

# Chemically Consistent Evolutionary Models with Dust

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## Abstract.

As a tool to interpret nearby and high redshift galaxy data from optical to K-band we present our chemically consistent spectrophotometric evolutionary synthesis models. These models take into account the increasing initial metallicity of successive stellar generations using recently published metallicity dependent stellar evolutionary tracks, stellar yields and model atmosphere spectra.

The influence of the metallicity is analysed. Dust absorption is included on the basis of gas content and abundance as it varies with time and galaxy type. We compare our models with IUE template spectra and are able to predict UV fluxes for different spectral types. Combined with a cosmological model we obtain evolutionary and k-corrections for various galaxy types and show the differences to models using only solar metallicity input physics as a function of redshift, wavelength band and galaxy type.

## 1. Introduction

The data on high and very high redshift galaxies is rapidly increasing these days. Many U- and B-dropout galaxies with photometric redshift estimates are known from the HST HDF, more than 550 have confirmed redshifts at  $z \sim 3$  (Steidel et al. 1998). Many more will be detected in ground-based large and deep field projects (e.g. FORS – Deep Field on VLT). Deep surveys are conducted at all wavelengths from UV through IR and far into the submm range (SCUBA on JCMT). These brilliant data require mature galaxy evolution models for adequate interpretation. Ideally, these models should cover the wavelength range from UV through FIR and submm and describe the evolution of as many observable quantities as possible (spectrum, luminosities, colours, emission and absorption features for the stellar population, the gas content and a large number of element abundances for the ISM) and, at the same time, be as simple as possible, involving the smallest possible number of free parameters. A realistic galaxy evolution model should consistently take into account both the age and metallicity distributions of the stellar populations that inevitably result from any extended SF history. This is what we attempt with our chemically consistent



spectrophotometric, chemical and cosmological evolutionary synthesis model. The chemical evolution aspects of this model are presented in Lindner et al. (1999)) and in Fritze-v. Alvensleben et al. (this conference) in comparison with and interpretation of the observed redshift evolution of damped Ly $\alpha$  (DLA) abundances.

Spectrophotometric and cosmological evolutionary synthesis models generally applied in current interpretations of high redshift galaxy data are using solar metallicity input physics (Bruzual & Charlot 1993), Guiderdoni & Rocca – Volmerange 1987, 1988, Fioc & Rocca – Volmerange (1997), Poggianti (1997), Bressan et al. 1994) together with specific parametrisations for the SF histories of various spectral types of galaxies. The first attempts to account for non-solar abundances and their impact on the photometric evolution of galaxies go back to Arimoto & Yoshii (1986). Einsel et al. (1995) used more recent and complete stellar evolutionary tracks and colour calibrations for initial stellar metallicities  $10^{-4} \dots 4 \cdot 10^{-2}$  to describe the photometric evolution of galaxy types E through Sd. In Möller et al. (1997) we introduced the concept of chemical consistency into the spectrophotometric evolution of galaxies and investigated the time evolution of ISM metallicity and luminosity – weighted mean stellar metallicities in various wavelength bands. For models that well agree with observed template spectra (Kennicutt 1992) of various types (E, Sb, Sd) we gave decompositions of the total light emitted at wavelengths from U through K in terms of luminosity contributions from various metallicity subpopulations. This clearly shows the considerable widths of the metallicity distributions in all 3 galaxy types.

While in earlier investigations the main focus was on the role of  $Z > Z_{\odot}$  stars in bulges and the centers of luminous elliptical galaxies, it is clear by today that the average stellar metallicity is  $\sim Z_{\odot}$  in L\* ellipticals e.g. (Loewenstein & Mushotzky 1997) and  $< Z_{\odot}$  in lower luminosity ellipticals as well as in bulges (Mc Williams & Rich 1994). HII region abundances in spirals show negative radial gradients and characteristic oxygen abundances (at  $r = 1R_e$ ) in the range  $0.5 \dots 1.6 \cdot Z_{\odot}$  (cf. Oey & Kennicutt 1993, Zaritsky et al. 1994, Ferguson et al. 1998). These characteristic HII region abundances are well reproduced by our chemically consistent chemical evolution models for galaxy types Sa through Sd and are expected to give an upper limit to the metallicity of the youngest stars. Galactic B-star abundances point to a modest  $Z \sim \frac{1}{2} \cdot Z_{\odot}$  in the ISM of the Milky Way (e.g. Kilian-Montenbruck et al. 1997). Thus, it is evident that sub-solar abundances as well as chemically consistent modelling become more and more important for the global properties of galaxies when going to later spiral types or dwarf galaxies, already at  $z \sim 0$ , and even more so towards higher redshift.

In recent years it has also become increasingly clear that dust in galaxies plays a non-negligible role in determining the appearance and their observed spectral energy distributions both for nearby and high redshift galaxies. Dust obscuration of a factor of a few has been inferred in the spectral energy distributions of young galaxies at redshift  $z \geq 1$  (Steidel et al. 1999, Glazebrook et al. 1999). In light of the potential importance of dust, we present our galaxy evolution models for both cases with/without dust.

Here we present the extended spectrophotometric model which includes the effects of dust in a chemically consistent manner, with the amount of dust tied to the amount and metallicity of gas as they evolve with time for various galaxy types.

## 2. Model description

Our galaxy evolution model was first described by Fritze - v.A. (1989), the extended version allowing for a chemically consistent modelling for the photometric evolution and in detail by Möller et al. (1997), for the spectral and spectrophotometric evolution.

In the following we briefly outline the principle of our concept of chemical consistency which we consider an important step towards a more realistic galaxy modelling. In contrast to single burst single metallicity stellar populations like star clusters our chemically consistent galaxy evolution model follows the metal enrichment of the ISM and accounts for the resulting metallicity distribution of the composite stellar population, both with respect to the evolution of ISM abundances (Lindner et al. 1998) and to the spectral evolution as presented here. We use various sets of stellar tracks and yields from the Padova group (Bressan et al. 1993, Fagotto et al. 1994a,b,c) and from Chabrier & Baraffe (1997) for  $m_* < 0.8M_\odot$  for five different metallicities from  $Z = 4 \cdot 10^{-4}$  to  $5 \cdot 10^{-2}$ . The evolution of each star is followed in the HR diagram from birth to its final phases for five discrete metallicity ranges. If the ISM metallicity increases above one of our limiting metallicities, the evolution of stars formed thereafter is followed with the tracks for the next higher metallicity. At any timestep the HRD population is used to synthesize an integrated galaxy spectrum from a library of stellar spectra. This library contains stellar model atmosphere spectra from UV to the IR for all spectral types, luminosity classes and 5 metallicities (Lejeune et al. 1998). The total galaxy spectrum is obtained by summing the stellar spectra, weighted by the population of the HRD for each metallicity and, finally, by coadding the spectra of the various single metallicity subpopulations.

For a given IMF, the spectral galaxy types E, ..., Sd are described by appropriate SF histories. Our E/S0 model has a SFR  $\sim e^{-\frac{t}{t_*}}$  with an e-folding time  $t_* = 1 - 1.5$  Gyr, while for spiral models we assume SFRs linearly proportional to the gas-to-total mass ratio with characteristic timescales for SF  $t_* = 4-5, 7-8, 9-10$  Gyr for the Sa, Sb, Sc model respectively. The Sd model is described by a constant SFR. The total mass of the galaxy is  $2 \cdot 10^{11} M_\odot$  (E/S0),  $10^{11} M_\odot$  (Sa, ..., Sc),  $5 \cdot 10^{10} M_\odot$  (Sd) to yield after a Hubble time the observed type specific  $M_B^*$ .

Our model is simply a closed box with instantaneous gas mixing, but it fully takes into account the finite stellar lifetimes.

We adopt a simplified model of the dust distribution in galaxies, discriminating between spheroidal and disk configurations. For purely spheroidal systems (e.g. ellipticals), we assume that the dust has the same distribution as the stars, and that the two components are well mixed. Thus, dust extinguishes light according to the standard formula  $\frac{1-e^{-\tau}}{\tau}$ , with  $\tau = \tau(\lambda)$  the optical depth at wavelength  $\lambda$ . For disk systems, we assume the dust is distributed homogeneously in the disk, with a vertical scale height which is the same as that of the young, UV-bright stellar component (Wang & Heckman 1996). The ratio of dust-to-stellar scale heights decreases from unity in the UV to  $\sim 0.25$  at optical wavelengths where the emission is dominated by older stars. This configuration mimics the disk/bulge separation as observed (e.g. Kylafis & Bahcall 1987). The extinction curve we use is the one appropriate for the Small Magellanic Cloud (Bouchet et al. 1985). The choice of the extinction curve has very little, if any, effect longward of  $3000 \text{ \AA}$ , where all three known extinction curves (MW, LMC, SMC) are similar; in the UV, however, differences are more important (cf. Figure 1 in Calzetti et al. 1994). Since we are modelling galaxies with a wide variety of properties, we adopt as a preliminary approach the SMC extinction curve in the UV. This is equivalent to picking up the low-metallicity, moderately star-forming environment of the SMC as typical for the galaxies we model. We calculate the extinction in a chemically consistent way assuming that the amount of dust is proportional to the gas column density and the ISM metallicity which keeps dust/metals constant over the time evolution (Dwek 1998).

Combining the spectrophotometric time evolution with a cosmological model and some assumed redshift of galaxy formation we calculate the evolutionary and cosmological corrections as well as the evolution of apparent magnitudes from optical to NIR for various spectral types and cosmological parameters taking into account the attenuation by intervening HI as described by Madau (1995).

## 2.1. EXTINCTION IN DIFFERENT HUBBLE TYPES

In Figure 1 we show for various galaxy models the time evolution of ISM metallicity, gas content and extinction. In the following we classify the various spectral types from E, S0,..., Sd with their characteristic timescales. After a Hubble time, our models not only have the observed colours and spectral energy distributions of the respective nearby galaxy types (see comparison with Kennicutt templates in Möller et al. 1999) but also the observed average ISM abundances at  $\sim 1R_e$ , gas content and  $E(B-V)$  of nearby galaxies. To represent the wide range of observed properties for elliptical and S0's we calculate two different models varying  $t_*$  from 1 (a) to 1.5 (b) Gyr which has no remarkable effect on the spectral energy distribution except for the resulting extinction  $E(B-V)$  over the entire time evolution. After a Hubble time both E/S0 models have the same ISM metallicity of about  $Z \sim Z_\odot$ . While in model a) SF stops after 2 Gyr and the amount of gas increases to a few percent due to the stellar yields, the star formation in model b) continues until the gas content is negligible. Therefore the extinction in both models varies between  $E(B-V) = 0$  and 0.1 after a Hubble time. These values are in good agreement with observations of field ellipticals (Goufrooij et al. 1994), for  $E(B-V)$  can go up to 0.2. The influence of the IMF is seen in the comparison of the two Sa models with Salpeter IMF (c) and Scalo IMF (d). All other models are calculated with Salpeter IMF. The model with Salpeter IMF produces more metals and therefore results in a higher metallicity but also consumes more gas for the same SFR and gives a lower extinction after a Hubble time. The model with  $t_* = 8$  Gyr (e) shows the highest present day extinction of about 0.3 to 0.4 mag which is also observed in Gonzalez et al. (1998). The chemically consistent model with constant SF also shows an evolutionary effect because of the increasing abundances and decreasing gas content not only in the time evolution of its SED but also due to its increasing extinction.

In all models, except for the constant SFR, we see that the evolution of the extinction over redshift shows a maximum at high  $z$ , which is different for the various spectral types, and then decreases again to very high  $z$  due to the low metallicity.

## 3. Comparison with nearby galaxies

Our model describes the entire spectrophotometric evolution of field galaxies, e.g. metallicities and colours measured at  $1 R_{\text{eff}}$ . In particular our E model represents a medium luminosity elliptical galaxy.

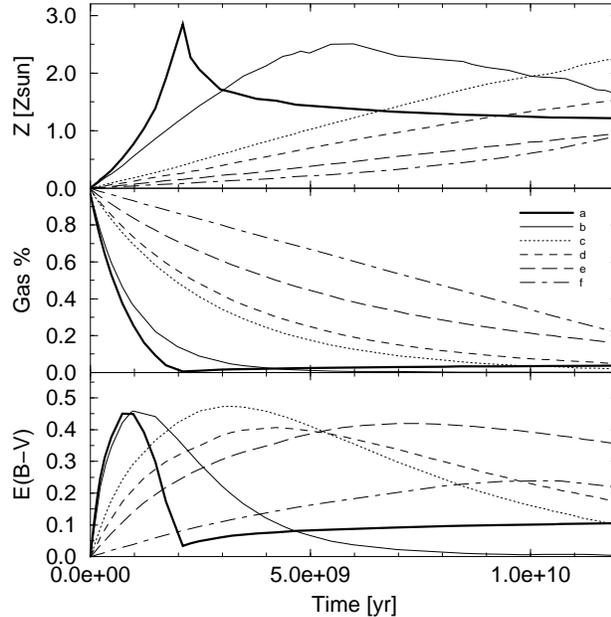


Figure 1. Time evolution of ISM metallicity (top), gas content (middle) and extinction (bottom) for galaxy models E/S0 (a) and (b), Sa (b) and (c), Sb (e), Sd (f).

We have shown that our model well describes the stellar metallicity observed by absorption indices (Möller et al. 1997) and the chemical evolution of nearby and high redshift spiral galaxies (Lindner et al. 1999). Our model SEDs for various types E, Sa,..., Sd show very good agreement with the templates NGC 3379, NGC 3368, ..., NGC 4449 from Kennicutt's atlas in the wavelength range (3600 - 6800) Å.

The galaxy NGC 1553 (Kinney et al. 1996) is best reproduced by a  $t_*$  = 1 Gyr model with an  $\sim 11$  Gyr old stellar population, a mean ISM metallicity of  $Z = 1.2 Z_{\odot}$  and  $E(B-V) = 0.1$ .

The UV and optical spectrum of NGC 210, a template Sb galaxy, from Kinney et al.'s atlas are compared to our model spectra in Figure 2. While our Sb or ( $t_* = 8$  Gyr) model with or without dust only gives a very poor match, we find good agreement over the entire wavelength range (912 - 10000 Å) with our  $t_* = 1$  Gyr model at an age of the stellar population of  $\sim 9$  Gyr,  $Z = 1.3Z_{\odot}$  and  $E(B-V)=0.1$ . The point is that for nearby galaxies the IUE Aperture of 10"x20" only covers the central 300 - 500 pc which are dominated by the bulge component. The optical aperture in this case matches the one in the UV so that the agreement with our  $t_* = 1$  Gyr model, which is appropriate for

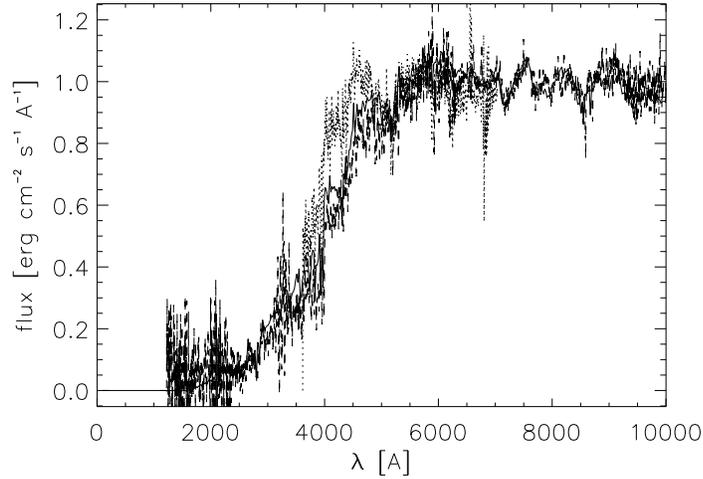


Figure 2. Comparison of Sb templates NGC3147 (dotted), NGC210 (dashed) with galaxy model  $t_* = 1$  Gyr (solid). Fluxes are normalized at 5500 Å.

spheroidals and bulge components, is a result of this small aperture effect: while the integrated spectrum of the Sb template NGC 210 should be well described by our  $t_* = 7-8$  Gyr model as is e.g. the case for Kennicutt’s integrated Sb template spectrum of NGC 3147, its bulge spectrum clearly requires a short SF timescale  $t_* = 1$  Gyr.

It would be necessary to observe the UV flux over a wider area. So far our models give predictions for the extinction and the metallicity, and it should be possible to disentangle extinction and metallicity with a wide wavelength basis from far UV to opt. or NIR bands.

#### 4. Summary and outlook

We have extended our spectrophotometric and chemical evolutionary synthesis model in a chemically consistent way. We present the time and redshift evolution of the extinction in various galaxy types resulting from the evolution of their gas contents and metallicities. Comparing our model SED’s with templates from Kennicutt’s and Kinney et al.’s atlas we show the detailed agreement of our model spectra with **integrated** spectra of galaxies and point out the importance of aperture effects on the example of an Sb galaxy.

We have compiled a large grid of evolutionary and cosmological corrections from UV to IR and compare the models using only solar metallicity with the chemically consistent models (Möller et al. 1998).

A detailed description and comparison of model results w/o dust with observations of colors and luminosity of high redshift galaxies will be presented in Möller et al. 1999.

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