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SYNTHETIC H-R DIAGRAMS AS AN OBSERVATIONAL TEST OF STELLAR EVOLUTION THEORY

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Synthetic H-R diagrams are constructed from a grid of stellar models. These are compared directly with observations of young clusters in the LMC and SMC as a test of the models and as a means to determine the age, age dispersion, and composition of the clusters. Significant discrepancies between the observed and model H-R diagrams indicate the possible influences of convective overshoot, large AGB mass-loss rates, and the best value for the mixing length parameter.

1. INTRODUCTION

As we have already heard at this workshop, the Magellanic Clouds are an important arena for the study of stellar evolution. One reason for this is that they have experienced a recent burst of star formation activity during the last 100 million years and therefore contain numerous young clusters whose H-R diagrams are well populated in the various evolutionary phases of intermediate-mass ($3M_{\odot}<M<10M_{\odot}$) stars. Such stars are of interest in the study of stellar evolution and nucleosynthesis as progenitors of planetary nebulae, asymptotic giant branch (AGB) stars, and even as possible progenitors of carbon-deflagration or core-bounce supernovae.

In this work we construct synthetic H-R diagrams from theoretical evolutionary tracks as a function of mass and composition to directly compare with the observations. Such comparisons serve a two-fold purpose. For one, they are a sensitive means to estimate the age and composition of the observed clusters. Perhaps more importantly, such comparisons allow for a determination of the quality of the stellar models and highlight the areas in which new input physics is required.

2. CONSTRUCTION OF SYNTHETIC DIAGRAMS

The basis for the construction of the theoretical H-R diagrams is a three-dimensional grid in M, Y, and Z of evolutionary models mostly

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from Becker (1981). AGB evolution to the first thermal pulse is interpolated from Becker and Iben (1979, 1980). The remaining AGB evolution is extrapolated as described in Becker and Mathews (1983). A few additional tracks were computed to complete the grid (Becker and Brunish 1983), and more massive tracks are from Brunish and Truran (1982a, b). These tracks span a range in mass from 3 to 40 $M_\odot$, and helium mass fractions from 0.20 to 0.36, as well as metallicities from 0.001 to 0.030. Thus, by interpolation (Becker and Mathews 1983) we are able to infer the evolution for essentially any mass or composition likely to be encountered in young Magellanic-Cloud clusters. For the first time a simultaneous age and composition fit can be attempted.

The synthetic HR diagrams are constructed from a random population of stars with a gaussian dispersion in ages and an appropriate initial mass function. (We chose IMF $\propto m^{-2.3}$). The mass and metallicity-dependent color-magnitude conversions of Kurucz (1979) are applied for regions where applicable, and the spectral-class-dependent conversions of Flower (1977) are used for temperatures and luminousities outside the range of the Kurucz tables. We estimate a theoretical uncertainty of about 0.1 magnitudes in V and B-V in these conversions from the difference between the two tables when compared at solar metallicity.

3. RESULTS

Figures 1a-b are examples of theoretical diagrams as a function of age (15, 30, 60, 90, 120, 240 x 10^6 yrs) for two different compositions.

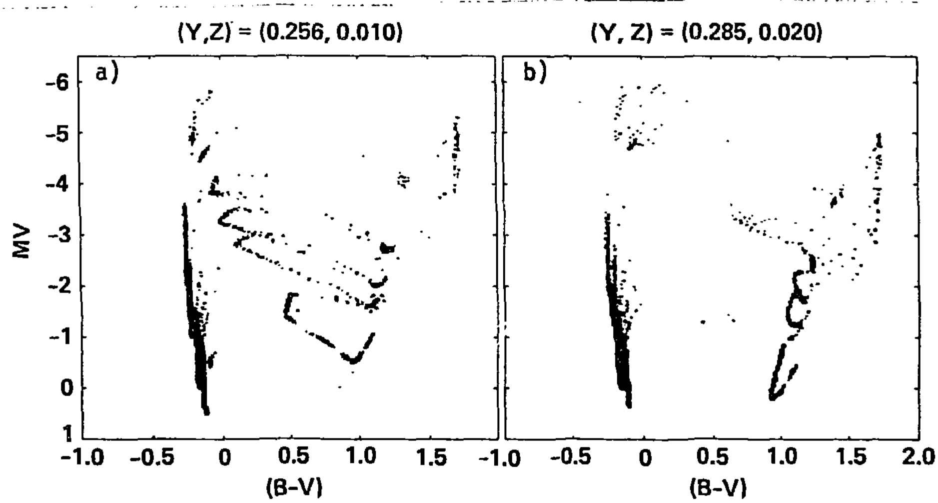

Figure 1. Synthetic H-R diagrams as a function of age for different compositions.

We assume that Y is correlated with Z according to the relation given in Lequeux et al. (1979). The most dramatic changes in the diagrams of figures 1a-b are in the location of the core helium burning loop (CHBL) which roughly decreases in brightness with increasing age, and reddens with increasing metallicity and helium abundance. These connections between age and luminousity, and composition and color can be understood for the most part in terms of the influences on the evolutionary tracks from the stellar mass, opacity, and mean molecular weight (Iben 1967).

Figure 2 is a summary of the locations of the blue tip of the CHBL as a function of age for various compositions. Overlayed on this are the locations of the CHBL for eight clusters in the LMC with sufficient data to easily identify a CHBL blue tip (Alcaino 1975). It is interesting to note that nearly all of these clusters lie approximately along a line corresponding to a single composition of (Y,Z) = (0.27, 0.015). The SMC contains fewer clusters with a recognizable CHBL. They tend to indicate a lower metallicity

Comparisons between synthetic and observed H-R diagrams for three of the best studied LMC clusters are given in Figures 3-5. The synthetic clusters are normalized to the same number of stars in the observed ranges of V and (B-V). An artificial dispersion (Robertson 1974) has been added to the theoretical points for faint stars to simulate the dispersion in the observations. These clusters span a range in ages and turnoff masses from fairly young clusters like NGC 1854 ($\sim$30 x 10^6 yrs) with an estimated turnoff mass of 8-9 $M_\odot$, to older clusters like NGC 1866 with an estimated turnoff mass of $5M_\odot$.

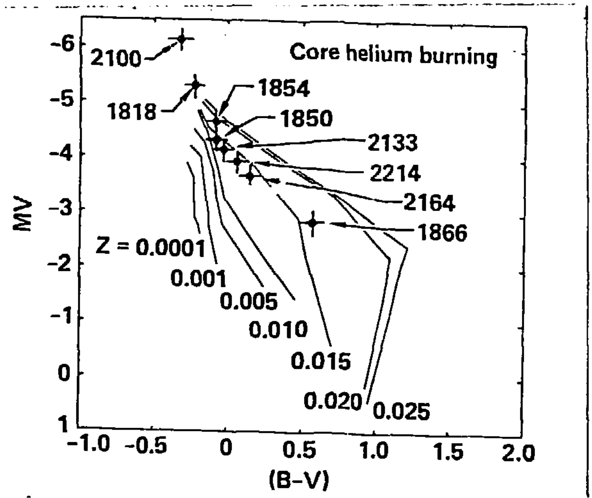

Figure 2. Summary of the location of the tip of the CHBL as a function of age along lines of constant composition.

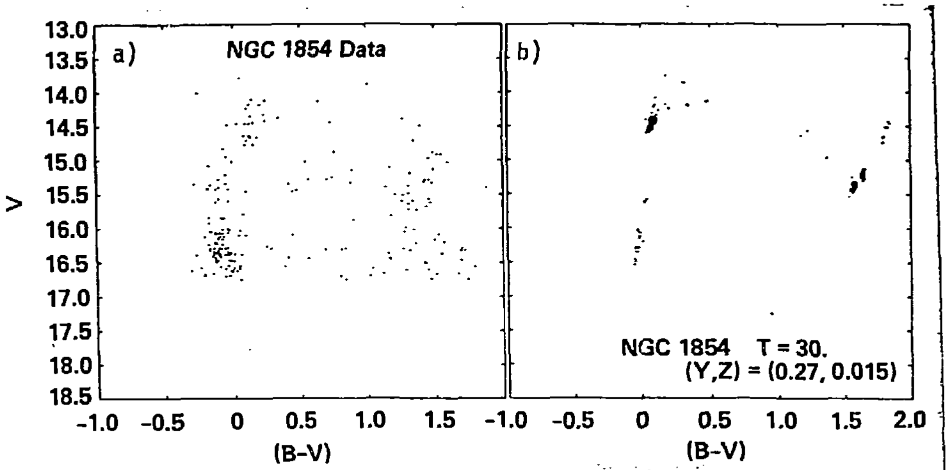

Figure 3. Comparison of observed and model H-R diagrams for the LMC cluster NGC 1854.

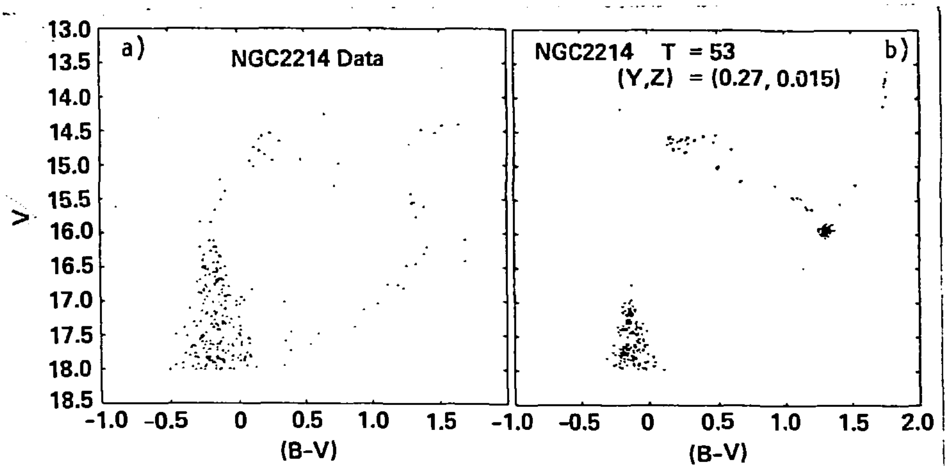

Figure 4. Comparison between observed and theoretical H-R diagrams for the LMC cluster NGC 2214.

4. INTERPRETATION

The basic features of the observed diagrams are well reproduced in Figures 3b-5b but there are some significant discrepancies which may

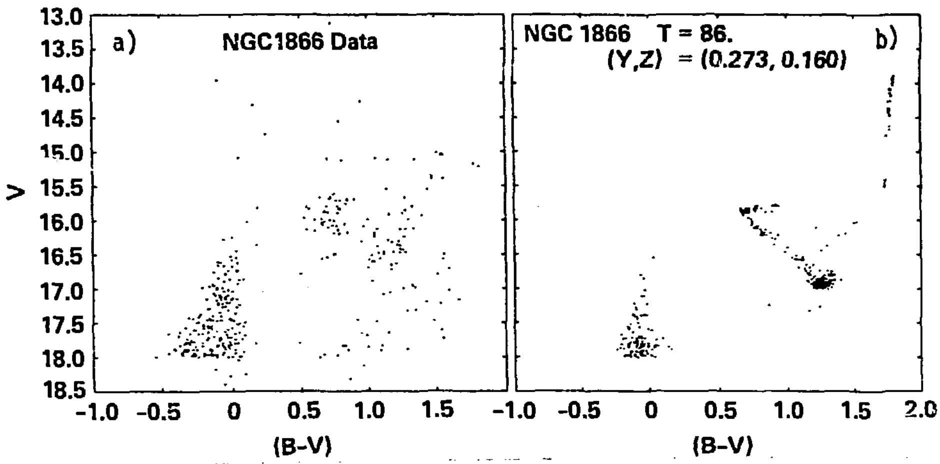

Figure 5. Comparison between observed and model H-R diagrams for the LMC star cluster NGC1866.

indicate the need for refinements in the input physics to the stellar models. These descrepancies are visible in all of the synthetic clusters and are best apparent in the comparison between theory and observations for NGC 1866. (Figs. 5a-b) for which the largest number of stars have been studied.

4.1. Populations

The first discrepancy which we note is the apparent deficiency of main sequence stars relative to red giant stars in the model clusters shown in Figures 3b-5b. This is particularly true for the brightest blue stars which actually correspond in the models to post main-sequence stars near the ignition of shell hydrogen burning. The implication is that either the calculated lifetimes of these stars are too short (particularly for the post main sequence), or that the red-giant lifetimes are too long in the stellar models. One possible explanation for this discrepancy is that the main-sequence lifetimes have been underestimated in the models by the neglect of convective overshoot. This additional mixing could introduce the necessary lengthening of the main-sequence lifetime (Maeder and Mermilliod 1981), but the effect of convective overshoot on the red-giant lifetimes must be considered. Among other possible interpretations for this discrepancy, the possible contributions from rotation, binary evolution, and uncertainties in the opacities should also be considered.

4.2. AGB Evolution

A second striking deviation between the observed and model H-R diagrams is the absence in the data of the asymptotic giant branch which is predicted in the models. The AGB evolution for the model clusters has been interpolated from the calculations of Becker and Iben (1979, 1980), based on the Reimers (1975) mass loss rate. These tracks predict an extended AGB evolution to high luminousities with eventual termination by explosive carbon ignition in an electron-degenerate core, i.e. a carbon-deflagration supernova. The data, on the other hand, appear to reach a limiting absolute visual magnitude of about -4 (assuming a distance modulus of 18.6 for the LMC). In NGC 1866 (Figure 5a), and to some extent in the other clusters, there is even evidence for stars turning off from the AGB toward becoming central stars of planetary nebulae. This is apparent in NGC 1866 as a string of stars with $V \sim 15$. Apparently the mass-loss rate exceeds the assumed Reimers estimate, or an envelope instability is reached early in the AGB evolution which leads to the ejection of the outer layers. Thus, even clusters with a turnoff mass of 8-9 $M_\odot$ (like NGC 1854 in Figure 3a) seem to exhibit white-dwarf formation rather than an extended AGB. This is consistent with recent searches for white dwarfs in young local galactic clusters which imply an upper mass limit for white-dwarf progenitors of about $8M_\odot$ (Reimers and Koester 1983; Koester and Weidemann 1983).

From the luminousity of the observed post AGB stars we estimate a core mass of $\sim 0.7M_\odot$. The ejecta mass divided by the time spent on the AGB then implies a mass loss rate of $\dot{M}/M_\odot > 10^{-6}$ yr^{-1} for a $5M_\odot$ star.

4.3. Mixing Length to Pressure Scale Height

We note another discrepancy which is that the AGB evolution for the model clusters is too red. The model tracks have been adjusted to a ratio of mixing length to pressure scale height of 1.0. The data seem to indicate that a value of 1.5 is preferable (assuming that the color-magnitude conversions are correct in this region of the H-R diagram).

4.4. Age Dispersion

Finally we point out that in these studies an upper limit of 5×10^6 yrs. could be derived for the dispersion in ages of stars in a cluster by the very fact that the CHBL is an identifiable collection of stars at about the same color and brightness. Large dispersions in age tend to produce a large dispersion in the CHBL which is not compatable with the observations (see Becker and Mathews 1983).

5. ACKNOWLEDGEMENT

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DISCUSSION

Bond--How much of this effect can be explained by variation of the IMF?

Mathews--Very little. To reproduce the ratio of red giants to main seqence stars would require an IMF $\sim m^{-14.3}$, which is unreasonably steep. Furthermore even this IMF would not account for the paucity of post main sequence stars. The reason for this insensitivity to the IMF is because a very narrow mass range (less than $1M_\odot$) is contributing to the red-giant population

Torres-Piembert--You used $\Delta Y \sim 3\Delta Z$ to compute the properties of the clusters, and certainly the clusters seem to be compatable with only one composition. I wonder what would happen if you used a fixed value for Y and varied Z only. Then would you find the same agreement or not?

Mathews--The location of the core helium burning loop depends both upon the helium abundance (via the mean molecular weight) and the metallicity (via the opacity). Therefore a change in the metallicity can be compensated by an opposite change in Y to keep the CHBL in the same position. On the other hand, stars with higher opacities have longer main sequence lifetimes. Therefore, the red giant to main sequence ratio could be reproduced by a low ($\sim$primordial) helium abundance, and a high ($\sim$solar) metallicity. This seems to me to be an exotic composition, however, and probably would not correct for the low number of post main-sequence stars.

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