Chemically Consistent Evolutionary Synthesis Models

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Abstract. Any stellar system with a star formation history (SFH) more extended than a massive star’s lifetime will be composite in metallicity. Our method of chemically consistent evolutionary synthesis tries to account for the increasing initial metallicity of successive generations of stars. Using various sets of input physics for a range of metallicities $10^{-4} \leq Z \leq 0.05$ we keep track of the ISM enrichment and follow successive generations of stars using stellar evolutionary tracks, yields, model atmosphere spectra, index calibrations, etc., appropriate for their respective initial metallicities. Since the SFH determines the evolution not only of the metallicity, but, in particular, of abundance ratios of specific elements, stellar evolution and galaxy evolution become intimately coupled. I review the concept of chemically consistent evolution, present results for the photometric, spectral, and chemical evolution of galaxies of various types in the local Universe and at high redshift, and discuss its advantages as well as its current limitations.

1. Introduction

In principle, any stellar system with star formation (SF) going on over more than the lifetime of the most massive stars plus the cooling time of the gas is composite in terms of age and metallicity. Since this is the case for any composite stellar system like a galaxy – as opposed to star clusters – the importance to account for realistic metallicity distributions in evolutionary galaxy models is evident. For quite some time, observational evidence has been a cumulating for finite and often very large metallicity distributions, e.g., spanning a range of more than a factor of 100 in bulges from $(0.01 - 3) \cdot Z_{\odot}$ (e.g. Jacoby & Ciardullo 1999). While some years ago, the focus was on super-solar metallicities e.g. in (the centers of) massive ellipticals, bulges, X-halos around ellipticals, and the hot ICM, by today, it is clear that the average metallicities in all those cases are subsolar. When averaged over 1 $R_e$, line strength gradients in E/S0s show $\langle Z_e \rangle \sim (0.5 - 1) \cdot Z_{\odot}$ (Carollo & Danziger 1994). For stars in bulges $\langle Z_e \rangle \sim (0.3 - 0.7) \cdot Z_{\odot}$ (e.g. McWilliam & Rich 1994), for the X-gas halos of ellipticals ASCA observations give $0.1 \leq [\text{Fe/H}] \leq 0.7$ (e.g. Loewenstein 1999). Characteristic HII region abundances (i.e. measured at 1 $R_e$) range from $Z \gtrsim Z_{\odot}$ for Sa spirals down to $\sim \frac{1}{2} Z_{\odot}$ for Sd galaxies (e.g. Oey & Kennicutt 1993, Zaritsky et al. 1994, Ferguson et al. 1998, van Zee et al. 1998). The sun, our reference star, stands out in metallicity among solar neighborhood stars. For F, G, K dwarfs the $[\text{Fe/H}]$ distributions extend from $-0.8$ to $+ 0.4$ (Rocha-Pinto
While B-stars show $\langle [O/H] \rangle = -0.31$ (Kilian-Montenbruck et al. 1994). Locally already, dwarf irregulars have metallicities in the range $(2-30)\% Z_\odot$ (e.g. Richer & McCall 1995). The first spectra of Lyman break galaxies at $z \sim 3-4$ have shown that their metallicities, derived from stellar wind features, are considerably subsolar, sometimes even sub-SMC (Lowenthal et al. 1997, Trager et al. 1997). Neutral gas in damped Ly$\alpha$ absorbers observed to $z > 4$ shows abundances $-3 \lesssim [\text{Zn/H}] \lesssim 0$ (cf. Sect.5).

2. Chemically Consistent Modelling

Evolutionary synthesis models start from a gas cloud of mass $G$, initially comprising the total mass $M$, with primordial abundances, give a star formation rate $\Psi(t)$ and an IMF, and form the 1$^{st}$ generation of stars with $Z = 0$. We solve a modified form of Tinsley’s equations with stellar yields for SNII, SNI, PN, and stellar mass loss for $Z = 0$ to obtain ISM abundances and abundance ratios. The next generation of stars is formed with abundances $Z > 0$ and abundance ratios $[X_i/X_j] \neq 0$, and again, the modified Tinsley equations are to be solved with yields for $Z > 0$ and $[X_i/X_j] \neq 0$, ...

It is seen that via the SFH galaxy evolution and stellar evolution become intimately coupled. In principle, stellar evolutionary tracks and yields would be required not only for various metallicities (and He contents), but also for various abundance ratios. The SFH – if short and burst-like or mild and $\sim const$ – leads to different abundance ratios between elements with different nucleosynthetic origin, as e.g. $[\text{C/O}]$ or $[\text{O, Mg, ..., Fe}]$, where C comes from intermediate mass stars and Fe has important SNI contributions (cf. Sect.5), both leading to a delayed production with respect to the SNII products O, Mg, etc. However, no complete grid of stellar evolutionary tracks or yields for varying abundance ratios $[\text{Mg/Fe}]$ or $[\alpha/\text{Fe}]$ is available.

Our chemically consistent (= cc) evolutionary synthesis models follow the evolution of ISM abundances together with the spectrophotometric properties of galaxies and account for the increasing initial metallicity of successive generations of stars by using various sets of input physics – stellar evolutionary tracks, model atmosphere spectra, color and absorption index calibrations, yields, lifetimes, and remnant masses – ranging in metallicity from $Z = 10^{-4}$ up to $Z = 0.05$.

The two basic parameters of our evolutionary synthesis model are the IMF, which we take from Scalo, and SFHs, which we appropriately chose for different galaxy types. For ellipticals we use $\Psi(t) \sim e^{-t/t_*}$, for spiral types Sa ... Sc $\Psi(t) \sim \frac{G(t)}{t}$, and for Sd $\Psi(t) = const.$ with characteristic timescales for SF $t_*$ (for spirals defined via $\int_0^{t_*} \Psi \cdot dt = 0.63 \cdot G |_{t=0}$) ranging from 1 Gyr (E) to 2, 3, 10, and 16 Gyr for Sa, Sb, Sc, and Sd, respectively.

Our chemically consistent models simultaneously describe the spectrophotometric evolution in terms of spectra, luminosities, colors (UV – IR), emission and absorption lines as a function of time or – for any cosmological model as given by $H_0, \Omega_0, \Lambda_0$, and a redshift of galaxy formation $z_{\text{form}}$ – the redshift evolution of apparent magnitudes UBVRIJHK and colors, including evolutionary and cosmological corrections, as well as the attenuation by intervening HI, and
the chemical evolution in terms of ISM abundances of individual elements $^{12}\text{C}$, $^{56}\text{Fe}$ as a function of time or, again, of redshift.

The SFHs have been chosen as to provide agreement, together with the IMF, of our model galaxies after a Hubble time with integrated colors, luminosities, absorption features (E/S0s), emission line strengths (spirals), typical for the respective galaxy types, as well as with template spectra (Kennicutt 1992, see Möller et al. 1999a for details), and characteristic HII region abundances.

As compared to models using solar metallicity input physics only, our cc models use somewhat different SFHs, even for galaxies that by today come close to $Z_\odot$. Clearly, differences between cc and $Z_\odot$ models become increasingly important towards higher redshift for all galaxy models.

We caution that our models are simple 1-zone descriptions without any dynamics or spatial resolution, meant to describe global average quantities like integrated spectra or colors, and absorption line strengths or HII region abundances around $\sim 1 R_e$.

### 3. Chemically Consistent Photometric Evolution

Having only available a very incomplete grid of stellar evolutionary tracks and color calibrations, Arimoto & Yoshii 1986 were the first to attempt a cc approach to photometric evolution. Einsel et al. 1995 compiled more complete data sets for 5 metallicities to describe the photometric evolution in terms of colors and absorption line indices on the basis of stellar tracks from the Geneva, color calibrations from the Yale, and index calibrations from the Lick groups, respectively.

In Möller et al. 1997 we present cc spectrophotometric evolution models based on most recent input physics. We discuss the comparison between the (mass-weighted) ISM metallicities for various galaxy types and the luminosity-weighted metallicities of the stellar population seen in different wavelength bands. At late stages, stars in models with const. SF (Sd) show a stellar metallicity distribution strongly peaked at $\frac{1}{2}Z_\odot$ at all wavelengths and close to the ISM metallicity. Elliptical models, on the other hand, show broad stellar metallicity distributions extending from $Z = 10^{-4}$ to $Z = 0.05$ in all bands with the maximum luminosity contribution in U coming from stars with $< \frac{1}{2}Z_\odot$, and in K from stars with $\sim Z_\odot$, as shown in Fig.1. The largest difference of as much as a factor 2 is obtained in our Sb model between the luminosity-weighted stellar metallicity (e.g. in V) and the ISM metallicity. The time evolution of all these metallicities for different galaxy types are presented in Möller et al. 1997 together with the evolution of colors and absorption line indices. In Kurth et al. 1999 we present single burst single metallicity models using stellar tracks from the Padova group and compare the time evolution of colors and absorption indices to globular cluster observations. We give theoretical color and index calibrations in terms of [Fe/H] and investigate how they evolve with age.

Stellar abundance ratios, like $[\text{Mg}/\text{Fe}]_*$, as derived from absorption line ratios, depend on the initial abundance ratio $[\text{Mg}/\text{Fe}]_*$ of the star, on modifications through nucleosynthesis and mixing during the life of the star, and on physical parameters in the stellar atmosphere. The Fe index, e.g., is as sensitive to Fe as to global metallicity Z, which to 50% is made up by oxygen from SNII (Tripicco & Bell 1995). Abundance ratios in galaxies additionally depend on the
age and metallicity distributions of the stars and, hence, on the SFH, the IMF, any possible pre-enrichment (from Pop 3, halo, ...), on metal-poor infall and/or metal selective outflow, which determine the ISM abundance ratio $[\text{Mg/Fe}]_{\text{ISM}}$ before the birth of the stars. In particular do solar abundance ratios, taken for reference, reflect the local SFH, IMF, and all pre-enrichment & dilution effects of the local ISM. Looking at the metallicity dependent SNII – yields (cf. Sect.5) we notice that, integrated over the IMF, the ejected mass ratio $M(\text{Mg})/M(\text{Fe})$ increases by large factor when going down in metallicity from $Z_{\odot}$ to $10^{-3} \cdot Z_{\odot}$. A lower metallicity limit for SNIa, as discussed by Kobayashi et al. 1998 would further increase $[\text{Mg/Fe}]_{\text{ISM}}$ at early stages. Therefore, all conclusions drawn for galaxies from a comparison of observed $[\text{Mg/Fe}]_{*} > 0$ with $Z_{\odot}$ models concerning a top-heavy IMF, a shorter SF timescale in massive Es, a higher SFE, etc. – should be taken with extreme caution (cf. Fritze - v. Alvensleben 1998).

4. Chemically Consistent Spectro-Cosmological Evolution

Using sets of model atmosphere spectra covering all spectral types, luminosity classes, and our 5 metallicities (Lejeune et al. 1997, 1998) we describe the cc spectral evolution of our model galaxies. The agreement of our model spectra after a Hubble time with nearby templates is shown by Möller et al. 1997 and 1999a. With any kind of cosmological model we calculate evolutionary and cosmological corrections, apparent magnitudes U, ..., K, and colors as a function of redshift $z$. Attenuation by intervening hydrogen (Madau 1995) is included, dust extinction depending on metallicity and gas content is currently being added in collaboration with D. Calzetti (cf. Möller et al. 1999b).

For the Sd galaxy model, Fig.2a shows the cc $(e + k)$ corrections in B and K as compared to those for the $Z_{\odot}$ model. In B, cc models give $(e + k)$ corrections that make Sd galaxies brighter by $\gtrsim 1$ mag at $z \sim 0.7$ and by $\gtrsim 2$ mag for $z \gtrsim 2$ as compared to $Z_{\odot}$ models. In the K-band as well, differences are quite significant with Sd galaxies being brighter in cc models by $\gtrsim 1$ mag at $z \gtrsim 1$. Moreover, the
successive building-up of the stellar metallicity distributions tends to increase the evolutionary effects as compared to Z⊙ models. In addition to the cosmological dimming (kUBVRI > 0) the Sd model is brightened by the evolutionary correction by ≳ 2 mag at z ≳ 0.7 and by ≳ 3.5 mag at z ≳ 3 in B (cf. Fig.2b), while in K, Sd models still have (e + k) ≲ −1.5 mag at all z ≳ 0.7 − 3. The cc spectro-cosmological models and the comparison with high redshift galaxy data will be presented in detail in Möller et al. (in prep.).

5. Chemically Consistent Chemo-Cosmological Evolution

Timmes et al. 1995 and Portinari et al. 1998 were the first to use stellar yields for a range of metallicities in models for the chemical evolution of the Milky Way and the solar neighbourhood, respectively. For our “spectroscopically successful” models for various galaxy types we now use element yields for different metallicities for successive generations of stars to describe the time evolution of a series of individual elements from 12C through 56Fe. For any cosmological model the time evolution directly transforms into a redshift evolution. SNII yields for massive stars (> 8 M⊙) are from Woosley & Weaver 1995, yields for intermediate mass stars from van den Hoek & Groenewegen 1997. SNIa contributions to Fe, C, ..., are included for the carbon deflagration white dwarf binary scenario as outlined by Matteucci & Greggio 1986. SNIa yields are only available for Z⊙ (Nomoto et al. 1997, model W7), however, no important metallicity dependence is expected for SNIa yields except for a possible lower metallicity limit to the explosion (Kobayashi et al. 1998). Mass loss from stellar winds as e.g. given by Portinari et al. 1998 is not included yet. We recall that metallicity dependent stellar yields are only available for solar abundance ratios and we have no idea, if and in how far non-solar abundance ratios would influence the stellar shell structure and, hence, the yields. Moreover, stellar yields depend on ΔY, explosion energies, remnant masses, etc. and the metallicity dependence of these
factors is still poorly understood. No clear trends are seen, neither in the output of element $X_i$ from stars of given mass as a function of metallicity, nor, at const. metallicity, as a function of stellar mass.

We stress that for a given SF history and IMF our models yield absolute abundances that do not require any scaling or normalisation.

We compared the redshift evolution of C and Mg abundances with CIV- and MgII-QSO absorber statistics (Fritze - v. Alvensleben et al. 1989, 1991 using yields for $Z_{⊙}$ stars only). CIV- and MgII-absorption is caused by the moderate column density gas in extended galaxy halos $(17.5 \leq \log N(\text{HI}) \text{[cm}^{-2}\text{]} \leq 20)$. We argued that the cross section for CIV- and MgII-absorption should scale with the abundance of the respective elements and that, hence, the redshift evolution of the comoving number density of absorbers should trace the abundance evolution. The first direct abundance determinations (Stengler - Larrea 1995) a posteriori justified our assumption. We found good agreement of the observations with a standard model for halo SF ($t_* \sim 1 \text{ Gyr}$), derived constraints for $t_*$, the IMF, and the cosmological parameters, and predicted a low number of CIV systems at low redshift, which was impressively confirmed by HST key project data (Bahcall et al. 1993).

Our cc chemo-cosmological models are compared with observed abundances in damped Lyα absorbers (=DLAs) in Lindner et al. 1999. DLAs show radiation damped Lyα lines due to high column density gas $(\log N(\text{HI}) \text{[cm}^{-2}\text{]} \geq 20.3)$ and a large number of associated low ionisation lines of C, N, O, Al, Si, S, Cr, Mn, Fe, Ni, Zn, ... High resolution observations (KECK and WHT) that fully resolve the complex velocity structure in the lines allow to derive precise element abundances in a large number of DLAs over the redshift range $0 \ldots \geq 4$ (Boissé et al. 1998, Lu et al. 1993, 1996, Pettini et al. 1994, 1999, Prochaska & Wolfe 1997, ...). Based on similarities of their HI column densities with those of local spiral disks, of their comoving gas densities at high z with (gas + star)-densities in local galaxies, and based on line asymmetries indicative of rotation, damped Lyα absorption is thought to arise in (proto-)galactic disks along the line of sight to a distant QSO (e.g. Wolfe 1995). Alternatively, Matteucci et al. 1997 propose starbursting dwarf galaxies on the basis of $[\text{N}/\text{O}]$ ratios, while Jimenez et al. 1999 propose LSB galaxies, and Haehnelt et al. 1998 subgalactic fragments to explain DLA galaxies at low and high redshift, respectively.

After referring all observed DLA abundances to one homogeneous set of oscillator strengths and solar reference values, we compare with our spiral galaxy models Sa, ..., Sd, earlier shown to agree with characteristic HII region abundances at $z = 0$, and with spectrophotometric properties as observed to $z \gtrsim 1$. As can be seen in Fig.3 on the example of Zn, our Sa and Sd models bracket the redshift evolution of DLA abundances from $z \geq 4.4$ to $z \sim 0.4$. Similar agreement is found for all 8 elements with a reasonable number of DLA data available. Since Phillipps & Edmunds 1996 and Edmunds & Phillipps 1997 have shown that the probability for an arbitrary QSO sightline to cut through an intervening gas disk and produce DLA absorption is highest around $1 \text{ Re}$, our models bridge the gap from high-z DLAs to nearby spiral HII region abundances. We conclude that from the point of view of abundance evolution, DLA galaxies may well be the progenitors of normal spirals Sa – Sd, although we cannot
exclude that some starbursting dwarf or LSB galaxies may also be among the DLA galaxy sample.

The influence of the metallicity dependent yields is seen from the comparison with $Z_\odot$ models in Fig.3 and varies from element to element. Whenever a significant difference is seen, the cc models give a good representation of the data while the $Z_\odot$ models lose data points above the Sa or below the Sd curves. We also show models with SNII yields calculated under the assumption of higher explosion energies (model C of Woosley & Weaver 95), which does not make much difference. Curves for Sb and Sc models run between those for Sa and Sd and are omitted for clarity.

Comparison of cc chemo-cosmological models with observed DLA abundances further shows that the weak redshift evolution of DLA abundances is a natural result of the long SF timescales for disks galaxies, and the range of SF timescales $t_\ast$ for spirals from Sa through Sd fully explains the abundance scatter among DLAs at any redshift.

Somewhat surprisingly, abundances of elements which locally are known to strongly deplete onto dust grains (like Fe or Cr) are as well described by our models as are non-refractory elements like Zn. We prefer, however, not to draw conclusions about the importance of dust in DLAs in view of the uncertainties in the stellar yields and the simplicity of our closed-box 1-zone model.

Fig.3 also shows that while at high redshift all spiral types seem to give rise to DLA absorption, no more data points at $z \lesssim 1.5$ reach close to our early type spiral models. At low redshift, the gas poor early type spirals seem to drop out of DLA samples. While a deficiency of high N(HI) systems at low z has been noted before (Lanzetta et al. 1997), and attributed to their high metallicity and dust content (Steidel et al. 1997), our models indicate an additional reason: as the global gas content drops, the probability for a QSO sightline to cut through a high N(HI) part of the galaxy decreases, i.e. the cross
section for damped Lyα absorption gets reduced. If this were confirmed by further low-z DLA data, it would have serious implications as to the possibility to optically identify DLA galaxies. Locally, on average, Sd galaxies are fainter by \( \sim 2 \) mag in B than Sa’s and our cc spectro-cosmological models predict that the low-z DLA galaxies should be about as faint in B, \( R \), and K as the brightest members of the high-z population: B \( \sim 25 \), \( R \sim 24.5 \), K \( \sim 22 \) mag. Luminosities of the few optically identified DLA galaxies (and candidates) to date are in good agreement with our predictions (cf. Fritze - v. Alvensleben et al. 1999a, b, c).

Optically identified DLA absorbers with information about ISM abundances from the metal absorption lines and spectrophotometric properties of the stellar population allow to much better constrain the model parameters than either aspect (ISM or stars) alone (cf. Lindner et al. 1996). Since DLA galaxies are within the reach of 10m-class telescopes up to redshifts \( z > 3 \) and trace the normal galaxy population to these high redshifts without any bias as to high luminosity, radio power, or the like, they can give powerful constraints on the evolutionary histories and ages, and, ultimately, even on the cosmological parameters. Accurate abundance data in very low metallicity DLAs may provide valuable clues for the nucleosynthesis at low metallicity.

6. Conclusions and Outlook

I pointed out the importance of a chemically consistent modelling of the spectrophotometric and chemical evolution of galaxies that takes into account the evolving metallicity distribution of the stellar population. The comparison with models using solar metallicity input physics only showed substantial differences due to important contributions of subsolar metallicity stars both to the yields of various elements and to the spectrophotometric properties for all galaxy types, in particular when going to high redshift. I stressed the need for reliable low metallicity input physics (stellar tracks, mass loss, lifetimes, yields, remnant masses, spectra, and absorption index calibrations) and cautioned the use of solar metallicity models to derive conclusions from non-solar absorption line ratios in the clearly composite stellar populations of E/S0 galaxies. Observations of the stellar metallicity distributions in nearby galaxies will be necessary before we can reasonably relax the crude simplification of closed box models. With the same number of parameters (IMF and SF history) as standard chemical or spectrophotometric models, our unified chemical, spectrophotometric and cosmological model provides a powerful tool to constrain the parameters and ages of galaxies for which both kind of information is available.

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