25, 15, and 9 $M_\odot$ and various estimates of the HD-limits from Garmany, Conti and Massey (1987) (solid line), Humphreys and Davidson (1979) (dashed line) and Humphreys (1987) (dotted line).

and we see no reason to make any additional refinements, given that the exact placement of the line cannot be determined from the relatively sparse data at the brightest M_{bol}'s. A second, and unexpected, feature of the HRD in Figures 1 and 2 is the diagonal "ridge" line running through the data from upper left to lower right. Above this well-defined ridge the density of stars decreases significantly. This line runs roughly parallel to lines of constant absolute magnitude and is located at an M_V of about -6.5 mag. The stars above the line are mostly Ia supergiants. Note that this ridge is nowhere near the end of H burning as defined by Maeder's models except for the 40 and 60 $M_\odot$ tracks. We do not understand the physical significance of this ridge, but it is tempting to ask if it could represent the end of H burning. If so, the main sequence widening discussed by Meylan and Maeder (1982) and others is even greater than assumed. Alternatively, the ridge may indicate the location of some instability occurring in the stellar atmospheres. Obviously, further study is needed.

3. THE SMALL MAGELLANIC CLOUD

The data on SMC stars have been treated in the same manner as for the LMC stars. We started with the catalog by Azzopardi and Vigneau (1982), which consists of 524 stars having UBV photometry, and in some cases, spectral types. To this we added slit spectral types from Walborn (1983), Humphreys (1983) and Garmany, Conti and Massey (1987). Conversion to M_{bol} and T_{eff} was done as for the LMC, with an assumed distance modulus of 18.8. A major uncertainty in producing the SMC HRD is in the temperature calibration. For lack of better information, we adopted the same spectral type vs. temperature and intrinsic color calibrations as for the LMC. However, the lower metallicity of the SMC means that this method is undoubtedly incorrect, although the size of the error is unknown. Better measurements of the physical properties of the SMC stars are certainly required. The results of our procedure are shown in Figure 3. The location of the upper luminosity limit for the SMC may be slightly lower than for the LMC, but this may only be an effect of the smaller number of stars. There is also a suggestion in the SMC data of the same ridge line as seen for the LMC. But, again, the smaller number of stars makes the feature difficult to pinpoint.

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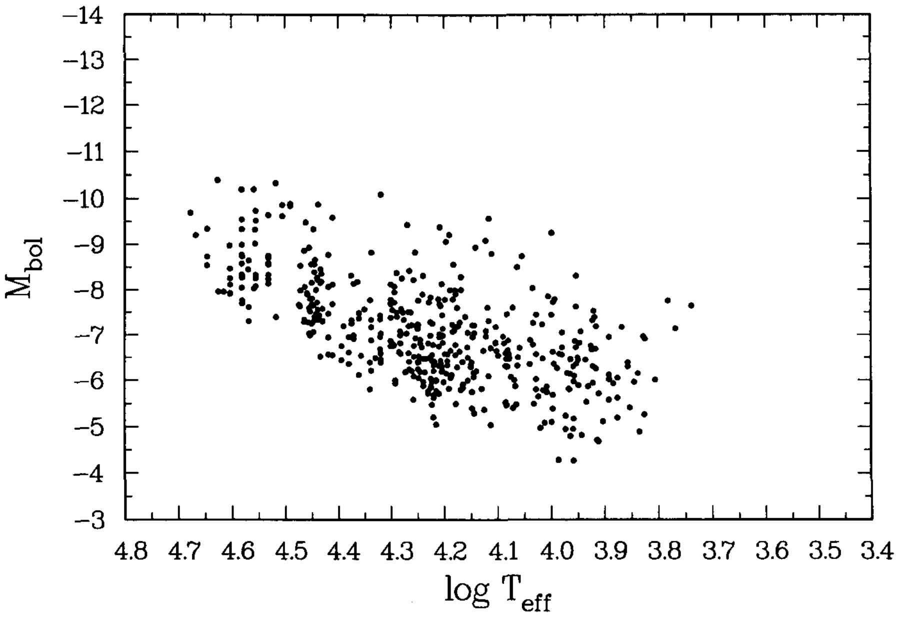

Figure 3. HRD for the SMC.

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DISCUSSION

Sreenivasan: Are you suggesting that LBV's are in or close to the main sequence or hydrogen-burning phase?

Garmany: At least in the LMC, the LBV's are intermingled in the H-R diagram with normal supergiants (luminosity Ia). We are not suggesting that the LBV's are still in the core-hydrogen-burning phase, but the emergence of the ridge in our treatment of the data raises questions about where hydrogen burning stops. This ridge line must have some physical significance.

Maeder: I am very fond of observational constraints, but for a given contraint one unique picture should emerge and that is not the case here. The color-magnitude diagrams of well-studied clusters and associations (*cf.* Mermilliod) do not show the enormous main sequence extension that you suggest. There is only a moderate extension which has been used to calibrate the distance of overshooting. I very much prefer to rely on well-analyzed cluster sequences rather than on a mixture of field stars of different ages.

Garmany: We agree that this effect has not been seen in young clusters. However, a complete data set for a galaxy such as the LMC should represent a steady-state situation. If young clusters and associations expand and disperse on a timescale that is much smaller than the nuclear timescale, as suggested many years ago by Blaauw and others, then one might not expect the older stars that form our ridge to still be identified as cluster or association members. In fact, as we showed, only a third of the supergiants in the LMC are within association boundaries.

Humphreys: Two incidental remarks. (1) It is important to remember that there are many more M-type supergiants in both the LMC and SMC; Katy's diagram shows just a few of these. (2) The rough original upper boundary (Humphreys & Davidson 1979) was based on a hotter temperature scale, which caused it to be steeper than it is in more recent H-R diagrams. (The upper left end was **not** intended to be determined by η Car, by the way.)

Garmany: We added some representative M stars to the diagram just to show where they lie, but all we are really concerned with here are types O to early G.

Gallagher: Could the bunching of stars along the ridge line be due to problems in the conversion between spectra and effective temperatures?

Garmany: I don't think so. We see the effect with both the spectral type -- temperature conversion and the $(U-B)_0$ -- temperature conversion. Temperatures for B stars, the most important subset in the ridge, have been determined by Fitzpatrick (1987) from Kurucz models using lower gravities than in the published models. The use of a different temperature scale will probably not eliminate the ridge.

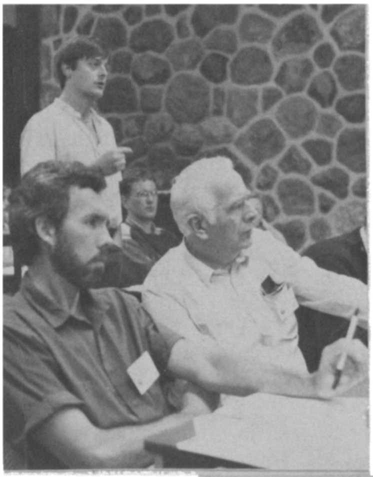
Vanbeveren: Observers and theoreticians like to compare the data with evolutionary tracks in the H-R diagram. However, when T_{eff} is considered, are you sure that T_{eff}*(observed)* can be compared with T_{eff}*(evolution)*, *i.e.*, that the observed core-hydrogen-burning band can be compared with the theoretically predicted one?

Garmany: Well, one hopes that observers and theoreticians are talking about the same temperature scale. It seems unlikely that there is a large difference between them -- at least the ZAMS is agrees!

Kudritzki: No, Danny [Vanbeveren], I do not think this effect is large enough (factor of 1.5 to 2 in T_{eff}) to explain Katy's results.

Garmany: Binaries would raise the ridge by some amount, and a starburst could also be considered --

Gallagher: No, I do not think a starburst could produce the ridge line; the time scale would have to be too short for stars so widely dispersed across the LMC.



Vanbeveren,
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Wolf,
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