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SYNTHESIS OF RED SUPERGIANT SENSITIVE SPECTRAL FEATURES IN STARBURSTS

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RESUMEN

Investigamos técnicas que pueden ser usadas para determinar las edades de las regiones de formación estelar que contienen poblaciones más allá de su fase nebular temprana. En particular, estudiamos la intensidad del triplete de Ca II ($\lambda\lambda$8498, 8542, 8662) y el índice de CO (en la banda de 2.31–2.40 μm), usando modelos sintéticos durante el desarrollo de la evolución estelar. Para un brote instantáneo de formación estelar ambos rasgos de esta absorción permanecen más intensos entre 7–14 Myr, correspondiendo a la población de supergigantes rojas. El comportamiento detallado de la evolución de la formación estelar depende fuertemente de la metalicidad. Los modelos de formación estelar de baja metalicidad reproducen satisfactoriamente la distribución de anchos equivalentes del triplete de Ca II con la edad, en los cúmulos de la Nube Mayor de Magallanes. Los cúmulos en la fase de las supergigantes rojas favorecen fuertemente los modelos evolucionados estelares incorporando tasas mayores de pérdida de masa que los valores estándar.

ABSTRACT

We investigate techniques that can be used to determine ages of starburst regions containing populations beyond their early nebular phase. In particular, we study the strength of the Ca II triplet ($\lambda\lambda$8498, 8542, 8662) and the CO index (2.31–2.40 μm band) using synthetic models as the starburst evolves. For an instantaneous burst of star formation both of these absorption features remain strongest between 7–14 Myr corresponding to the red supergiant population. The detailed evolutionary behavior of the starburst is strongly metallicity dependent. Low metallicity starburst models successfully reproduce the distribution of equivalent widths of Ca II triplet with age in Large Magellanic Cloud clusters. The clusters in the red supergiant phase strongly favor the stellar evolutionary models incorporating mass-loss rates higher than the standard values.

Key words: **GALAXIES: STARBURST — MAGELLANIC CLOUDS — SUPERGIANTS**

1. INTRODUCTION

Detection of Ca II triplet (CaT) lines in a circumnuclear H II region of the starburst galaxy NGC 3310 by Terlevich et al. (1990) offered a new tool to study aging starburst systems. The CaT lines originate in the atmospheres of cool stars with the absorption being the strongest in red supergiants (RSGs). It is known from the stellar evolutionary models at solar metallicity ($Z_{\odot}$= 0.02) that O stars in the mass range 15–25 $M_{\odot}$ evolve into RSGs in 7–14 Myr, and hence the detection of the CaT lines in starburst systems is often used to infer the presence of a stellar population of around 10 Myr age. The CO absorption strength is also sensitive to the population of RSGs, providing a second observable which can be used as an age indicator of starburst regions.

However, the CaT and CO absorption strengths of long-lived cool giants are non-negligible and hence the detection of the lines is not an unambiguous signature of the presence of RSGs. Moreover, the evolutionary history of massive stars, and hence the presence of RSGs, is a strong function of metallicity (Maeder 1991), and that starbursts are found in a wide range of metallic environments. Thus a quantitative interpretation of the observed strengths of CaT and CO lines in starbursts requires studies of the evolutionary behavior of starbursts at different metallicities. We carry out such a study with special emphasis on reproducing the observed line strength-age relation in star clusters of Large Magellanic Cloud (LMC) as established by Bica, Alloin, & Santos (1990).

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The synthesis technique and the stellar data used are described in Sec. 2. Evolutionary results are presented in Sec. 3 and are discussed from the context of observational data of LMC clusters in Sec. 4. Results are summarized in Sec. 5. A more detailed discussion of the work presented here can be found in Mayya (1997).

2. SYNTHESIS MODEL AND STELLAR DATA

We use the conventional evolutionary population synthesis technique to compute the starburst related quantities. The synthesis code we use in the computation is described in detail in Mayya (1995) and the results are compared with other existing codes in Charlot (1996). The equivalent width of the CaT absorption lines is computed for an instantaneous burst (IB) of star formation using the formula,

$$\mathrm{EW}_{\mathrm{CaT}}(\mathrm{imf}, t, Z) = \frac{\int_{m_l}^{m_u} L_{\mathrm{CaT}}(m;t;Z)m^{-\alpha}\,\mathrm{dm}}{\int_{m_l}^{m_u} L_{8600}(m;t;Z)m^{-\alpha}\,\mathrm{dm}} ,$$

where L_{CaT} is the strength of the CaT absorption feature and L_{8600} is the underlying continuum luminosity per unit Å at the rest wavelength of 8600Å. The initial mass function (IMF) with Salpeter slope $\alpha = 2.35$ is chosen with mass limits $m_l = 1$ and $m_u = 100$ in solar units. The CO index is computed by a similar formula with L_{CO} replacing L_{CaT} and the corresponding continuum wavelength being 2.36 μm. It is expressed in magnitude units following the conventional definition. Stellar spectra from Kurucz (1992) and Lejeune, Cuisinier, & Buser (1996) are used for effective temperatures of stars above and below 3500 K respectively. We use stellar evolutionary models from Geneva for starburst evolutions at metallicities $Z = 0.001$, 0.008, 0.02 and 0.04. Following Meynet (1992), we use the standard Geneva tracks (Schaller et al. 1992; Schaerer et al. 1993a,b) at $Z \geq Z_{\odot}$ and Meynet et al. (1994) tracks with enhanced mass loss rates (by a factor of two over standard mass-loss rate) at lower metallicities.

The most comprehensive investigation on the dependence of the equivalent width of the CaT with spectral type, luminosity class and metallicity of stars was carried out by Diaz, Terlevich, & Terlevich (1989). They defined the CaT equivalent width, EW(CaT), as the sum of the equivalent widths of two of the brightest lines ($\lambda\lambda$8542, 8662 Å) and provided an expression relating EW(CaT) with $\log g$ and $\log(Z/Z_{\odot})$. We use their expressions at $Z = 0.001$ and $Z = 0.008$. At higher metallicities, the theoretical expressions of Jorgensen, Carlsson, & Johnson (1992) are used. Doyon, Joseph, & Wright (1994) defined the CO index based on observed spectra and obtained relations for the CO index as a function of effective temperature for dwarfs, giants and supergiants separately. We use these relations in our computation. The index used here ($\mathrm{CO_{sp}}$) is related to the photometrically measured index ($\mathrm{CO_{ph}}$; Frogel et al. 1978) by $\mathrm{CO_{sp}} = 1.46\ \mathrm{CO_{ph}} - 0.02$.

3. SYNTHETIC RESULTS FOR Ca II TRIPLET AND CO INDEX

Evolutionary behavior of the EW(CaT) at the four metallicities is shown in Figure 1*a*. The following important stages can be recognized during the evolution of solar metallicity starbursts.
Stage 1. EW(CaT) rises to detectable levels in starbursts, 5 Myr after the onset of the IB, reaching the highest values of $\sim$ 11 Å between 7–14 Myr.
Stage 2. The EW abruptly drops to around 5 Å at $\sim$ 15 Myr, remaining at these low values up to around 20 Myr.
Stage 3. The EW rises again above 6.5 Å at 25 Myr, showing a secondary peak at 60 Myr.
Stage 4. The EW attains an asymptotic value of around 3 Å after 100 Myr.

The evolutionary behaviors at $Z = Z_{\odot}/2.5$ and $Z_{\odot}$ are qualitatively similar. At lower metallicities, the evolution is characterized by the absence of the primary peak at 10 Myr (Stage 1). At higher than solar metallicities, Stage 2 is missing, resulting in a smooth decrease of the EW from Stage 1 to the end of Stage 3. The Stages 1–4 as well as their dependence on metallicity can be understood by identifying the individual phases, which contribute significantly to the EW(CaT), during stellar evolution. It is the RSGs which are responsible for the Stage 1, where as red giants, asymptotic giants and cool dwarfs control the EW at Stages 3–4. Stage 2 arises due to the "blue loop" in the Hertzsprung-Russel diagram during the core helium burning phase of stellar masses $\leq$12 $M_{\odot}$at $Z \leq Z_{\odot}$. The absence of "blue loop" at $Z > Z_{\odot}$ is the cause of the smooth transition from the RSG-dominated phase to the red giant and asymptotic giant branch dominated phases at $Z = 2\ Z_{\odot}$. Successively lower mass stars spend a lesser fraction of their post-main sequence lifetime in

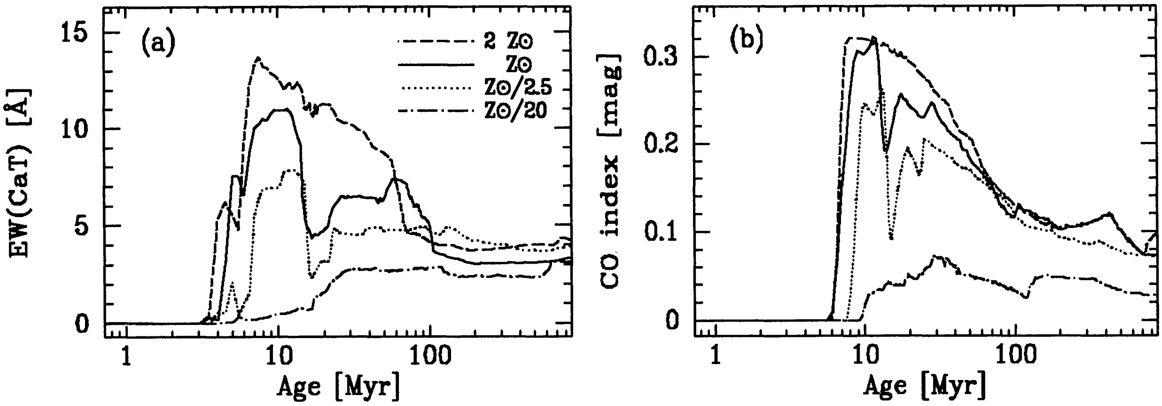

Fig. 1. Evolution of (*a*) the equivalent width of Ca II triplet, and (*b*) the CO index for an instantaneous burst of star formation for the assumed Salpeter initial mass function, at the four chosen metallicities.

"blue loop", resulting in the accumulation of red giant and asymptotic giant branch stars and leading to the secondary peak at 60 Myr for $Z_{\odot}$ models. The adopted scaling between mass-loss rate and metallicity, and also the corresponding phases for a star of given mass being warmer at lower metallicities, result in the net decrease of the number of stars contributing to CaT absorption at lower metallicities. This is the reason for lower peak values as well as lesser contrast between different Stages at lower metallicities. After 100 Myr, the EW(CaT) is controlled by the cool giant and dwarf stars of mass $< 5\ M_{\odot}$.

Evolution of the CO_{sp} index is shown in Fig. 1*b*. Note that the metallicity dependence in this plot arises only due to the dependence of stellar evolution on metallicity; there is no data-set on its dependence on line formation. The evolutionary behavior, as well as its dependence on metallicity, can be understood by the same physical phenomenon as that for the EW(CaT). However, the following quantitative differences in the four Stages are noteworthy.

Stage 1. The RSG peak is narrower for $Z \leq Z_{\odot}$ (8–12 Myr).
Stage 2. The CO index rises faster after the drop following the "blue loop" phase.
Stage 3. The secondary maximum occurs at 20–30 Myr. There is a smooth decrease from this epoch onwards.
Stage 4. The CO index do not reach asymptotic values beyond 100 Myr.

These differences arise firstly, due to a stronger dependence of the CO index on the effective temperature and secondly, due to the same stars contributing to the continuum as well as the CO absorption strength. The CO index of the starburst is essentially that of the most luminous cool star, as these cool stars contribute both to the line depth as well as the continuum. In contrast the continuum at CaT has a significant contribution from hotter stars and hence the EW(CaT) evolves differently than that of the CO index.

4. COMPARISON WITH LMC CLUSTERS

The blue clusters of the LMC provide a unique opportunity of checking the evolutionary results discussed above, before these results can be used to derive ages of starburst systems. The special advantage of these clusters is the availability of well-determined turn-off ages. The EW(CaT) and CO index for LMC clusters, treating each cluster as a single entity, are available in Bica et al. (1990). We superimpose our model results on these observed data in Figure 2. The strength of the fainter λ8498 Å line has been subtracted from the Bica et al. value to convert the observed values to the more commonly used definition of Diaz et al. (1989). Photometrically derived CO indices are converted into CO_{sp} using the relation given in Sec. 2.

The ages of the clusters with the highest EW(CaT) and CO index agree very well with the RSG dominated bump (Stage 1) of our model. The absolute values of the RSG peak with stellar evolution incorporating standard mass-loss rate is too low to account for the observations, confirming the under-estimation of RSGs in these models. Even with enhanced mass-loss rate models, the observed CO index is higher by around 0.08 mag, which might be caused by errors introduced in converting the photometrically observed indices to spectroscopic indices. The larger scatter in this plot compared to the EW(CaT) plot also suggests larger errors in the observed CO indices. Thus we conclude that the stellar evolution with enhanced mass-loss rates, and not the standard, is a better representation of the observed values in LMC.

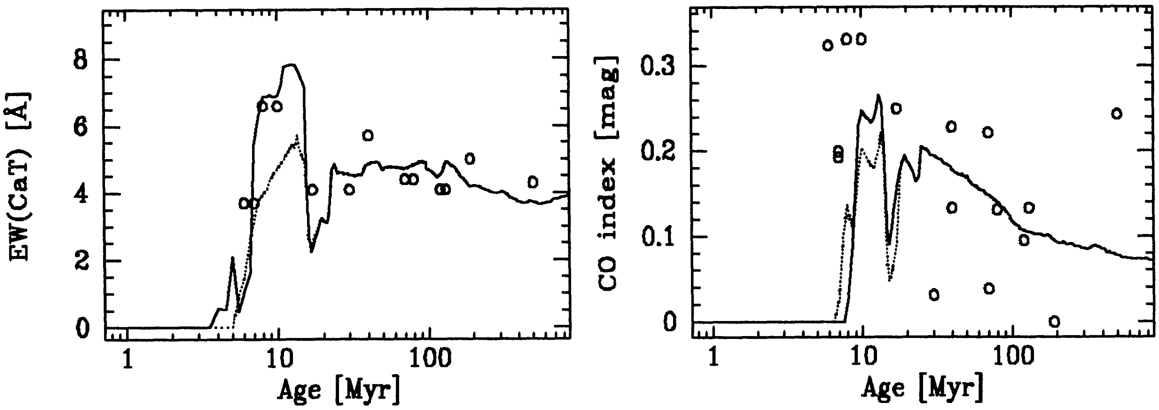

Fig. 2. Comparison of the computed quantities at $Z = Z_{\odot}/2.5$ with the observational data (circles) of Bica et al. (1990) for the LMC clusters. Stellar evolutionary models incorporating twice the standard mass-loss rate (solid line) reproduce the observed characteristics better than those with standard mass-loss rate (dotted line).

5. SUMMARY

We have synthesized the CaT equivalent width and the CO index for all the important phases during stellar evolution over a wide range of metallicities. The computed quantities are strongly dependent on the metallicity and age. The absorption features are the strongest between 8–12 Myr for starburst systems at metallicities equal or higher than that of LMC. Details in the evolutionary behavior of the EW(CaT) and the CO index allow use of these feature for estimating age of starbursts up to around 100 Myr, especially at high metallicities. Lower metallicity systems such as the blue compact galaxies ($Z < Z_{\odot}/5$) are not expected to have EW(CaT) and CO index values above 5 Å and 0.1 dex respectively. The computed values agree well with the observed values in LMC clusters.

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