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Letter to the Editor

Metallicity dependent calibrations of flux based SFR tracers

J. Bicker and U. Fritze–v. Alvensleben

Institut für Astrophysik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany
e-mail: ufritze@astro.physik.uni-goettingen.de

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ABSTRACT

We present new calibrations of the widely used H_α, [OII], and UV luminosity vs. star formation rate (SFR) relations. Using our evolutionary synthesis code GALEV we compute the different calibrations for 5 metallicities, from 1/50 solar up to 2.5 solar. We find significant changes in the calibrations for lower metallicities compared to the standard calibrations using solar input physics.

Key words. galaxies: fundamental parameters – galaxies: general

1. Introduction

Determining the Star Formation Rate (SFR) of galaxies is one of the most important steps to understand their nature and evolution. This is usually done by using the luminosity of the H_α or the [OII]line, as well as the luminosity at 1500 Å and 2800 Å in the UV, as tracer of the ongoing star formation (SF) (Kennicutt 1998; Gallagher et al. 1989; Madau et al. 1998, hereafter K98, G+89, M+98). These methods use the fact that the UV continuum and the output of ionising Lyman continuum (Lyc) photons, responsible for the gaseous emission, are dominated by young massive stars with masses $\gtrsim 10\ M_\odot$ and lifetimes $\lesssim 2 \times 10^7$ yr.

Conventionally, the standard calibrations are derived on local samples of normal, i.e. big galaxies, assuming solar metallicity, as appropriate. In the local universe, most of the actively star-forming galaxies are moderate to low luminosity late-type and dwarf galaxies having subsolar metallicities, and a significant amount is contributed by these systems to the local SFR density (e.g. Brinchmann & Ellis 2000; Brinchmann et al. 2004). Going to higher redshift, spectroscopic studies are clearly biased towards the brightest and most metal rich systems at every redshift. Even those, however, reveal substantially subsolar metallicities (e.g. Mehlert et al. 2003) and multiband photometry of deep fields reaching the bulk of the intrinsically fainter galaxy population will clearly be dominated by subsolar metallicity galaxies and protogalaxies.

While the effects of the initial mass function (IMF) (K98) or the absorption by dust are often discussed as sources of uncertainty in determining the SFR (e.g. Inoue et al. 2001), metallicity effects are rarely addressed. Concentrating on the SFR of star-bursting dwarf galaxies derived from H_α line fluxes, the metallicity dependence was examined e.g. by Weilbacher & Fritze–v. Alvensleben (2001). For a first extensive observationally based investigation into the metallicity dependence of [OII]as a SFR indicator see Kewley et al. (2004).

We here investigate the effect of metallicity on the calibration of the various SFR estimators, using our evolutionary synthesis code GALEV, described in Bicker et al. (2004), extended to include the gaseous emission, for 5 metallicities from 1/50 solar up to 2.5 solar.

We first present some details of the gaseous emission as included into our code in Sect. 2. We then discuss the derived calibrations aacounting for the effects of metallicity as well as their dependence on the mass limits of the IMF and on the stellar evolutionary input physics in Sect. 3. Finally we summarize our results in Sect. 4.

2. GALEV: galaxy evolution models

Our chemically consistent evolutionary synthesis code GALEV is based on a modified version of Tinsley's equations for the chemical enrichment of the inter stellar medium and on isochrones from the Padova group (Bertelli et al. 1994) in the Nov. 1999 version, and the spectral library from Lejeune et al. (1997, 1998) for the spectral and photometric evolution of the stellar component. For a detailed description see Bicker et al. (2004). Now we have included the effects of gaseous emission, in terms of lines as well as continuous emission. This was already included into our GALEV models for single bursts single metallicity stellar populations (SSPs) by Anders & Fritze–v. Alvensleben (2003), so we follow the method used there to implement the gaseous emission into our chemically consistent galaxy models. To clarify the effects of metallicity we use galaxy models with fixed metallicities in this Letter.

2.1. Gaseous emission

The gaseous emission is dominated by very hot stars, which produce hydrogen ionising (Lyc) photons. This means, that the emission is important in the early phases of an SSP (cf. Anders & Fritze–v. Alvensleben 2003), or, in case of a galaxy, in stages of (high) star formation activity. For every star on every isochrone we calculate the flux of Lyc photons from up-to-date non-LTE expanding model atmospheres (Schaerer & de Koter 1997; Vacca et al. 1996; Smith et al. 2002). Summing up all Lyc photons of all stars on all isochrones at every timestep gives us the total number of Lyc photons ($N_{\rm Lyc}$) at each time. On the basis of $N_{\rm Lyc}$ we calculate the gaseous continuum emission and the hydrogen line fluxes as described in Krüger et al. (1995) and Weilbacher et al. (2000). So the H_β flux is given by:

$$F({\rm H}_\beta) = 4.757 \times 10^{-13} \cdot N_{\rm Lyc} \cdot f,$$

where f describes the fraction of Lyc photons actually involved in ionising the ISM. For higher metallicities ($Z \geq 0.008$) we assume that 30% ($f = 0.7$) of the Lyc photons are absorbed by dust immediately and cannot ionise the gas, i.e. $f = 0.7$ (Mezger 1978; Weilbacher et al. 2000). For the lower metallicities we take $f = 1$. Note that in this respect our models are not completely self-consistent. The input we use implies that the most massive stars at low metallicity rapidly emerge from their dust cocoons. Lines other than H_β are calculated from line ratios relative to H_β. Line ratios for hydrogen lines are taken from Stasinska's (1984) theoretical models, while for lines of other elements we prefer to use empirical line ratios as derived from observations by Izotov et al. (1994, 1997) and Izotov & Thuan (1998). We include a total of 31 hydrogen lines up to the Brackett series and 36 lines of other elements. For the continuous emission and a detailed description see Anders & Fritze–v. Alvensleben (2003). We recall that the metallicity dependence of the isochrones induces a metallicity dependence for the flux of ionising Lyc photons that, in turn, leads to a metallicity dependence of the hydrogen lines. For lines of other elements, additional metallicity dependences come into play in a variety of ways. Line ratios themselves depend on the metallicity of the gas in a specific and complicated way for each element/line and differences in the typical electron temperatures and densities in different metallicity environments add to this. That is the reason why we use for these lines ratios derived from observations of a large number of different galaxies at each of our subsolar metallicity intervals.

In addition to young massive stars white dwarfs also have a significant output of Lyc photons. Their emission, however, is associated with the planetary nebula phase, which is fairly short in comparison with our minimum timestep ($\sim 25 \times 10^3$ yr vs. 4×10^6 yr). Hence, we decide to ignore the contribution of the WDs to the total Lyc flux of actively star-forming galaxies. Binary stars are not yet included in our models at that stage.

2.2. ZAMS extension of the Isochrones

The youngest age provided by the Padova isochrones that we use is 4 Myr. This corresponds to an upper mass limit of $\sim 70\ M_\odot$. For the gaseous emission, however, the youngest and most massive stars play a very important role, because the number of Lyc photons ($N_{\rm Lyc}$) increases dramatically with stellar temperature, $N_{\rm Lyc} \sim T_{\rm eff}^4$. The original isochrones hence unavoidably implied a severe underestimate of the Lyc flux.

Stellar evolutionary tracks from the Padova group, however, start from zero age main sequence (ZAMS) and are available for stars up to 120 $M_\odot$. Hence we decided to supplement our set of isochrones by adding ZAMS isochrone. Stars on the ZAMS are not evolved, so there is no need to consider equivalent stellar evolutionary stages, usually a challenge in converting tracks to isochrones. Now we are able to go to higher upper masses than the original isochrones provided.

For our models we now adopt an upper mass limit of 100 $M_\odot$ as our standard and investigate 120 $M_\odot$ for comparison.

3. Results

To study the metallicity dependence of the various SFR tracers we calculate models with constant SFR at the 5 available metallicities. We assume a Salpeter IMF with lower and upper mass limits of 0.15 and 100 $M_\odot$ as our standard and explore 0.1 and 120 $M_\odot$ for comparison. We have also explored different star formation histories (SFH) and found no differences in the calibrations as long as the SFR is evolving smoothly. For a discussion of rapidly changing SFRs, like in the short starbursts in dwarf galaxies, see Weilbacher & Fritze–v. Alvensleben (2001).

The derived calibrations for SFRs in terms of emission lines directly depend on the fraction f of actually ionising Lyc photons. For comparison purposes, we also give the values for $f = 1$ in the case of higher metallicities. The calibrations are not corrected to any amount of dust. Such a correction can easily be applied by calculating the ratio between the flux emerging from a dusty galaxy $F_{\rm dust}$ and the corresponding unextincted flux F_0. For any extinction law $k(\lambda)$ this is given by

$$\frac{F_{\rm dust}(\lambda)}{F_0(\lambda)} = 10^{-0.4 \cdot E(B-V)} \cdot k(\lambda).$$

Because of the wide range of extinction values and the variety of extinction laws appropriate for various types of galaxies (e.g. Calzetti 1997) we prefer to give the calibrations uncorrected for dust to be applied to extinction corrected observed galaxy spectra.

3.1. H_α

The standard calibration for SFRs derived from H_α luminosity is given by K98:

$$L_{{\rm H}_\alpha}\ ({\rm erg\ s^{-1}}) = C_{{\rm H}_\alpha} \cdot SFR_{{\rm H}_\alpha}\ (M_\odot\ {\rm yr}^{-1}).$$

K98 derives $C_{{\rm H}_\alpha} = 1.3 \times 10^{41}$ using population synthesis models with solar abundances and a Salpeter IMF with an upper mass limit of 100 $M_\odot$. For our solar metallicity model we find exactly the same value for $C_{{\rm H}_\alpha}$, but we also find a strong dependence of $C_{{\rm H}_\alpha}$ on metallicity of more than an factor of two between our solar metallicity and our lowest metallicity

Table 1. Calibration constants for the H_α and [OII] luminosity vs. SFR relations. (Values in brackets are for $f = 1$).

M_{up}	100 $M_\odot$		120 $M_\odot$	
Z	C_{H_α}	$C_{[OII]}$	C_{H_α}	$C_{[OII]}$
	$\left[\times 10^{41} \frac{\mathrm{erg\ s^{-1}}}{M_\odot\ \mathrm{yr^{-1}}}\right]$		$\left[\times 10^{41} \frac{\mathrm{erg\ s^{-1}}}{M_\odot\ \mathrm{yr^{-1}}}\right]$	
0.0004	2.7	0.5	3.0	0.5
0.004	2.3	1.4	2.6	1.6
0.008	1.4 (2.1)	1.5 (2.2)	1.7 (2.3)	1.8 (2.6)
0.02	1.3 (1.8)	1.3 (1.9)	1.6 (2.2)	1.6 (2.3)
0.05	1.2 (1.7)	1.2 (1.8)	1.4 (1.9)	1.4 (2.0)

model (1/50 solar) (cf. Table 1), even though the H_α line strength itself does not directly depend on the gas metallicity. The effect is caused by the higher temperatures and, hence, higher ionising fluxes of low metallicity stars as compared to higher metallicity stars. Using the standard calibration for solar abundance will overestimate the SFR in low metallicity galaxies by up to a factor ≥2.

If we choose 120 $M_\odot$ as our upper mass limit, model galaxies get higher Lyman continuum photon fluxes, resulting in stronger emission lines. Therefore, the calibration constant increases by 10−15%, slightly depending on metallicity, as seen in Table 1, resulting in lower SFRs at a given H_α luminosity.

3.2. [OII]

The forbidden [OII]line at 3727 Å is often used as a SF indicator for galaxies at higher redshift, where the H_α line is redshifted out of the optical window. Calibrations by G+89 and Kennicutt (1992) yield

$$L_{[OII]}\ (\mathrm{erg\ s^{-1}}) = C_{[OII]} \cdot SFR_{[OII]}\ (M_\odot\ \mathrm{yr^{-1}}),$$

with $C_{[OII]} = 1.5 \times 10^{41}$ and 5×10^{40}, respectively. Both calibrations are based on observed galaxy samples with SFRs previously derived from H_α. Differences in the galaxy samples are responsible for the differences in the calibration constants. G+89 used blue irregular galaxies, Kennicutt (1992) a sample of normal, mostly spiral-type galaxies. They probably reflect the lower extinctions and metallicities in irregular galaxies as compared to normal spirals. K98 derived a corrected (IMF, H_α calibration) average for the calibration constant of $C_{[OII]} = 0.7 \times 10^{41}$. Our model results are close to those of G+89, which better suit to our dust-free models (cf. Table 1). With increasing metallicity we find a rise in the calibration factor up to half-solar metallicity. The first step in metallicity from $Z = 0.0004$ to 0.004 alone increases $C_{[OII]}$ by a factor 3. This reflects the increasing oxygen abundance. Towards solar and super-solar abundances, however, the calibration factor drops as a result of the lower output of ionising photons of high metallicity stars. In a recent work by Kewley et al. (2004) the metallicity dependence of the [OII]calibration was investigated in great detail by examining the [OII]/H_α ratio in empirical and theoretical approaches. They also find that the calibration constant peaks at half solar metallicity, and their calibration constants correspond fairly well to our values for $Z = 0.02$, $Z = 0.008$, and $Z = 0.004$ with values of 1.4, 2.0, and 1.3, respectively. Unfortunately, their calibrations cannot be used for nor extrapolated to our lowest and highest metallicities, as their polynomial fit to the [OII]/H_α vs. Z relation would then give unphysical negative values.

Except for the lowest metallicity (1/50 solar), the metallicity effect on the calibration of the [OII]vs. SFR relation is small as compared to that of the H_α vs. SFR relation. This results from the counteracting effects of increasing metallicity and decreasing number of Lyc photons.

We reemphasize the need to accurately correct an observed spectrum for dust before using either H_α or [OII] as a SFR indicator (cf. Kewley et al. 2004).

3.3. Impact of the choice of stellar evolutionary input physics

The impact of the specific choice of stellar evolutionary input physics can be seen from a comparison between the present results based on recent Padova isochrones and those presented in Weilbacher & Fritze–v. Alvensleben (2001) using Geneva stellar evolution models for the three metallicities in common, $Z_\odot$, $Z = 0.008$, and $Z = 0.004$. Except for the stellar input physics, both approaches are identical, in particular, they both calculate the Lyman continuum photon fluxes on the basis of Schaerer & de Koter's $N_{\mathrm{Lyc}}(T_{\mathrm{eff}})$ calibrations. For solar metallicity, H_α- and [OII]-fluxes are lower by 12 and 6%, respectively, with Geneva than with Padova models, leading to emission line based SFR estimates higher by these percentages with Geneva than with Padova physics. Towards subsolar metallcities, the effect changes sign, and SFR estimates from H_α and [OII] are lower with Geneva than with Padova stellar evolutionary input physics by 9 and 4%, respectively, for $Z = 0.008$ and by as much as 25 and 30%, respectively, for $Z = 0.004$.

3.4. L_{UV}

The UV luminosity is also often used to derive SFRs. With the usable wavelength range being 1250−2800 Å, a couple of calibrations are used in the literature. We here use for our calibrations the wavelength ranges given by M+98 at 1500 Å and 2800 Å which are conventionally averaged over a rectangular bandpass of width $\Delta\lambda/\lambda = 20\%$.

$$L_{\mathrm{UV}}\ (\mathrm{erg\ s^{-1}\ Hz^{-1}}) = C_{\mathrm{UV}} \cdot SFR_{\mathrm{UV}}\ (M_\odot\ \mathrm{yr^{-1}}).$$

The calibration constants obtained with our models for galaxies with various metallicities and different upper mass limits for the IMF are given in Table 2. In contrast to the emission line vs. SFR calibrations, these UV vs. SFR calibrations turn out to be almost insensitive to the upper mass limit of the IMF. Going from 100 to 120 $M_\odot$ only increases the calibration constants by less than 2 and 4% for C_{1500} and even less for C_{2800} at solar and low metallicities, respectively.

Using Bruzual & Charlot (1993, BC93) models with solar metallicity and a Salpeter IMF from 0.1 to 125 $M_\odot$, M+98 found $C_{1500} = 8.0 \times 10^{27}$ and $C_{2800} = 7.9 \times 10^{27}$ after transformation from their L_ν to our L_λ, i.e. 27 and 23% smaller than

Table 2. Calibration constants for the UV luminosities vs. SFR relations.

M_{up}	100 $M_\odot$		120 $M_\odot$	
Z	C_{1500}	C_{2800}	C_{1500}	C_{2800}
	$\left[\times 10^{27} \frac{\mathrm{erg\ s^{-1}\ Hz^{-1}}}{M_\odot\ \mathrm{yr^{-1}}}\right]$		$\left[\times 10^{27} \frac{\mathrm{erg\ s^{-1}\ Hz^{-1}}}{M_\odot\ \mathrm{yr^{-1}}}\right]$	
0.0004	14.6	13.7	14.8	13.9
0.004	12.8	11.8	13.1	12.0
0.008	11.9	10.8	12.2	11.0
0.02	10.6	10.0	11.0	10.3
0.05	9.3	8.9	9.8	9.2

our values, $C_{1500} = 11.0 \times 10^{27}$ and $C_{2800} = 10.3 \times 10^{27}$, for an upper mass limit of 120 $M_\odot$. The difference in the upper mass limit has negligible effect, the difference in the lower mass limit, however, accounts for 15% of the difference. Another difference is that the continuous emission of the gas is included in our models, but not in those used by M+98. This causes a small increase in the UV luminosity for our models as compared to the BC93 models that M+98 use. Neglecting the continuum emission in our models reduces our C_{1500} and C_{2800} by another 7%. The remaining 5 and 1% differences in C_{1500} and C_{2800} must be due to differences in the stellar evolutionary tracks and model atmospheres.

Like for H_α vs. SFR, we find a strong metallicity dependence for the UV vs. SFR calibrations as a result of the higher luminosities low metallicity stars. Additionally, their higher Lyc photon fluxes increase the continuous emission. Taking all effects into account, we find that the SFR of low metallicity galaxies is overestimated by up to a factor 1.9 if using the M+98 calibration.

4. Conclusions

SFR determinations for galaxies on the basis of H_α and [OII] line luminosities, and luminosities in the UV are common techniques used to estimate the SFR in nearly all kinds of galaxies, from local ones to high redshifts. Even though galaxies show a large scatter in metallicity, the standard calibrations are derived from evolutionary synthesis using solar metallicity input physics. We present here a new set of calibrations for the most widely used SFR indicators H_α, [OII], and L_{UV} derived from evolutionary synthesis models and consistently accounting for a large range in galaxy metallicities. Using recent Padova isochrones, the spectral library from Lejeune et al. (1997, 1998) and recent compilations of Lyc photon rates as a function of stellar effective temperature (Schaerer & de Koter 1997; Smith et al. 2002), we find good agreement with standard calibrations in the literature for solar metallicity galaxy models. At higher and lower metallicities, however, we find significant deviations.

Towards lower metallicities, in particular, we find strong deviations from the SFR–H_α and SFR–L_{UV} relations and predict SFR of metal-poor galaxies derived from standard solar metallicity calibrations to be overestimated by factors up to 2 due to the hotter temperatures and the higher ionising fluxes and UV-luminosities of low-metallicity stars.

In case of [OII], on the other hand, the lower oxygen abundance and the higher output rate of Lyc photons act against each other and produce a maximum in $L_{[OII]}/SFR$ around $Z = 1/2\, Z_\odot$. Hence, the SFRs of galaxies around half solar metallicity tend to be slightly underestimated while those of very low metallicity galaxies are overestimated by the widely used standard calibrations. Our results on [OII] agree well with those obtained from an independent approach by Kewley et al. (2004).

Our results depend on the choice of stellar evolution models as far as hot star temperatures and lifetimes are concerned. Differences between Padova and Geneva stellar evolutionary input physics are small at half-solar to solar metallicities ($\lesssim$10%), but increase to ~30% towards $Z = 0.004$. Stellar model atmosphere calculations have reached a comforting agreement in the last years as far as the UV- and the H-ionising fluxes are concerned, divergences only appear around He-ionisation.

Our results depend on the upper mass limit of the IMF with calibration constants for the H_α and [OII] vs. SFR relations increasing by 13 and 20% for low and solar metallicity, respectively, but only by less than 2 and 4% for the UV vs. SFR constants in the sense that SFRs assuming too low an upper mass limit are overestimated by these percentages. Results also depend on the lower mass limit, since mass normalisation requires e.g. a higher number of low mass stars be compensated for by a smaller number of ionising UV-bright high mass stars. Going from 0.15 to 0.1 $M_\odot$ lowers the Lyc and UV fluxes at a given SFR by ~15%.

Spectroscopy at all redshifts picks out the most luminous and, hence, the most metal-rich galaxies. Hence, SFRs and SFR densities determined from H_α and [OII] fluxes are expected to only be affected by metallicity effects at the highest redshifts. SFRs and SFR densities determined on the basis of restframe UV-luminosities of high redshift galaxies in deep fields that also include the bulk of the lower luminosity and more metal-poor objects at each redshift, in contrast, are expected/predicted to be severely overestimated when using the standard calibrations.

We therefore stress the necessity to simultaneously determine the metallicity of a galaxy and its SFR – as can be done both from spectroscopy if enough emission lines are seen and from multi-band imaging via the comparison between observed and model spectral energy distributions.

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