Is the [CO] index an age indicator for star forming galaxies?

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Abstract. The classical [CO] index, i.e. the strength of the $\Delta v=2$ CO absorption bands starting at 2.29 μm, is sometimes used to constrain the maximum age of star formation events in galaxies. In this paper we critically analyze

i) theoretical models which could predict either a factor of >2 drop or a pronounced increase of [CO] at ages older than 100 Myr, depending on the evolutionary tracks one adopts (see Fig. 1).
ii) observational data for young clusters in the LMC which do not show any strong relationship between the CO index and cluster age (see Fig. 3).

The above scenario indicates that the value of [CO] does not provide a reliable tool for estimating the age of stellar populations older than $\sim$10 Myr, i.e. after the first red supergiants have been formed. The contradictory results of theoretical models reflect problems in treating the evolution along the Asymptotic Giant Branch (AGB). In particular, those evolutionary synthesis models using stellar tracks which do not include the thermal pulsing AGB phase produce too weak CO features at 100–1000 Myr, i.e. in the range of ages when the near infrared emission is dominated by thermal pulsing AGB stars.

Key words: galaxies: starburst – galaxies: star clusters – galaxies: stellar content – infrared: stars

1. Introduction

An ideal instantaneous burst of star formation generates a so–called Simple Stellar Population (SSP), that is a stellar system which is coeval and initially chemically homogeneous (see Renzini & Buzzoni 1986). The integrated near IR luminosity of a SSP is dominated by red stars since its very early stage of evolution ($\simeq$10 Myr), when massive stars ($<$40 M$_\odot$) evolve as red supergiants. When the stellar system gets older ($\gtrsim$100 Myr) intermediate mass giants evolving along the AGB and, after a few Gyr, low mass giants near the tip of the Red Giant Branch (RGB) dominate the integrated IR and bolometric luminosities (e.g. Renzini & Buzzoni 1986, Chiosi et al. 1986). The time
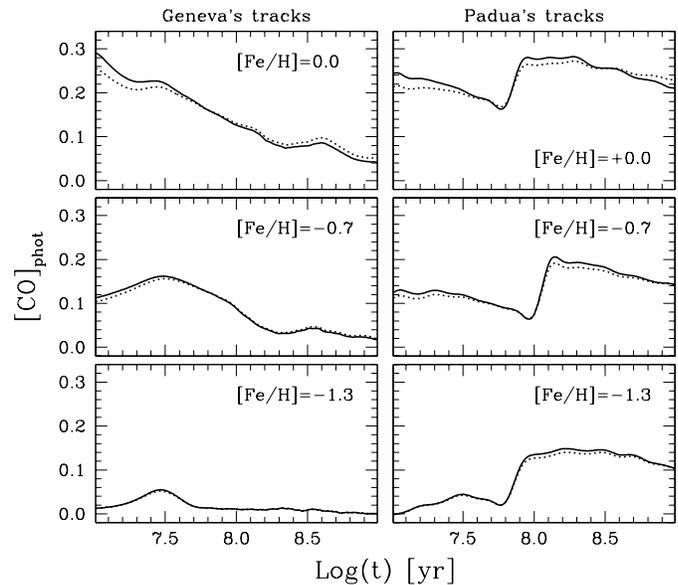
Fig. 1. Predicted evolution of the CO index for different metallicities and using different stellar evolutionary models. The left panels are based on the Geneva's tracks (Schaller et al. 1992, Charbonnel et al. 1993, Schaerer et al. 1993) while those in the right hand panels are based on the Padua's tracks (Bertelli et al. 1994). The solid lines represent our 'reference models' which are computed adopting an empirical relationship between microturbulent velocity and bolometric luminosity, i.e. using Eq. (3). For comparison, the dotted curves show the results obtained by assuming a constant value of microturbulent velocity ξ=4.0 (see Sects. 2.2,3 for details). Note the very different behaviours beyond $\sim$100 Myr, i.e. when the near IR emission is dominated by stars evolving on the AGB. This simply reflects the different extent of the AGB in the two sets of models (see Fig. 2).

evolution of the observable parameters related to a SSP, such as e.g. photometric colours and spectral indices, provides the basic ingredient for constructing evolutionary models of star forming galaxies.

Among the photometric and spectroscopic indices used to study the red stars of a SSP, the CO index has attracted quite some attention as a potential tool to trace red supergiants, i.e. young stellar systems. This idea primarily derives from the fact that field stars of similar spectral types show different CO indices depending on their spectral class, the strongest features
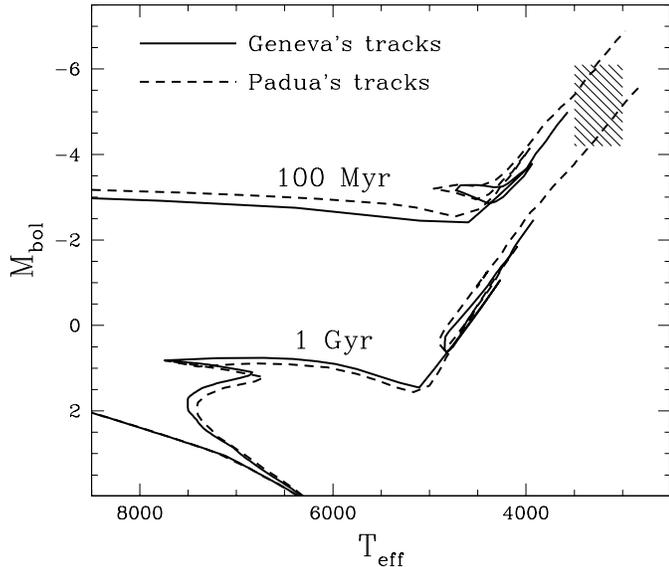
Fig. 2. HR diagram with theoretical isochrones from different stellar evolutionary models, all curves are for solar metallicities. The solid lines are based on the Geneva's tracks (Schaller et al. 1992, Charbonnel et al. 1993, Schaerer et al. 1993) which stop the computation at the onset of thermal pulses and, therefore, cuts the AGB at unrealistically high temperatures and low luminosities. The dotted curves are from Bertelli et al. (1994) which follow the evolution through the thermal pulse phase and hence produce more luminous and cooler AGB stars. However, the extent of the AGB is probably overestimated by these models which assume quite low mass loss rates along the AGB (see Sect. 3). The shaded region shows the loci of AGB stars in intermediate age Magellanic Cloud clusters (Aaronson & Mould 1982, Frogel et al. 1990).

Fig. 3. Observed [CO] in different samples of stellar clusters and galaxies. The first panel includes old Galactic globular clusters (Origlia et al. 1997, equivalent widths scaled to $[CO]_{phot}$ using Eqs. (1) and (2)), note the quite tight correlation between CO index and metallicity. The second plot includes younger clusters in the LMC, open circles are from the photometric data of Persson et al. (1983) while the filled symbols are from the spectroscopic equivalent widths of Oliva & Origlia (1998), scaled to $[CO]_{phot}$ using Eqs. (1) and (2). The large scatter of the points at a given age reflects variations of metallicities, statistical effects related to the intrinsic small number of luminous red stars in the clusters and, possibly, field contamination (see also Sect. 4). The third panel shows the distribution of the CO indices observed in starburst galaxies. The data are from Oliva et al. (1995, 1999, equivalent widths transformed into $[CO]_{phot}$ using Eqs. (1),(2)) and from Shier et al. (1996), Goldader et al. (1997) and Doyon et al. (1994) whose "broad spectroscopic index" is translated into $[CO]_{phot}$ using the prescriptions in the latter reference. Note that virtually all of the starbursters are within the range covered by 10^7–10^9 yr old LMC clusters.

being found in supergiants (see e.g. Fig. 4 of Kleinmann & Hall 1986, hereafter KH86). Several attempts of predicting the evolution of the CO index of a SSP appeared in the literature and were applied to the interpretation of IR spectral observations of starburst galaxies (e.g. Doyon et al. 1994, Shier et al. 1996, Goldader et al. 1997, Mayya 1997, Leitherer et al. 1999). Most of the models are restricted to solar metallicities and predict a pronounced maximum at $\simeq$10 Myr followed by a quite rapid and steady decline. The CO index drops by almost a factor of 3 at $\simeq$100 Myr and, noticeably, reaches values much lower than those observed in old ($\gtrsim$10 Gyr) Galactic globular clusters and spheroidal galaxies of quasi–solar metallicities. The few models at sub–solar metallicities predict a similar time evolution with shallower CO features at all epochs.

Taken at face value, these models would imply that star forming galaxies with prominent CO absorption features must be dominated by a young (<100 Myr) star formation event, while more mature, but still relatively young systems of a few $\times$ 100 Myr should be characterized by quite weak CO absorption features. In other words, the CO index could provide a powerful tool to constrain the age of the major star formation event of galaxies.

This paper is a critical re–analysis of the time evolution of the CO index in simple SSPs and star forming galaxies. In Sect. 2
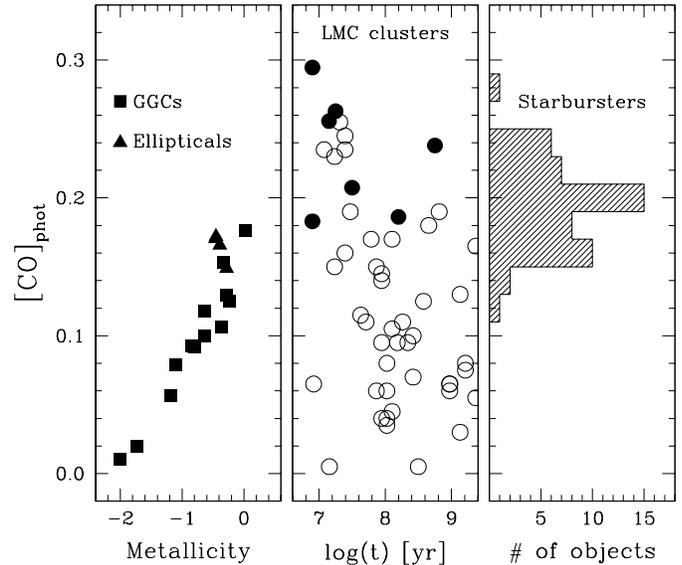
we describe the, sometimes confusing, definition of CO index and discuss its relationship with stellar parameters. In Sect. 3 we present theoretical curves based on different stellar evolutionary models and briefly discuss the possible reasons for their very different behaviours. In Sect. 4 we compare the predicted evolution of [CO] with measured parameters of template stellar clusters in the Magellanic Clouds, old globular clusters in the Galaxy, normal and starburst galaxies. In Sect. 5 we draw our conclusions.

2. The CO index

2.1. Spectroscopic and photometric definitions

The CO index was originally defined as the magnitude difference between a relatively narrow filter ($\Delta\lambda \simeq 0.1$ μm) centered at 2.3 μm, which includes the first four band–heads of Δv=2 CO roto–vibrational transitions, and a similarly narrow filter centered at 2.2 μm (Baldwin et al. 1973). The central wavelength of the CO filter was then increased to 2.36 μm and slightly

different filter parameters were adopted by different groups. A comprehensive database of CO photometric measurements was produced in the 70–80's. These include measurements of field stars (e.g. McWilliam & Lambert 1984), Galactic globular clusters (Frogel et al. 1983), young stellar clusters in Magellanic Clouds (Persson et al. 1983) and old spheroidal galaxies (Frogel et al. 1978). These data are still considered a fundamental benchmark for verifying the predictions of stellar evolutionary models.

The spectroscopic CO index was defined by KH86 who measured the (2,0) band–head at 2.29 μm from medium resolution ($\lambda/\Delta\lambda \simeq 2500$) spectra of a sample of field stars. The strength of this band is unequivocally defined as the ratio between the fluxes integrated over narrow wavelength ranges centered on the line and nearby continuum, i.e. 2.2924–2.2977 and 2.2867–2.2919 μm, and expressed in terms of magnitudes. The *same quantity* is sometimes given in terms of equivalent width (e.g. Origlia et al. 1993) and the numbers are simply related by

$$[CO]_{spec} = -2.5 \, \log \left(1 - \frac{W_\lambda(2.29)}{53\,\text{Å}} \right) \quad \text{mag} \qquad (1)$$

where $[CO]_{spec}$ is the spectroscopic index and $W_\lambda(2.29)$ is the equivalent width of the (2,0) band–head.

The relationship between spectroscopic and photometric indices is not obvious because they are based on measurements of different quantities which have different behaviours on the stellar physical parameters, e.g. $[CO]_{phot}$ also depends on the $^{12}C/^{13}C$ ratio (see McWilliam & Lambert 1984). Nevertheless, an empirical correlation between the two indices is generally adopted following from observations of giant stars in the field. This yields (see Fig. 3 of KH86)

$$[CO]_{phot} \simeq 0.57 \, [CO]_{spec} - 0.01 \quad \text{mag} \qquad (2)$$

To complicate the scenario further, other definitions of the spectroscopic index exist in the literature. These are based on spectroscopic measurements of equivalent widths over wavelength ranges much broader than those used by KH86 and similar to that adopted in the photometric definition. The most popular of these intermediate indices is that proposed by Doyon et al. (1994) which measures the equivalent width over the 2.31–2.40 μm range relative to a continuum which is extrapolated from shorter wavelengths. The specific advantage of this definition is that it allows measurements of [CO] even from spectra of relatively poor quality, while proper measurement of the spectroscopic index requires high s/n spectra with resolution $R \gtrsim 1000$.

These "broad spectral indices" are calibrated using measurements of field stars and can be therefore converted to photometric indices using empirical relationships similar to Eq. (2). To avoid confusion we will hereafter express measured and predicted quantities in terms of $[CO]_{phot}$ with additional comments on how it was obtained or scaled from spectroscopic measurements.

2.2. CO index and stellar parameters

In general, the strength of the CO features depends on the following stellar parameters (for a more detailed discussion see Sect. 4.1 of Origlia et al. 1993)

– Effective temperature, T_{eff}, which sets the CO/C relative abundance.
– Surface gravity, g, which influences the H^-/H equilibrium and hence modifies the total gas column density of the photosphere. In cool stars with CO/C$\simeq$1 the column density of CO scales as $\approx g^{-1/3}$ and, therefore, the lines become more opaque when the gravity decreases.
– Microturbulent velocity, ξ, which determines the Gaussian width of the lines and, therefore, the equivalent width of saturated lines (the CO transitions are semi-forbidden and have very weak Lorentzian wings).
– Metallicity and carbon relative abundance, which define the value of C/H. For a given set of T_{eff} and g, all CO line opacities scale linearly with the carbon abundance C/H.

The well known correlation between CO index and spectral type of giant stars is due to a complex combination of the effects of the first three parameters. The variation of T_{eff} is important only up to early K stars where most of the carbon is already in the form of CO. Therefore, in later spectral types the variation of T_{eff} has virtually no direct effect on [CO], i.e. *the CO index is not a thermometer for cool stars*.

The steady deepening of the CO features along the K4 III–M7 III sequence is driven by the decrease of surface gravity and increase of microturbulent velocity. The variation of surface gravity, $\Delta \log g \simeq -0.8$ from early K to late M giants (McWilliam & Lambert 1984), follows from the fact that field red giants are stars with similar mass and quasi–solar metallicities taken at different phases of their evolution on the RGB. Thus M III stars, being cooler and more luminous, have a lower surface gravity than K giants.

The value of ξ cannot be directly related to the stellar parameters but, based on detailed spectroscopic observations, is found to increase when the bolometric luminosity increases. To a first approximation, ξ scales linearly with $\log(L_{bol})$ and, therefore, late M giants have microturbulent velocities about 0.8 km/s higher than early K III stars (see e.g. Tsuji 1986, 1991).

The effect of microturbulent velocity becomes particularly prominent in red supergiants and accounts for the fact that class I stars have much stronger [CO] than giants of similar temperatures and gravities (see e.g. Tsuji et al. 1994, McWilliam & Lambert 1984). The derived values of ξ scale $\simeq$ linearly with $\log(L_{bol})$, i.e. a behaviour similar to that found in giant stars. Therefore, for practical purposes, the variation of [CO] in red giants and supergiants can be reproduced adopting an empirical, linear relationship between ξ and bolometric luminosity, namely:

$$\xi \simeq 2.0 - 0.4 \, M_{bol} \quad \text{km/s} \qquad (3)$$

An indirect test (and confirmation) of this equation comes from integrated spectral analysis of old and metallic stellar systems

(Origlia et al. 1997) and young clusters in Magellanic Clouds (Oliva & Origlia 1998). The derived values of average micro-turbulent velocities, namely $\overline{\xi} \simeq 2$ and $\overline{\xi} \simeq 4-5$ km/s for old and young systems, respectively, are in good agreement with those derived from spectral synthesis models adopting Eq. (3).

The effect of carbon abundance is relatively unimportant in field stars, which span a relatively narrow range of metallicities, but becomes evident in stellar clusters of low metallicity which are characterized by very weak CO features (see the left panel of Fig. 3). However, it should be kept in mind that the nice correlation between [CO] and metallicity of Fig. 3 also reflects the metallicity dependence of the temperature of giant stars, i.e. lower metallicity clusters have weaker [CO] not only because their giant stars have less carbon, but also because they are warmer than those in more metallic stellar systems (e.g. Origlia et al. 1997).

3. Modelling the evolution of [CO] in a SSP

The integrated CO index of a SSP with a given metallicity and age can be most conveniently determined from the integrated synthetic spectrum using the same methods adopted for measuring the index from the observational data. The integrated synthetic spectrum can be expressed as

$$F_\lambda = \int \phi(M)\, L_{\rm K}(M)\, f_\lambda(T, g, \xi, {\rm [C/Fe]})\, dM \qquad (4)$$

where $T=T(M)$, $g=g(M)$ and $L_{\rm K}(M)$ are the stellar temperature, gravity and monochromatic luminosity [1] along the isochrone. These parameters are explicitly tabulated by the Padua's models (Bertelli et al. 1994) while can be derived from the Geneva's evolutionary tracks as outlined in Leitherer et al. (1999).

The shape of the initial mass function, $\phi(M)$, has only a minor effect on the derived indices and, for all practical purposes, can be approximated by a standard Salpeter's IMF ($\phi(M) \propto M^{-2.35}$). The function f_λ is the spectrum (normalized to unity at 2.2 μm) appropriate for a star of the given metallicity, temperature and gravity. This function is often evaluated using observations of field stars whose spectral types are converted into surface temperatures and luminosities using empirical calibrations. However, this method is limited to stars with quasi–solar metallicity and is particularly uncertain for supergiants and AGB stars.

A more objective estimate of f_λ can be obtained from model stellar atmospheres which yield a synthetic spectrum with the desired resolution for a given set of metallicity (Z), effective temperature (T), surface gravity (g), microturbulent velocity (ξ) and carbon relative abundance ([C/Fe]). The last two quantities should be treated as free parameters because they cannot be unequivocally related to other physical parameters of the star. A detailed description of the procedure used to construct the synthetic spectra can be found in Origlia et al. (1993).

The time evolution of the CO index simply follows from Eq. (4) using theoretical isochrones at different ages. The re-

sults are plotted in Fig. 1 where we also evaluate the effect of using different stellar evolutionary models. These agree in predicting strong [CO] at early times, when the near IR emission is dominated by red supergiants (i.e. $t \lesssim 100$ Myr). Indeed, the comparison with observations is not yet satisfactory because models predict too warm red supergiants, especially at sub–solar metallicities (e.g. Oliva & Origlia 1998, Origlia et al. 1999).

The most striking result in Fig. 1 is the very different behaviour in the AGB phase (i.e. $t \gtrsim 100$ Myr) where the predicted CO index varies by large (>3) factors depending on the adopted stellar evolutionary tracks. In particular, the steady decay of [CO] in the curves based on the Geneva's models contrasts with the increase at the onset of the AGB predicted by the Padua's tracks. Interestingly, the latter predict strong CO at low metallicities where the other models give [CO]$\simeq$0.

To investigate the reason(s) for the very different behaviours in the AGB phase, it is instructive to compare the model isochrones which are displayed in Fig. 2 for two representative ages at solar metallicity. The Geneva's curves stop at relatively low luminosities and high temperatures (>3600 K), this implies that the stars dominating the IR emission are warm enough to dissociate CO, have quite large surface gravities and relatively low luminosity. Thus the CO bands are weak because the CO/C relative abundance, the column density of the photosphere and the microturbulent velocity are all relatively small (see Sect. 2.2). The AGB in the Padua's models, on the contrary, extends to very high luminosities and low temperatures. This implies low surface gravities and large microturbulent velocities, i.e. deep CO features.

The different extent of the AGB in Fig. 2 primarily follows from assumptions made by the models. The Geneva's tracks arbitrarily stop at the onset of thermal pulses, while the Padua's computations follow this phase up to the very end of the double shell burning using semi–analytical approximations. However, both approaches are unrealistic because the evolution along the AGB, which for sure extends well into the thermal pulses phase, is regulated and shortened by the strong mass–loss experienced by AGB stars, a parameter not included in the Bertelli et al. (1994) tracks. Moreover, one should keep in mind that the predicted stellar temperatures are also quite uncertain and, probably, too warm (Chieffi et al. 1995, Oliva & Origlia 1998). This effect is visible in Fig. 2 where one can notice that, within the part of the AGB covered by both models, the Padua's tracks are systematically warmer than those of Geneva. Indeed, recent developments of the theory of convective energy transfer indicate that all the temperatures of red stars in the Padua's tracks should be decreased by 200–300 K (Bressan, private communication).

Therefore, the "true" AGB is likely to be less extended but redder than predicted by the Padua's tracks and the two effects on the [CO] should compensate each others. In practice, the "true" CO index during the AGB phase is probably similar to that plotted in the right hand panels of Fig. 1. For the moment being, assuming [CO] $\simeq$ constant with time is probably a fair approximation which, at least, does not lead to far reaching conclusions on the age of stellar systems.

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[1] $L_{\rm K}$ (erg s^{-1} μm^{-1}) is the luminosity per λ-unit at 2.2 μm

4. Available data and SSP templates

Stellar clusters in the Large Magellanic Cloud provide a convenient and, in practice, unique set of templates for young and intermediate age stellar populations spanning a wide range of metallicities (between 1/100 and $\simeq$ solar, e.g. Sagar & Pandey 1989). The available [CO] data are summarized in Fig. 3. The large scatter of the points at a given age reflects variations of metallicities, statistical effects related to the intrinsic small number of luminous red stars in the clusters and, possibly, field contamination (see e.g. Chiosi et al. 1986, Santos et al. 1997). A further complication occurs beyond $\approx$600 Myr, when carbon stars appear. These often display a very red spectrum with strong continuum emission from the envelope which dilutes the CO bands and produce an anti–correlation between J–K colours and [CO] index (Persson et al. 1983). Note in particular that the mild anti–correlation between CO index and age visible in Fig. 3 also reflects the fact that the older clusters are, on average, less metallic than the youngest one's.

For the purposes of this paper, the most important fact is that several of the LMC clusters with ages $\geq$100 Myr display [CO] indices much larger than those predicted by the models based on the Geneva's tracks. In other words, a highly metallic stellar population of 100–1000 Myr could have a [CO] similar to that of a 10–100 Myr cluster of the same metallicity, as indeed predicted by models including the whole AGB evolution (see Sect. 3).

Therefore, finding a galaxy with a very deep CO index does not necessarily imply that its stellar population must be younger than 100 Myr, as sometimes assumed in literature.

Fig. 3 also shows results from a wider set of data, including old stellar systems (Galactic globular clusters and ellipticals) and starburst galaxies. In general, the only clear observational result is that objects with [CO] significantly larger than 0.18 cannot be old stellar systems of (sub)solar metallicities, but require younger stellar populations or, alternatively, old stellar populations much more metallic than ellipticals. Encouragingly, several starburst galaxies do indeed display CO indices significantly larger than the above threshold but, in most cases, within the range covered by LMC clusters of ages $\lesssim 10^9$ yr (see Fig. 3).

On the other hand, however, other well studied starbursters have values of [CO] lower than 0.18 and more similar to ellipticals and bulges. This probably reflects metallicity variations, i.e. weaker CO features can be associated with young stellar systems of lower metallicities.

5. Conclusions

Very large values of the CO index around 2.3 μm (i.e. [CO]>0.18, larger than those observed in the oldest, metal rich stellar systems) indicate that the near IR luminosity should be dominated by a relative young SP of RSG/AGB stars.

Any further attempt to better quantifying the age of this young SP in the range 10 Myr – 1 Gyr is unreliable since the theoretical evolutionary tracks are still too uncertain to properly describe the red supergiant and AGB evolution, especially at sub–solar metallicities.

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