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Research Note

Rapid changes in the integrated light of young star clusters

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Summary. We discuss the occurrence of rapid red phases in the integrated colours of star clusters by comparing a colour evolution model with spectral and broad band *UBVK* observations in the LMC. The model is computed with a very small age step and a fine mass grid of stellar tracks which allow to study the importance of the red supergiant (RSG) phase to the integrated light. This study is based on classical evolutionary tracks for massive stars, but we also infer on the effects of stellar mass loss and internal mixing processes. Taking into account the RSG phase, we find that the model colours are consistent with the observed ones for young clusters ($T_G < 2\ 10^7$ yr) if internal reddening in the range $0.1 < E(B-V) < 0.2$ is considered.

Key words: star clusters – stellar evolution – Large Magellanic Cloud

1. Introduction

The purpose of this paper is to call attention to rapid changes in the integrated light of young star clusters, due to the sudden appearance of red stars at certain stages of the stellar evolution in the HR diagram. The importance of "flashes" of red stars at young ages lies on its impact on population synthesis, in particular when a library of integrated spectra of star clusters is used (Bica and Alloin, 1986, 1987; Bica, 1988) or when the photometric evolution of a galaxy is synthesized with an evolutionary method (Arimoto and Yoshii, 1986, 1987, hereafter AY 86 and AY 87, respectively).

The first rapid change in the spectral evolution of a star cluster is due to the occurrence of a red supergiant (RSG) phase at $T_G \simeq 10^7$ yr, as for the LMC cluster NGC 2004 where the effect is directly seen in the HR diagram and in the integrated spectrum (Robertson, 1974; Bica and Alloin, 1986, 1987). These massive RSGs are in the core-helium (He) burning stage; they are labelled "HB" by Renzini and Buzzoni (1986). An example of the importance of this phase on the analysis of galactic light is its implications on the ratio of young to old stellar populations in dwarf galaxies (Aaronson, 1985). A second change, at $T_G \simeq 10^8$ yr, might be identified with the first occurrence of asymptotic giant branch (AGB) stars (Renzini and Buzzoni, 1986) and might be occuring in the LMC cluster NGC 1866 (Bica and Alloin, 1987).

In this paper we compute colour evolution models for star clusters using fine age steps and a detailed grid of stellar tracks (Sect. 2). We compare the results with spectra and visible to infrared colours of star clusters in the LMC (Sect. 3). The conclusions are given in Sect. 4.

2. The models

Recently, Yoshii and Arimoto (1987, hereafter YA 87) have applied a supernova (SN)-driven galactic wind model to spheroidal stellar systems and successfully reproduced the structural and chemical properties of giant and dwarf ellipticals as well as globular clusters. In particular for globular clusters, they have shown that the binding energy of such system is so small that a wind occurs as soon as the massive stars of the earliest generation explode as SNs, expelling all the remaining gas and preventing further star formation. Consequently, such systems are expected to be essentially single-generation objects without any metallicity increase with respect to the interstellar gas from which they were formed.

We have computed an age sequence of cluster models by using the wind model of AY 87. In this model, the gas mass turns into stars with mass between m and $m+dm$ at a rate $C(t)\,\phi(m)\,dm$, where $\phi(m)$ and $C(t)$ are the initial stellar mass function (IMF) and the star formation rate (SFR) per unit mass, respectively. The adopted IMF is the power mass law,

$$\phi(m) \propto m^{-\mu},$$

where μ is an IMF slope [$\mu = 1.35$ for the local Salpeter IMF] and the stellar mass range is $0.05\,M_\odot \leqq m \leqq 60\,M_\odot$. The SFR is assumed to be proportional to the fractional gas mass $f_g(t)$, including the effect of a wind:

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$$C(t) = (\nu/\nu_0) f_g(t)\,, \qquad (0 \leqq t < t_{GW})$$
$$= 0\,, \qquad (t \geqq t_{GW})\,,$$

where $\nu_0 = 6.08\ 10^{-18}\,\mathrm{s}^{-1}$ is the SFR per unit mass assumed for the solar neighbourhood; t_{GW} the time when a wind occurs.

Specifying constant parameters ν/ν_0 and μ, we numerically integrate the basic equations of chemical evolution [Eqs. (11), (12), (17), and (18) of AY 87] to compute the time variations of the gas fraction $f_g(t)$, the metal abundance $Z_g(t)$, the thermal energy $E_{th}(t)$ from SNs, and the binding energy of the gas $\Omega_g(t)$. The initial conditions used are $f_g(0) = 1$ and $Z_g(0) = Z_0$. Integration is continued until the thermal energy $E_{th}(t)$ exceeds the binding energy $\Omega_g(t)$ at $t = t_{GW}$ and star formation stops.

YA 87 demonstrated that globular clusters do not experience any self-enrichment of heavy elements. Thus, their metallicities should be the same as those of proto-cluster clouds. Since the integrated colours of stellar systems are very sensitive to their metallicities (AY 86), the choice of the initial metal abundance Z_0 is crucial. In this paper, we have adopted $Z_0 = 0.01$ which is a reasonable choice for young LMC clusters.

The number of stars formed with mass m and metallicity $Z = Z_g(t)$ between t and $t + \Delta t$ is given by $(M_G/m)\,\phi(m)\,C(t)\,\Delta t$, where M_G is the protocluster cloud mass. These stars are initially distributed on the zero age main sequence (ZAMS) for the metallicity at their birth and then evolve along their own evolutionary tracks onto the isochrone of age $T_G - t$ on the HR diagram. The distribution is converted into the colour-magnitude (CM) diagram by using the photometric calibration given by AY 86. Integrating on the $T_G - t$ distribution from $t = 0$ to t_{GW}, we obtain the distribution of composite stellar populations in the CM diagram from which the integrated cluster colours are derived.

As our interest is detecting possible rapid red phases, we have used 304 stellar tracks instead of 73 as previously adopted by AY 86. Additional tracks are inserted, if necessary, to obtain smooth distribution of stars on the HR diagram during the RGB and the core-He burning stages, by using the usual interpolation method for constructing isochrone (Ciardullo and Demarque, 1977). The importance of this fine grid is that it contains the core-He burning stage for massive (RSG) and intermediate mass core-He burning stars ($m \geqq 2.2\,M_\odot$). However, it lacks the horizontal branch (HB) stage for low mass stars ($m < 2.2\,M_\odot$) and AGB stars of any mass. Consequently, for $T_G \geqq 10^8$ yr we simply point out colour differences between our models and the observations, which can be accounted for by AGB stars (Sect. 3).

As the problem of the existence of convective overshooting is still open (Bertelli et al., 1985; Brocato and Castellani, 1988), we have adopted canonical stellar tracks (no overshooting and no mass loss) whose sources are listed in AY 86. With respect to the AY 86 and AY 87 models, the photometric calibration for the *JHKL* colours by Koornneef (1983) has been used instead of Johnson's. A detailed description of the evolutionary method of population synthesis is given in AY 86 and AY 87.

Cluster models are computed with i) an initial mass of proto-cluster cloud $M_G = 10^6\,M_\odot$; ii) age steps 10^6 yr for $10^6\,\mathrm{yr} \leqq T_G \leqq 10^8$ yr, $2\ 10^7$ yr for $10^8\,\mathrm{yr} \leqq T_G \leqq 10^9$ yr, and $2\ 10^8$ yr for $10^9\,\mathrm{yr} \leqq T_G \leqq 17\ 10^9$ yr; iii) a coefficient of the SFR $\nu/\nu_0 = 400$; and iv) a slope of the IMF $\mu = 0.95$. The value $\mu = 0.95$ was found to be the best choice to reproduce the photo-chemical and dynamical properties of globular clusters, dwarf and giant elliptical galaxies (YA 87).

Due to the astration, the total stellar mass M_* grows up until $t_{GW} = 4\ 10^6$ yr when a SN-driven wind is induced by the first generation of SNs and the gas is expelled from the system. The mass of the expelled gas is $M_{gas} = M_G(1 - M_*) = 7.8\ 10^5\,M_\odot$, while the mass of the stellar system is $M_* = 2.2\ 10^5\,M_\odot$ and remains constant after this wind has occurred ($t_G > 4\ 10^6$ yr).

The results consist of the evolution of *UBVRIJHKL* colours which can be obtained upon request. In Sect. 3 we discuss the *UBVK* results and compare them with observations of LMC clusters.

3. Comparison with observations

We present in Fig. 1a and b the model colour evolution in the $U-B$ vs $B-V$ and the $U-V$ vs $V-K$ diagrams, respectively. We compare it with LMC star clusters having *UBVK* photometry as well as at least one age estimate in the literature. The source for $U-B$ and $B-V$ is from van den Bergh (1981) and that for $V-K$ is Persson et al. (1983). We have grouped them into age intervals, which are indicated in the figures. The sources of ages for intermediate and old clusters is Bica et al. (1986). For blue star clusters we have used Hodge (1983) complemented with recent estimates as compiled in Bica and Alloin (1986) as well as those in Flower (1982).

In Fig. 2 we have merged the visible and near-infrared integrated spectra from Bica and Alloin (1986, 1987) for clusters of different ages in the LMC. This figure allows to compare the spectral energy distribution and absorption features with each age interval in the colour-colour diagrams (Fig. 1), where the relevant clusters are labelled, together with NGC 1835 which is a counterpart of metal-poor Galactic globular clusters with RR Lyrae stars (Hodge, 1984). All photometric and spectral observations are corrected of the LMC foreground reddening $E(B-V) = 0.06$ (Mould and Aaronson, 1980). The different age intervals are discussed as follows:

a) H II regions: We emphasize that the van den Bergh's *UBV* sample includes central parts of H II regions (mostly the very young star cluster, rather than the gas emission) which populate the upper part of the $U-B$ vs $B-V$ diagram (Fig. 1a). These objects have not been included in the infrared observations, and consequently they do not appear in Fig. 1b. We show in Fig. 1a the objects which are associated with H II regions (Henize, 1956; Davies et al., 1976). These H II regions can be used to estimate the internal reddening of star forming regions by comparing their positions in the $U-B$ vs $B-V$ diagram with respect to the model locus for ages $10^6 - 6\ 10^6$ yr. We find that $E(B-V)$ ranges 0.0–0.15 with an extreme value 0.40 for NGC 2070 (30 Dor). These results are in agreement with the $I_{H\alpha}/I_{H\beta}$ flux ratio of Caplan and Deharveng (1986) obtained from large aperture observation of the emitting gas for 38 LMC H II regions. In particular, their average value is $\langle I_{H\alpha}/I_{H\beta}\rangle = 3.47$ and the highest value, corresponding to NGC 2070, is $I_{H\alpha}/I_{H\beta} = 4.57$. Using $E(B-V) = 2.10 \log (I_{H\alpha}/(2.86 I_{H\beta}))$ (Sparks et al., 1987), we obtain $\langle E(B-V)\rangle = 0.18$ and $E(B-V) \simeq 0.43$, respectively. Thus, the reddening values estimated from Fig. 1a are on average consistent with those from the emitting gas. It is important to note that the van den Bergh's *UBV* data of NGC 2070 were obtained with a small aperture which covers essentially only the star cluster so that the contamination by emission lines is certainly small.

b) The red supergiant phase: The RSG phase at $T_G \simeq 10^7$ yr is clearly seen as a red excursion in Figs. 1a and 1b. In particular, the amplitude of the effect is much stronger in $V-K$ ($\simeq 3.0$ mag) than in $B-V$ ($\simeq 0.25$ mag) and is negligible in $U-B$ because the contribution of these cooler stars is obviously more prominent in the infrared than in the visible range. The RSG phase is prominent in Fig. 1 b because its amplitude is very large and the direction of the effect deviates significantly from the general evolutionary trend. Our synthetic colour-magnitude diagrams for clusters 6 10^6 to 1.6 10^7 years old show densely populated ZAMS, a very wide Hertzsprung gap and a clump of K and/or M type RSGs. The clump of RSGs is essential in reproducing such a large amount of redward colour excursion.

However, the HR diagrams of some young LMC clusters (e.g., NGC 2004; Robertson, 1974) do exhibit clump of RSGs. Recently, one of the authors (E. B.) has observed at least 10 new LMC and SMC clusters whose integrated spectra show the same RSG effect as NGC 2004. Therefore, we conclude that the redward excursion of cluster colours at the age around 10^7 yr is a real effect due to RSGs in the sense that most populous clusters pass through it, when massive stars evolve into the core-He burning stage. We also notice that integrated colours during the RSG phase might be different from cluster to cluster because of possible difference in stellar age dispersion and/or due to a finite number of massive stars in each cluster. Chiosi et al. (1988) have pointed out the same problem, but due to the brightest AGB stars, in the integrated colours of clusters older than 3 10^8 yr.

Persson et al. (1983) have suggested that the RSGs were necessary to explain the colours of SWB class I clusters. In Figs. 1a and 1 b, we can see that the RSG phase in the present model allows to explain the position of the observed youngest clusters ($\simeq 10^7$ yr), if a typical internal reddening correction in the range $0.1 < E(B-V) < 0.2$ is applied. A detailed discussion of this RSG phase in integrated colours has not been made in the literature. It was not included in Struck-Marcell and Tinsley (1978), whose evolutionary track is also plotted in Fig. 1 b. The recent extensive study of LMC clusters' colour evolution by Chiosi et al. (1988) confined its argument on the evolution of stars in the mass range 0.6 to 9 $M_\odot$ and did not give any results for clusters younger than 4 10^7 yr.

The spectrum of NGC 2004 clearly shows the presence of M-supergiants (Fig. 2), which are denoted by strong TiO bands and a strong near-infrared flux. The sequence of spectra in Fig. 2 allows to estimate the amplitude of the RSG effect in the integrated colours. Visible and infrared colours will be little sensitive when taken separately, but a colour combining a filter in the visible to one in the infrared, such as $V-K$ (Fig. 1 b), will show a strong effect.

As already pointed out in Sect. 2, we have used classical evolutionary tracks for massive stars, i.e., without stellar mass loss nor internal mixing process like convective overshooting. It will be important to compute integrated colours using recent stellar evolutionary tracks for massive stars incorporating these processes (e.g., Chiosi and Maeder, 1986 and references therein) and compare them with the present models. The main effect of mass loss is to reduce the upper mass limit of the stars which actually become RSGs, and to reduce in general the importance of the RSG phase. Nevertheless it is clear that after a few 10^6 years the most massive stars will explode as supernovae. These may not have gone through the RSG phase due to mass loss. However sometime later somewhat less massive stars will become RSGs and this will eventually produce an increase in the infrared flux. The main consequence of mass loss will be basically to change the epoch when the RSG flash occurs. The fact that there is strong observational evidence that the RSG phase occurs can be used to set constraints on the amount of mass loss from massive stars. The main effect of mixing is to change the appearance of the main sequence in the HR diagram, with effects such as widening (we thank Dr. J. Lequeux for these remarks).

c) The subsequent evolution: As already pointed out, our computed models lack AGB stars of any mass. Consequently we simply discuss the colour difference between models and observations which are to be assigned to these stars. The star clusters in the range 3 $10^7 < T_G < 1.5$ 10^8 yr are considerably redder in $V-K$ than the model (Fig. 1 b). Indeed Renzini and Buzzoni (1986) suggested an important contribution of AGB stars of spectral types late K to late M in this age interval.

The spectrum of NGC 1866 (Fig. 2) presents TiO and CN absorptions in the near infrared which are typical of M stars. The presence of these late type stars is indicated in the HR diagrams and surveys of individual luminous stars in NGC 1866 (Brocato and Castellani, 1988; Becker and Mathews, 1983; Flower, 1981; Aaronson and Mould, 1985). There is an evidence that the presence of these red stars is not stochastic because they are well distributed over the cluster as indicated by the similar spectra in different pixel rows for the CCD observation of NGC 1866 in Bica and Alloin (1987). We emphasize that the real existence of these red stars at such age is not based solely on NGC 1866. The same effect is present in the composite HR diagram of Galactic open clusters of comparable age (Mermilliod, 1981; see also Fig. 7 of Bica and Alloin, 1986). Other clusters at similar age, although with negligible molecular absorption (e.g., NGC 2157 and NGC 1856 in Fig. 2), still present strong Ca II triplet, which could still be assigned, at least in part, to AGB stars of spectral type K. We also indicate in Fig. 1 b that there are clusters which might have even stronger AGB contribution of M stars than NGC 1866. These are NGC 2058 and NGC 2164 with $2.5 < V-K < 3.0$.

The models agree with observations in the range 3 $10^8 < T_G < 8$ 10^8 yr. NGC 1831 (3 10^8 yr) is as blue as NGC 2157 (3 10^7 yr) in $V-K$ (Fig. 1b) and in energy flux distribution (Fig. 2). This can be assinged not only to an AGB contribution in the latter, but also to the possibility of non-negligible internal reddening in the younger cluster.

NGC 1868 should be identified with the phase when the major contributor to the light is switched from intermediate mass core-He burning stars to the red giant branch (RGB). NGC 1783, NGC 1978 are definitely in the RGB phase possibly with important contributions from red HB stars and low mass AGB stars.

The $V-K$ colours are much redder for intermediate age cluster ($10^9 < T_G < 5$ 10^9 yr) than the models (Fig. 1 b). The effects of low mass AGB stars are actually observed in the intermediate age clusters in the Magellanic Clouds (e.g., NGC 1651; Mould et al., 1986), and have been estimated empirically (Persson et al., 1983), resulting $\Delta(V-K) \simeq -\Delta K \simeq 0.8$ for LMC and SMC clusters, which is shown in Fig. 1 b. The inclusion of low mass AGB stars in the models would certainly explain the $V-K$ colours for these clusters. The models surely become again realistic for $T_G > 6$ 10^9 yr because the RGB stars dominate the integrated light. However, the old clusters are better described by the metal poor models for old populations by AY 87 and YA 87, which are also indicated in Figs. 1.

4. Conclusions

We have discussed rapid red phases in the integrated colours of star clusters in the LMC by comparing a colour evolution model with spectral and broad band *UBVK* observations. The model is computed with a very small age step and a fine mass grid of stellar tracks. The model accounts for the infrared colour excess of young clusters ($T_G \simeq 10^7$ yr) in terms of the red supergiant phase. We observationally find evidence of an important flux contribution

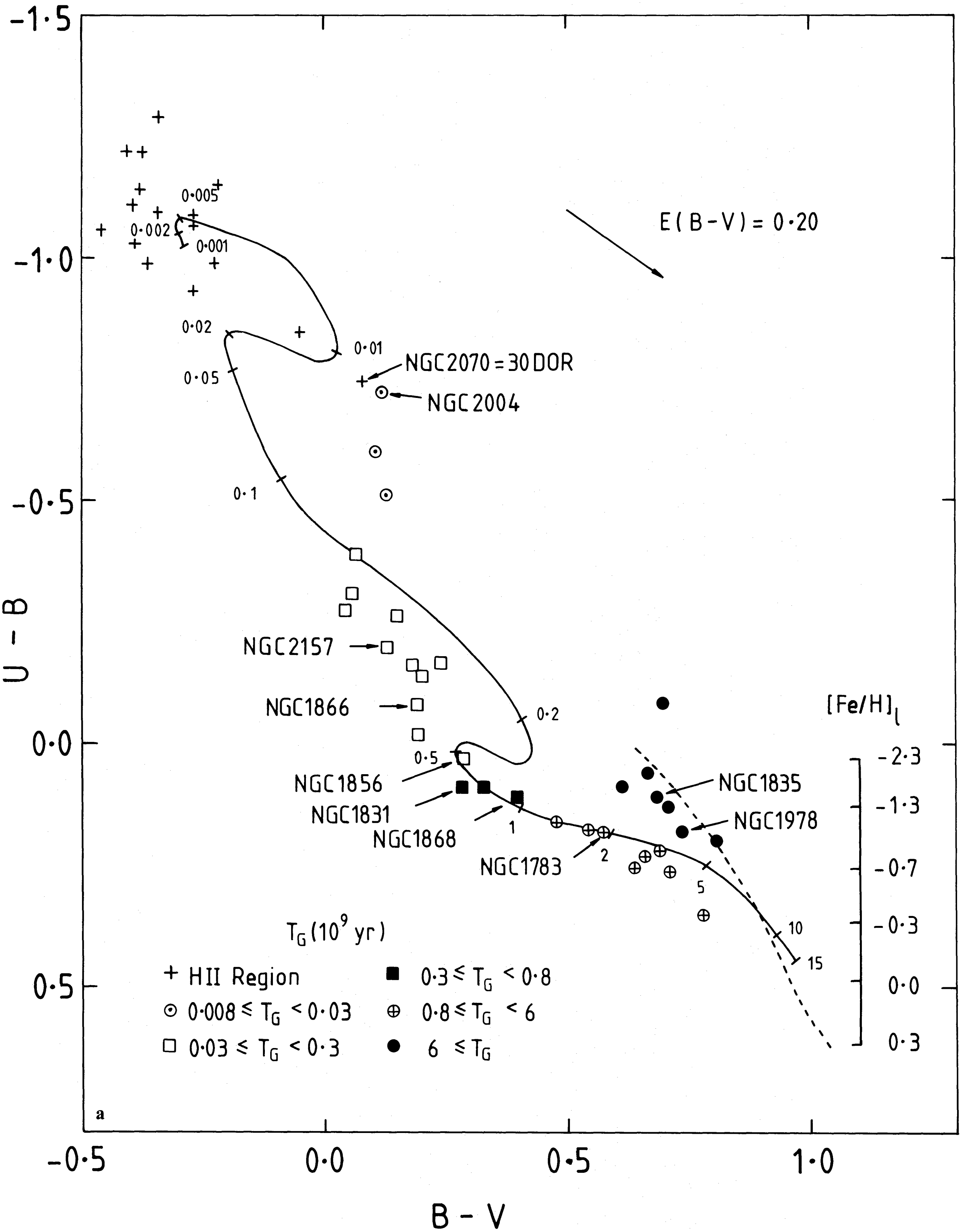

Fig. 1a and b. Comparison of models with observed colours for LMC clusters. Line gives cluster track according to Sect. 2, ages are given in units of 10^9 yr. Dashed line indicates the elliptical galaxy models with fixed age $T_G = 15\ 10^9$ yr of AY 87 and YA 87. The luminosity weighted average metallicity $[Fe/H]_l$ of the model galaxy is also indicated. Dotted line is the Struck-Marcell and Tinsley's (1978) model which does not include the RSG phase. The contribution of low mass AGB stars, $\Delta(V-K)$, estimated empirically by Persson et al. (1983) for the LMC is shown by an arrow, which indeed explains the difference between the calculated model and the observed colours of intermediate age clusters. **a** $U-B$ vs $B-V$ diagram. **b** $U-V$ vs $V-K$ diagram

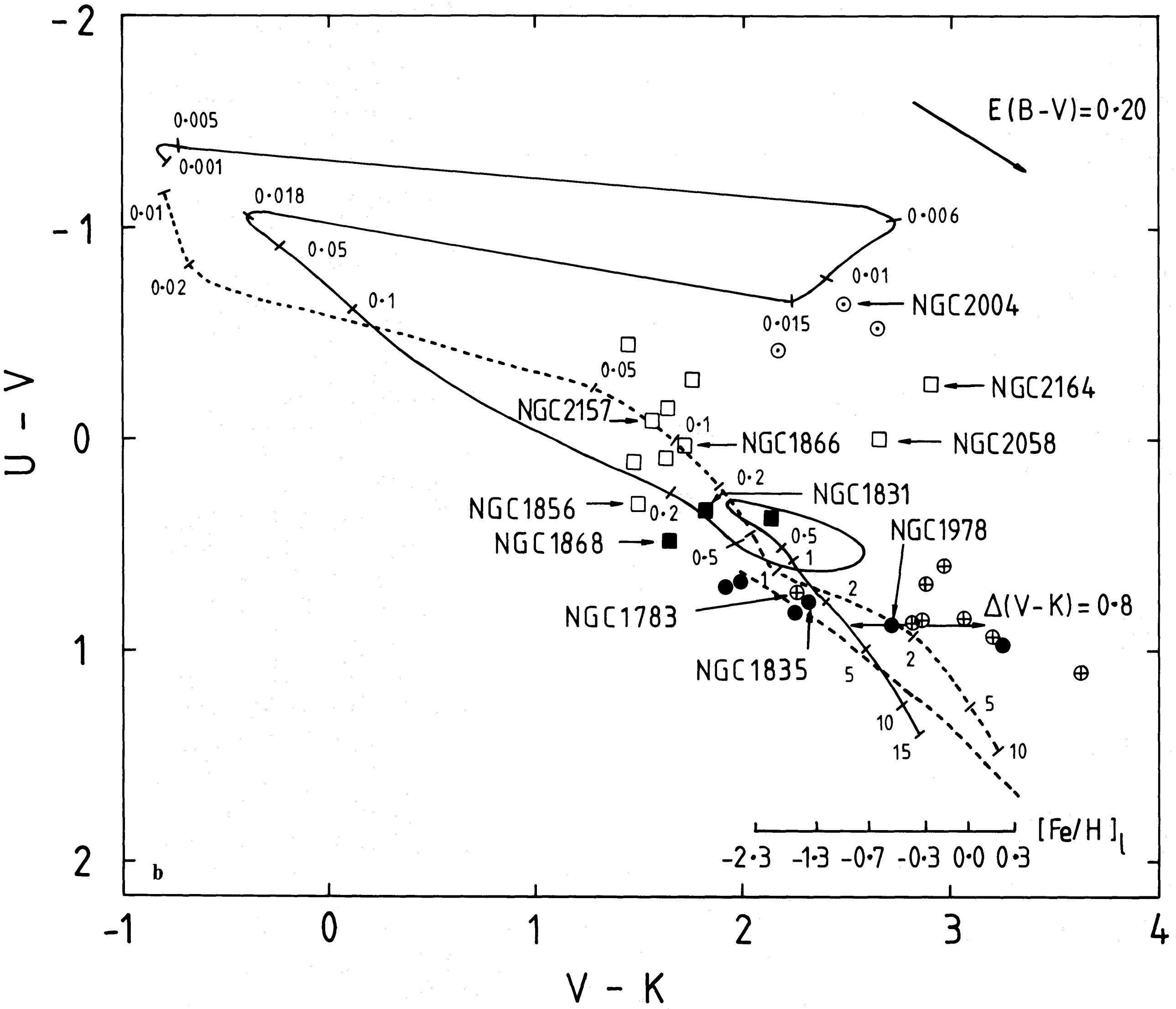

Fig. 1 (continued)

due to intermediate mass AGB stars around 10^8 yr. It also remains to be modelized in detail the contribution from AGB stars for intermediate age populations and low mass HB stars for old ones. A step in this direction was made by Chiosi et al. (1988).

Taking into account the RSG phase, we found that the model colours are consistent with the observed ones for young clusters ($T_G < 2\ 10^7$ yr), together with the consideration of internal reddening in the range $0.10 < E(B-V) < 0.20$. It will be important to study the integrated light behaviour using stellar tracks for massive stars incorporating mass loss and compare them with the present models.

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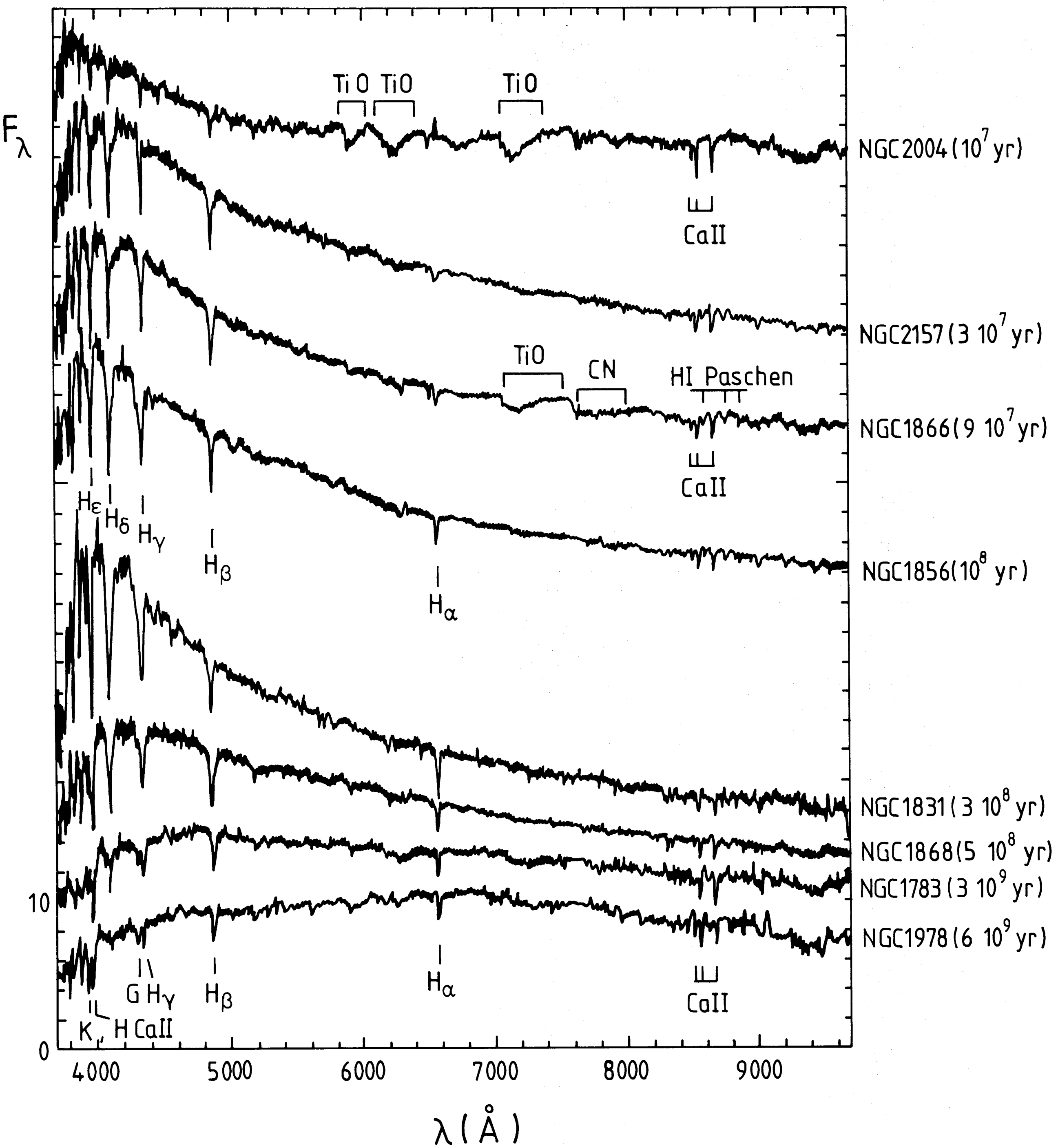

Fig. 2. Visible and near infrared spectra of young and intermediate age LMC clusters. Spectra are normalized to $F_\lambda = 10$ at 5870 Å. NGC 2004 contains the RSGs and NGC 1866 probably contains the AGB stars

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