Binary interactions on the calibrations of star formation rate

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ABSTRACT
Using the Yunnan evolutionary population synthesis (EPS) models with and without binary interactions, we present the luminosity of Hα recombination line (LHα), the luminosity of [OII]λ3727 forbidden-line doublet (LO[OII]), the ultraviolet (UV) fluxes at 1500 and 2800 Å (L_{i,UV}) and far-infrared flux (L_{FIR}) for Burst, S0, Sa-Sd and Irr galaxies, and present the calibrations of star formation rate (SFR) in terms of these diagnostics.

By comparison, we find that binary interactions lower the SFR.vs.LHα and SFR.vs.LO[OII] conversion factors by ∼0.2 dex. The main reason is that binary interactions raise the UV flux (shortward of the Lyman limit) of the stellar population (SP) in the age range 6.7 < log t/yr < 8.4 and thus more ionizing photons are present in the nebula. Moreover, binary interactions do not significantly vary the calibrations of SFR in terms of L_{i,UV}. This is because binary interactions raise the flux at 1500 Å of the SP in the range 8.75 < log t/yr < 9.2 and the maximal difference is about 1 dex. In addition, binary interactions have little effect on the flux at 2800 Å. At last, the calibration of SFR from L_{FIR} is almost unaffected by binary interactions. This is caused by the fact that binary interactions almost do not affect the bolometric magnitudes of SPs.

We also discuss the effects of initial mass function (IMF), gas-recycle assumption and EPS models (including GISSEL98, BCO93, STARBUST99, PopSTAR and PEGASE models) on these SFR calibrations. Comparing the results by using Salpeter (S55) IMF with those by using Miller & Scalo (MS79) IMF, we find that the SFR.vs.LHα and SFR.vs.LO[OII] conversion factors by using S55 IMF are greater by 0.4 and 0.2 dex than those by using MS79 IMF for the Yunnan models with and without binary interactions, respectively. The SFR.vs.L_{i,UV} and SFR.vs.L_{FIR} conversion factors by using S55 IMF are larger by an amount of 0.2 dex than the corresponding ones by using MS79 IMF. The inclusion of gas-recycle assumption only lowers these SFR calibrations at faint SFR. Moreover, comparing the results when using different EPS models, we find that the differences in the SFR.vs.LHα and SFR.vs.LO[OII] conversion factors reach ∼0.7 and 0.9 dex, the difference in the SFR.vs.L_{FIR} conversion factor reaches 0.4 and 0.8 dex, and the differences in the SFR.vs.L_{i,UV} conversion factors reach 0.3 and 0.2 dex when using S55 and NON-S55 IMF (including Cha03, K01, K93’ and MS79 IMFs, partly caused by the difference in the IMF), respectively. At last, we give the conversion coefficients between SFR and these diagnostics for all models.

Key words: binaries: general – galaxies: fundamental parameters – galaxies: general

1 INTRODUCTION
One of the most recognizable features of galaxies along the Hubble sequence (loose definition, including not only morphological type but also gas content, mass, bar structure and dynamical environment) is the wide range in young stellar content and star formation activity. Understanding its physical nature and origin of the variation in stellar content are fundamental to understand evolution of galaxies (Kennicutt1998, hereafter K98). Star formation rate (SFR)
can be used to compare with those distant galaxies at cosmological lookback times, and extrapolate the future timescales for star formation in galaxies by combining with HI and CO measurements (Kennicutt, Tamblyn & Congdon 1994). Moreover, star formation activity is usually correlated with cold gas and stars in galaxies: stars continuously produce mass, energy and metals during their evolution processes, and return them to galactic medium (gas), affecting the status of the next generation of stars. SFR carries the information on the evolution of galaxies. Therefore, it is important to determine SFR and its variation with Hubble type (loose definition) and environment, which can help us to understand the evolution of galaxies.

The commonly used SFR tracers include the flux of Hα nebular recombination line, the ultraviolet (UV) continuum flux, the flux of [OII]λ3727 forbidden-line doublet and far infra-red (FIR) continuum flux (K98). These SFR tracers are more or less correlated with the UV passband.

• First, the UV flux is directly tied to the photospheric emission of the young stellar population (SP).
• Second, the integrated luminosity of galaxy shortward of the Lyman limit (Far-UV) can ionize the hydrogen in the nebula and produce the recombination lines (such as Hα, Hβ, and so on). Thus the luminosities of these lines can be used to trace SFR.
• Third, the luminosity of the strong [OII]λ3727 forbidden-line doublet is often empirically obtained through the Hα luminosity, although it is not coupled to the ionizing luminosity and the excitation of this line is sensitive to abundance and the ionization state of the gas.
• Finally, the last SFR trace, the FIR luminosity, is also correlated with the UV passband. The interstellar dust can absorb the bolometric luminosity of galaxy and re-emit it in the thermal IR passband. The absorption cross section of the dust peaks in the UV passband, and, since the UV flux is considered as a tracer of young SP, the FIR luminosity can also diagnose SFR.

Furthermore, the last three diagnostics and the corresponding calibrations of SFR are correlated with the UV flux. Since in our previous studies, we found that the inclusion of binary interactions in evolutionary population synthesis (EPS) models can raise the UV flux by 2-3 magnitudes for SP at an age of ~1 Gyr (Zhang et al. 2004, 2005), in this study we will discuss the effect of binary interactions on these calibrations.

The outline of the paper is as follows. In Section 2 we describe the used EPS models and algorithm. In Section 3 we overview the previous results about SFR calibrations, and the advantages and disadvantages of these SFR tracers. In Section 4 we give the effect of binary interactions on these SFR calibrations. In Section 5 we discuss the effects of initial mass function (IMF), gas-recycle assumption and the EPS models on these SFR calibrations, and give the conversion coefficients between SFR and these tracers for all models. Finally we present a summary and conclusions in Section 6.

2 MODELS AND ALGORITHM

2.1 Spectral synthesis models

First, we use the Yunnan EPS models, which have been built by Zhang and her colleagues since 2002 (Zhang et al. 2002). The main characteristic of Yunnan EPS models is the inclusion of various binary interactions. Yunnan EPS models have given the results of SPS with and without binary interactions at seven metallicities (from 0.0001 to 0.03) and 90 ages (from 0.1Myr to 15Gyr).

The Yunnan EPS models were built on the basis of the Cambridge stellar evolutionary tracks (Eggleton 1972, 1973, 1974, DabES-2.0 stellar atmosphere models (Lejeune, Cuisinier & Buser 1997, 1998, hereafter LCB98) and various initial distributions of stars. The Cambridge stellar evolutionary tracks are obtained by using the rapid stellar evolution code (Hurley, Pols & Tout 2000, 2002), which is based on the stellar evolutionary tracks by Pols et al. (1998).

In this work we use a set of standard Yunnan EPS models at solar metallicity. The description of standard models is as follows: (i) the initial mass of the primary MS79 is given by

\[ M_1 = \frac{0.19X}{(1 - X)^{0.75} + 0.032(1 - X)^{0.25}} \]

where \( X \) is a random variable uniformly distributed in the range [0, 1]. This expression is the approximation by Eggleton, Fitchett & Tout (1989, hereafter EFT) to the IMF \( \phi(M) = dN/dM \) of Miller & Scalo (1979, hereafter MS79):

\[ \phi(M)_{\text{MS79}} \propto \begin{cases} M^{-1.4}, & 0.10 \leq M \leq 1.00 \\ M^{-2.5}, & 1.00 < M \leq 10.0 \\ M^{-3.3}, & 10.0 < M \leq 100. \end{cases} \]

in which \( M \) is the stellar mass in units of \( M_\odot \); (ii) the initial masses of the component stars in a binary system are assumed to be correlated, and the initial mass of the secondary is obtained from a uniform mass-ratio \( q \) distribution \( q \sim 1 \) (Mazeh et al. 1992, Goldberg & Mazeh 1994); (iii) the distribution of separation between two component stars takes the following form:

\[ a \cdot n(a) = \begin{cases} a_{\text{sep}}(a/a_0)^m, & a \leq a_0 \\ a_{\text{sep}}, & a_0 < a \leq a_1 \end{cases} \]

in which \( a_{\text{sep}} \approx 0.070, a_0 = 10R_\odot, a_1 = 5.75 \times 10^6R_\odot \) and \( m \approx 1.2 \) (Han, Podsiaiedowski & Eggleton 1997); and (iv) the eccentricity values follow a uniform distribution.

In the standard Yunnan EPS models, approximately 50% of stellar systems are binary systems with orbital periods less than 100yr. This fraction is a typical value for the Galaxy, resulting in ~10.1% of the binaries experiencing Roche lobe overflow during the past 13Gyr (see Han et al. 1995).

To investigate the effect of IMF on the results, we use another set of solar-metallicity Yunnan EPS models, which differs from the standard models by the initial mass distributions of the primary and secondary stars. In this set of models, (i) the initial mass of the primary is given by

\[ M_1 = 0.3(\frac{X}{1 - X})^{0.55}. \]

This expression is the approximation by EFT to the IMF of Salpeter (1955, hereafter S55) with \( \alpha = -2.35 \), i.e.,
Table 1. Description of the used Yunyan, BC03, GISSEL98, PopSTAR, STARBURST99-v6.02 and PÉGASE-v2 EPS models. The superscript ‘C’ means that it is available to choose, ‘A’ means that it is added by this work.

| name               | evolutionary LIB, Z, age range (yr) | spectral LIB. | IMF                  | \(M_1, M_2\) (\(M_\odot\)) | OUTPUT |
|--------------------|-------------------------------------|---------------|----------------------|-----------------------------|--------|
| Yunyan            | Cambridge, solar, 0.1M-15G           | BaSeL-2.0     | S55/MS79\(^\ast\)   | \(0.1-100\) Y/Y/Y           |        |
| BC03              | Padova\(^\ast\), solar, 1.0M-20G    | BaSeL-3.0\(^C\) | S55/Cha03            | 0.1-100 Y/N/N               |        |
| GISSEL98          | Geneva\(^\ast\), solar, 1.0M-20G    | combined\(^\ast\) | MS79                 | 0.1-100 Y/N/N               |        |
| PopSTAR           | Padova, solar, 0.1M-6.0             | BaSeL\(^\ast\) | S55/K01\(^C\)       | 0.15-100 N/Y/Y\(^5\)        |        |
| STARBURST99-v6.02 | Padova, AGB\(^\ast\), solar, 1.0M-15G | BaSeL\(^C\)  | S55/K93\(^A\)       | 0.1-100 Y/Y/Y\(^6\)         |        |
| PÉGASE-v2         | Padova, 1.0M-20G                    | BaSeL-2.0+CM  | S55/K93\(^C\)       | 0.1-100 Y/Y/Y\(^7\)         |        |

\(^1\) In the Yunyan models the IMF is for the primary in binary system.

\(^2\) GISSEL98 models use several stellar evolutionary libraries, Geneva is the main one.

\(^3\) GISSEL98 models use the combination of several stellar spectral libraries.

\(^4\) PopSTAR models use several stellar spectral libraries, BaSeL is the main one.

\(^5\) PopSTAR models provide the number of ionizing photons \(Q(H, HeI, HeII, OI)\) and the luminosities of emission-lines \(L_{(\text{H}\alpha, \text{H}\beta)}\). In the 2nd of a series, the luminosities of the other 18 emission-lines are provided as a function of \(Q(H)\) for HII region.

\(^6\) STARBURST99 models provide \(Q(H, HeI, HeII)\) and \(L_{(\text{H}\alpha, \text{H}\beta, P, B, R)}\).

\(^7\) PÉGASE models provide \(Q(H)\) and the luminosities of 61 spectral lines.

\(\phi(M)_{S55} = M^{-2.35}\), \(\phi(M)_{Cha03} = \left\{ \begin{array}{ll} C_1 M^{-3} \exp \left(\frac{-\log M - \log M_c}{\sigma}\right)^2, & M \leq 1.0 \vspace{0.5cm} \\ C_2 M^{-2.3}, & M > 1.0 \end{array}\right. \) \(M_c = 0.08 M_\odot, \sigma = 0.69\) and \(M = \text{the stellar mass in units of } M_\odot\).

2.1.1 Other spectral synthesis models

To check the effect of spectral synthesis models on these SFR calibrations, we also use the GISSEL98 (Galaxy Isochrone Synthesis Spectral Evolution Library, Bruzual & Charlot 1993), BC03 (Bruzual & Charlot 2003), PopSTAR (Mollá, García-Vargas & Bressan 2004), STARBURST99 v6.02 (Leitherer et al. 1999), Vázquez & Leitherer 2005, Leitherer et al. 2010, and PÉGASE v2 (Fioc & Rocca-Volmerange 1997, 1999) models. All these models do not include binary interactions, and the characteristics of them are also summarized in Table 1. Next we describe in more detail the main ingredients of these additional EPS models.

a. GISSEL98 and BC03 models

GISSEL98 and BC03 models were built by Bruzual & Charlot in 1993 and 2003, respectively, and provided the results of SPs at six metallicities (from 0.0001 to 0.05) and 221 ages (from 1 Myr to 20 Gyr) in tabular form.

GISSEL98 models were based on the Geneva stellar evolutionary tracks (Maecker & Meynet 1989, 1991) mainly, the MS79 IMF with the lower and upper mass limits \(M_l = 0.1\) and \(M_u = 100 M_\odot\) (see Eq. 2), and the combination of several stellar spectral libraries (we refer the interested reader to their paper for details).

b. PopSTAR models

The PopSTAR models were built by Mollá, García-Vargas & Bressan (2000). In their models, they used a revision of the Padova Bressan, Granato & Silva (1998) isochrones used in García-Vargas, Mollá & Bressan (1998), and the BaSeL stellar atmosphere models (LCB97, LCB98) mainly. All the results [the number of ionizing photons \(Q(H, HeI, HeII, OI)\) and the emission-line luminosities \(L_{(\text{H}\alpha, \text{H}\beta)}\) of SPs are provided in tabular form, including six metallicities, six IMFs and 93 ages (from 0.1 Myr to 9.78). We choose the two solar-metallicity sets, \(\phi(M)_{K01} = \left\{ \begin{array}{ll} C_1 M^{-0.30}, & 0.01 \leq M \leq 0.08 \vspace{0.5cm} & \text{IMFs}\text{\footnotesize{\cite{K01}}}} \\ C_2 M^{-1.30}, & 0.08 \leq M \leq 0.50 \vspace{0.5cm} \end{array}\right. \) (7)
in which \( M \) is the stellar mass in units of \( M_\odot \).

Moreover in the 2nd paper of a series (Martín-Manjón et al. 2010), the luminosities of other 18 emission-lines are given.

c. STARBURST99-v6.02 code

STARBURST99 is a web based software and data package designed to model spectrophotometric and related properties of star-forming galaxies. It was developed by researchers in Space Telescope Science Institute. We use the 6.02 version. The description of the model input physics is given by Leitherer et al. (1999), Vázquez & Leitherer (2005) and Leitherer et al. (2010).

- For the STARBURST99-v6.02 code, four sets of stellar evolutionary tracks are provided, each set including 5 metallicities. We choose the set of solar-metallicity Padova AGB tracks (including thermally pulsing AGB stars, the 44th tracks).
- Five sets of stellar atmosphere libraries are provided, we choose the BaSeL stellar atmosphere models (LCB97, LCB98).
- By default, the Kroupa IMF with two mass intervals (the exponent \( \alpha = [-1.3, -2.3] \), the mass boundary \( M_{\text{cut}} = [0.1, 0.5, 100] M_\odot \) ) is used. To be consistent with those of the other spectral synthesis models, we change this IMF form to (i) the SS5 IMF with \( \alpha = -2.35 \) and (ii) the Kroupa (1993, hereafter K93) IMF with three mass intervals:

\[
\phi(M)_{\text{K93}} = \begin{cases} 
C_1 M^{-1.3}, & 0.10 \leq M \leq 0.50 \\
C_2 M^{-2.3}, & 0.50 \leq M \leq 1.00 \\
C_3 M^{-2.7}, & 1.00 \leq M \leq 100. 
\end{cases}
\]

in which \( C_1 = 0.035, \ C_2 = 0.019, \ C_3 = 0.019 \) and \( M \) is the stellar mass in units of \( M_\odot \). Because all coefficients in Eq. 8 are set to 1 in this study (see also PÉGASE), we call K93’ IMF in Table 14.

- Two cases of star formation (const, without) are provided to choose, we choose the case of fixed mass (i.e., without star formation).

At last, we obtain the ISEDs, the number of ionizing photons \( Q(H, \text{He}, \text{HeII}) \), the emission-line luminosities \( L_{(\text{H}\alpha, \text{HeI}, \text{HeII})} \) of solar-metallicity SPs at 83 ages in the range 1Myr-15Gyr at an interval of \( \log t/yr = 0.05 \).

d. PÉGASE-v2 code

PÉGASE is a code to compute the spectral evolution of galaxies, and was developed by Fioc & Rocca-Volmerange (1997, 1999). The evolution of the stars, gas and metals is followed for a law of star formation and a stellar IMF. The stellar evolutionary tracks extend from the main sequence to the white dwarf stage. The emission of the gas in HII regions is also taken into account. We use the 2.0 version. The main improvement in version 2 is the use of evolutionary tracks of different metallicities (from \( 10^{-4} \) to \( 5 Z_\odot \)). The effect of extinction by dust is also modeled using a radiative transfer code.

- For the PÉGASE-v2 code, a set of Padova stellar evolutionary tracks (7 metallicities, \( Z=0.0001, 0.0004, 0.0008, 0.02, 0.05 \) and \( 0.1 \)), the combination of BaSeL-2.0 (LCB97, LCB98, for \( T_{\text{eff}} \leq 50000 \) K) with Clegg & Middlemass (1987, hereafter CM, for \( T_{\text{eff}} > 50000 \) K) stellar spectral libraries are used.
  - Among the nine IMFs provided, we choose the SS5 IMF with \( \alpha = -2.35 \) and K93 IMF. The upper and lower mass limits of both IMFs are set to 0.1 and 100 \( M_\odot \) (by default, \( M_\odot = 120 M_\odot \)), respectively. Because the coefficients of K93 IMF (see Eq. 8) are set to 1 in the PÉGASE code, we also call K93’ IMF in Table 14.
  - Among the six forms of SFR provided, we choose the instantaneous burst, the const SFR and the exponentially decreasing form \( (SFR = p_2 \cdot \exp(-\tau/p_1)/p_1, \ p_2=1.0) \) with the timescales \( (p_1) \) of 1, 2, 3, 5, 15 and 30 Gyr. They are used to built Burst, Irr, E-Sd types of galaxies, respectively.
  - For the other model input parameters, the default values are used. Metallicity (mass fraction) of the interstellar medium (ISM) at \( t = 0 \) is zero, the fraction of close binary systems is 0.5, and the mass fraction of sub-stellar objects formed is 0.0. And the default evolution processes are used, the evolution of stellar metallicity is consistent, stellar wind, infall, galactic winds and global extinction are neglected and nebular emission is considered.

Using the above set of input parameters and physics, we obtain the number of ionizing photons \( Q(H) \) and the luminosity of recombination line \( L_{\text{H}\alpha} \) for Burst, E, S0, Sa-Sd and Irr galaxies at 68 ages in the range of 1Myr-20Gyr.

2.1.2 Comments on the above mentioned models

For PÉGASE models we directly use their results because they consider the star formation and nebular emission. For the other models (GIUSEPPE, BC03, PEPSTAR and STARBURST99), we need to generate the results of galaxies with different galaxy types by means of spectral synthesis models. Because the ISEDs are not provided for PEPSTAR models, we could not give the ISEDs of galaxies with different galaxy types (therefore the UV and FIR continuum fluxes), we only could give the luminosities of the Hα recombination line and the \([\text{OII}] \lambda 3727 \) forbidden-line doublet, and the nebular emission continuum by using the number of ionizing photons \( Q(H) \) provided by them.

2.2 Construction of galaxies with different galaxy types

The construction of galaxies with different galaxy types has been described in our previous paper (Zhang et al. 2010). In brief, we use the BC03 software package to build them. Eight galaxy types (Burst, E, S0, Sa-Sd and Irr) are included, and they are built by a delta-form SFR, six exponentially decreasing SFRs with characteristic time-decays \( \tau = 1, 2, 3, 5, 10, 15, \) and \( 30 \) Gyr and a constant-form SFR, respectively. The exponentially decreasing SFR is given by

\[
\psi(t) = [1 + \epsilon M_{\text{PC}}(t)]^{-1} \exp(-t/\tau),
\]

where \( \tau \) is the e-folding timescale, \( M_{\text{PC}}(t) = [1 - \exp(-t/\tau)] - M_{\text{stars}} - M_{\text{remnants}} \) is the mass of gas that has been processed into stars and then returned to the ISM at time \( t \), \( M_{\text{stars}} \) and \( M_{\text{remnants}} \) are the masses of stars and
remnants at \( t \), and \( \varepsilon \) denotes the fraction of \( M_{\text{PG}}(t) \) that can be recycled into new star formation.

### 2.3 Computations of \( L_{\text{H}\alpha}, L_{\text{[OII]}}, L_{\text{FIR}} \) and nebular continuum

In this part, we will describe the computations of the luminosity of the \( \text{H}\alpha \) recombination line \( L_{\text{H}\alpha} \), the luminosity of the \([\text{OII}] \lambda 3727 \) forbidden-line double \( L_{\text{[OII]}} \), the FIR flux \( L_{\text{FIR}} \) and the emission of nebular continuum \( F_{\text{neb,}\lambda} \).

Before the computation of \( L_{\text{H}\alpha} \), we must calculate the number of ionizing photons \( Q(\text{H}) \). During the computation of \( Q(\text{H}) \), one method assumes that it only comes from young (< 10 Myr) and massive \(( \gtrsim 20-25 M_\odot)\) stars (such as K98, \textsc{starburst99}). Another method obtains that number by integrating the photons below 912Å (such as \textsc{popstar}). We choose the second method, i.e.,

\[
Q(\text{H}) = \int \frac{F_v}{h} dv,
\]

where \( F_v \) is the stellar flux in Hz, \( \nu \) is frequency and \( h \) is the Planck constant \(( = 6.6262 \times 10^{-27} \text{erg s} \)).

Then, we assume that all the star formation is traced by the ionized gas, although in the \textsc{pegase} code 70 per cent of the Lyman continuum photons computed from the spectral synthesis models are absorbed by the gas (i.e., ionize the gas) and the rest (30%) are absorbed by dust when considering extinction. At last, we use Case B recombination at electron temperature \( T_e = 10,000 \text{K} \) and number density \( n_e = 100 \text{cm}^{-3} \). The same set of the parameter values (Case B, \( T_e \) and \( n_e \)) is used by K98, \textsc{starburst99} and other studies. Under the above assumptions, the luminosity of \( \text{H}\alpha \) can be obtained by the following expression \((\text{\textsc{popstar}})\):

\[
L_{\text{H}\alpha} = Q(\text{H}) \frac{\alpha_j}{\alpha_\beta} \frac{1}{\alpha_\beta A_B}.
\]

where \( \alpha_\beta \) is the recombination coefficient to the excited level in hydrogen, which depends on the electronic temperature, \( j_B \) and \( A_B \) are from \textsc{ferland} \((1980)\), and the ratio \( \alpha/\beta \) is taken from \textsc{oosterbroek} \((1989)\).

The luminosity of \([\text{OII}] \lambda 3727, L_{\text{[OII]}} \), is often obtained by an empirical method. In this paper we obtain it by assuming the ratio of the luminosity of \([\text{OII}] \lambda 3727\) to \( \text{H}\alpha, L_{\text{[OII]}}/L_{\text{H}\alpha} = 0.45 \), as used by K98, although in the \textsc{pegase} code it equals to 3.0/2.915, and the discrepancy in the \( L_{\text{[OII]}}/L_{\text{H}\alpha} \) is large for the different types of galaxies.

The FIR luminosity is mainly used to calibrate the SFR of starburst galaxies, for which the FIR luminosity is often assumed to equal to the bolometric luminosity, \( L_{\text{FIR}} = L_{\text{BOL}} \).

At last, the emission of nebular continuum can be obtained by:

\[
F_{\text{neb,}\lambda} = \Gamma \frac{c}{\lambda^2 \alpha_\beta} Q(\text{H}),
\]

where \( c \) is the light velocity and \( \Gamma \) is the emission coefficient for hydrogen and helium (He/H=0.1), which includes free-free and free-bound contributions and the emission coefficient due to the two-photon continuum. The \( \Gamma \) coefficient is wavelength-dependent and is taken from \textsc{allera} \((1984)\) and \textsc{ferland} \((1980)\).

### 3 Overview of SFR calibrations and properties of SFR tracers

In order to compare our derived results with the previous studies, in this part we will overview the previous results about SFR calibrations in terms of luminosities of recombination-line, forbidden-line, UV and FIR continuum, and overview the properties (advantages and drawbacks) of these SFR tracers.

#### 3.1 Overview of S\( F_{\text{R,UV}}, L_{\text{FIR}} \)

The UV luminosity, \( L_{\text{UV}} \), is directly tied to the emission of the young SP. For convenience, it is often expressed as the linear relation with SFR by previous studies: \( SFR_{\text{UV}} = F_{\text{UV}} \times L_{\text{UV}} \), where \( SFR_{\text{UV}} \) and \( L_{\text{UV}} \) are in units of \( M_\odot \text{yr}^{-1} \) and \( \text{erg s}^{-1} \text{Hz}^{-1} \). This kind of SFR calibration is valid only for galaxies with continuous SFR over timescales of \( 10^8 \) or longer (K98). Its advantage is that it can be applied to star-forming galaxies over a wide range of redshifts. Its drawback is that it is sensitive to extinction and the form of the IMF.

Because different EPS models and methods are used, the obtained conversion factor \( F_{\text{UV}} \) between \( SFR_{\text{UV}} \) and \( L_{\text{UV}} \) is different, being the difference as big as 0.3 dex (K98):

- K98 has obtained \( F_{\text{UV}} = 1.4 \times 10^{-28} \) by using the S55 IMF with mass limits \( 0.1 \) and \( 100 M_\odot \) and solar abundance.
- Madau, Pozzetti & Dickinson \((1998\), hereafter MPD98\) have obtained \( F_{\text{UV}} = (1.25 \times 10^{-28}, 1.26 \times 10^{-28}) \) at \((1500 \text{Å}, 2800 \text{Å})\) by using the S55 IMF, and \( F_{\text{UV}} = (2.86 \times 10^{-28}, 1.96 \times 10^{-28}) \) by using the Scalo \((1983)\) IMF. In their studies the calibration factors are from models with an exponentially decreasing SFR.
- Gilbank et al. \((2010\), hereafter G10\) have obtained \( F_{\text{UV}} = 0.71 \times 10^{-28} \) by using the \textsc{pegase} code (assuming a constant SFR over 1 Gyr and a Kroupa IMF around solar metallicity).

#### 3.2 Overview of S\( F_{\text{R,UV}}, L_{\text{H}\alpha} \)

Also, the luminosity of \( \text{H}\alpha \) recombination line, \( L_{\text{H}\alpha} \), is often expressed as the linear relation with SFR: \( SFR_{\text{H}\alpha} = F_{\text{H}\alpha} \times L_{\text{H}\alpha} \), where \( SFR_{\text{H}\alpha} \) and \( L_{\text{H}\alpha} \) are in units of \( M_\odot \text{yr}^{-1} \) and \( \text{erg s}^{-1} \). This equation traces the instantaneous SFR. Its primary advantage is its high sensitivity. In addition, \( \text{H}\alpha \) is typically so conspicuous that it can easily be detected. Its drawback is that it is sensitive to extinction, IMF and the assumption that all of the massive star formation is traced by the ionizing gas. The conversion factor \( F_{\text{H}\alpha} \) obtained by different studies is as follows:

- K98 has obtained \( F_{\text{H}\alpha} = 7.9 \times 10^{-42} \) by using the S55 IMF with \( \alpha = 2.35 \) and the upper and lower mass limits \( M_l = 0.1 \) and \( M_u = 100 M_\odot \). This value is obtained from a constant star formation model at 'equilibrium'. The similar value has also been obtained by Kennicutt, Tamblyn & Congdon \((1994)\) and MPD98 when using the S55 IMF. This factor has been adopted by Shi, Gu & Pung \((2006)\) and G10. In the work of G10, they have pointed out that the factor is similar to that obtained from the \textsc{pegase} code.
- Brinchmann et al. \((2004\), hereafter B04\) have obtained
\[ SFR = \frac{\text{mass}}{\text{time}} \times \text{conversion factor} \]

This conversion factor has been used by Huang & Gu (2009).

\[ \frac{\text{mass}}{\text{time}} \times \text{conversion factor} = \frac{1.5 \times 10^{-41} \text{Msol yr}^{-1}}{\text{erg s}^{-1}} \]

4 EFFECT OF BINARY INTERACTIONS ON SFR CALIBRATIONS AND COMPARISONS

For the sake of clarity, we define eight sets of models. The two sets of Models A and B use the Yunnan EPS models with and without binary interactions, respectively. The six sets of Models C(Cr), D, E, F and G use the BC03, GISSEL98, PopSTAR, STARBURST99 and PÉGASE models, respectively. In Table 2 we give the name of each set of models in the 1st...
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Figure 4. The distribution of stars in the log$T_{\text{eff}}$-log$g$ plane for the Burst galaxy type (SP) at an age of log$/ yr =7.2$. In each panel black and red symbols are for considering (i.e., Model A-X) and neglecting (i.e., Model B-X) binary interactions. Left and right panels are for Models A/B-MS79 and A/B-S55, respectively.

Figure 6. Top panels are the comparison in $SFR-L_{\text{H}\alpha}$ relation between model (red symbols) and fitting (green symbols) results for Model A-MS79. Left and right panels are for using Eqs. 13 and 14 respectively. Bottom panels are the residuals (log$SFR$-log$SFR_{\text{fit}}$) as a function of log$L_{\text{H}\alpha}$.

In this section we mainly discuss the effect of binary interactions on the calibrations. Therefore, only Models A-MS79 and B-MS79 are used, which are based on the standard Yumama EPS models. The other models will be used in the next section to discuss the effects of IMF, gas-recycle assumption and EPS models on the results.

In this section we obtain the number of ionizing photons $Q(\text{H})$, the luminosity of H$\alpha$ recombination line $L_{\text{H}\alpha}$, the luminosity of [OII]$\lambda3727$ forbidden-line doublet $L_{\text{[OII]}}$, the UV fluxes at 1500 and 2800 Å, $L_{\text{UV}}$, and FIR flux $L_{\text{FIR}}$ of Burst, E, S0, Sa-Sd and Irr galaxies for both Models A-MS79 and B-MS79. We also give the conversion factors between SFR and these SFR diagnostics.
Figure 7. Relations between $SFR$ and $L_{i,\text{UV}}$ of E, S0, Sa, Sb, Sc and Sd galaxies (corresponding to $\tau = 1, 2, 3, 5, 15$ and 30 Gyr in Eq. 9 from top to bottom) for Models A-MS79 (black solid line + solid rectangles) and B-MS79 (red solid line + solid circles). Left panel is for $L_{1500}$, and right panel is for $L_{2800}$. Also shown are the results of K98 (grey dashed line), MPD98 (grey dotted line, open and solid triangles are for using the S55 and Scalo IMFs, respectively) and G10 (grey dash-dotted line).

Figure 8. Similar to Fig. 2, but the left panel is for $L_{1500}$ and the right panel is for $L_{2800}$.

Figure 3. The stellar (solid line) and nebular (dotted line) spectra of the Burst galaxy type (SP) at an age of $\log(t/\text{yr}) = 7.5$ for Models A-MS79 (black + rectangles) and B-MS79 (red + circles).

4.1 SFR vs. $L_{H\alpha}$

In Fig. 1 we give the relation between $\log(SFR)$ and $\log(L_{H\alpha})$ (note the logarithmic scale) of E, S0, Sa-Sc and Sd galaxy types in the range of 0.1 Myr-15 Gyr for Models A-MS79 and B-MS79. Also shown are the SFR($L_{H\alpha}$) calibrations of K98 and B04. If the aperture effect is neglected, the conversion factor of Mateus et al. (2007) is similar to that of B04 (see Section 3), so we do not show it in Fig. 1 for the sake of clarity.

From Fig. 1 we see that the $\log(SFR)$ varies linearly with $\log(L_{H\alpha})$ within a certain age range (from $\log(t/\text{yr}) > 7.5$ for E-type to $\log(t/\text{yr}) > 7.1$ for E-type to $\log(t/\text{yr}) > 8.5$ for Sd-type in Model A-MS79, from $\log(t/\text{yr}) > 7.1$ for E-type to $\log(t/\text{yr}) > 8.5$ for Sd-type in Model B-MS79) for both Models A-MS79 and B-MS79. And, for a given $\log(L_{H\alpha})$, the $\log(SFR)$ of Model A-MS79 is smaller by an amount of $\sim 0.2$ dex than that of Model B-MS79 when $\log(SFR) > -11$, i.e., the inclusion of binary interactions can lower the derived $SFR$ in terms of $L_{H\alpha}$. When comparing with the SFR of K98 and B04 at a given $L_{H\alpha}$, we find that the $\log(SFR)$ increases from B04, K98,
Binary interactions on the calibrations of SFR models except for Models Cr-Cha03 and Cr-S55.

Table 3. Conversion coefficients between SFR and $L_{\text{H}\alpha}$ for all models except for Models Cr-Cha03 and Cr-S55.

| Model   | Eq. (13) | Eq. (14) |
|---------|----------|----------|
| $C_{\text{H}\alpha}$ | $\sigma_{\text{H}\alpha}$ | $C'_{\text{H}\alpha}$ | $\sigma'_{\text{H}\alpha}$ |
| A-MS79  | $-41.0556$ | $0.0096$ | $-41.4316$ | $1.0121$ | $0.0076$ |
| B-MS79  | $-40.8942$ | $0.0141$ | $-41.4904$ | $1.0193$ | $0.0104$ |
| A-S55   | $-40.7408$ | $0.0206$ | $-41.6298$ | $1.0289$ | $0.0151$ |
| B-S55   | $-40.6939$ | $0.0216$ | $-41.6182$ | $1.0301$ | $0.0159$ |
| C-Cha03 | $-40.3025$ | $0.0054$ | $-41.5413$ | $1.0077$ | $0.0040$ |
| C-S55   | $-41.0785$ | $0.0065$ | $-41.3640$ | $1.0093$ | $0.0048$ |
| D-MS79  | $-41.2936$ | $0.0055$ | $-41.5374$ | $1.0079$ | $0.0041$ |
| E-K01   | $-40.7390$ | $0.0003$ | $-40.7296$ | $0.9997$ | $0.0002$ |
| E-S55   | $-41.5047$ | $0.0008$ | $-41.4959$ | $0.9997$ | $0.0002$ |
| F-K93'  | $-40.4930$ | $0.0004$ | $-40.4773$ | $0.9995$ | $0.0004$ |
| F-S55   | $-40.8002$ | $0.0004$ | $-40.7850$ | $0.9995$ | $0.0003$ |
| G-K93'  | $-40.8519$ | $0.0653$ | $-38.7983$ | $0.9333$ | $0.0533$ |
| G-S55   | $-41.1342$ | $0.0724$ | $-38.8548$ | $0.9267$ | $0.0592$ |

Table 4. Conversion coefficients between SFR and $L_{1500}$ (i.e., $i = 1$ in Eqs. (16) and (17) for all models except for Models Cr-Cha03, Cr-S55, E-K01 and E-S55’.

| Model   | Eq. (16) | Eq. (17) |
|---------|----------|----------|
| $(C'_{1500})$ | $(\sigma'_{1500})$ | $(C'_{1500})$ | $(\sigma'_{1500})$ |
| A-MS79  | $-28.0681$ | $0.0219$ | $-28.4138$ | $1.0193$ | $0.0176$ |
| B-MS79  | $-28.0037$ | $0.0212$ | $-28.3104$ | $1.0171$ | $0.0178$ |
| A-S55   | $-27.8032$ | $0.0302$ | $-28.2842$ | $1.0272$ | $0.0242$ |
| B-S55   | $-27.7751$ | $0.0305$ | $-28.2403$ | $1.0263$ | $0.0249$ |
| C-Cha03 | $-28.1430$ | $0.0207$ | $-28.4825$ | $1.0193$ | $0.0154$ |
| C-S55   | $-27.9437$ | $0.0232$ | $-28.3225$ | $1.0218$ | $0.0172$ |
| D-MS79  | $-28.1410$ | $0.0208$ | $-28.4820$ | $1.0194$ | $0.0154$ |
| F-K93'  | $-27.7758$ | $0.0092$ | $-27.8092$ | $1.0019$ | $0.0091$ |
| F-S55   | $-27.8955$ | $0.0059$ | $-27.9120$ | $1.0009$ | $0.0059$ |
| G-K93'  | $-27.9137$ | $0.0635$ | $-27.7433$ | $0.9903$ | $0.0630$ |
| G-S55   | $-27.9968$ | $0.0413$ | $-27.6359$ | $0.9796$ | $0.0380$ |

Model A-MS79 and Model B-MS79 in turn, and the discrepancy in the log(SFR) between K98 and Model A-MS79 is small.

The reason that binary interactions lower the SFR at a given $L_{\text{H}\alpha}$ is that they raise the number of ionizing photons $Q(H)$. In Fig. 2 we give the evolution of log(Q(H)) for Burst, E, S0-Sc and Sd galaxy types. From it we see that the log(Q(H)) of Model A-MS79 is significantly greater than that of Model B-MS79 for Bursts in the age range 6.7 $\leq$ log(t/yr) $\leq$ 8.4, the difference in log(Q(H)) reaching ~2 dex at an age of log(t/yr)=7.5. For E-S0-Sd galaxy types binary interactions also can raise log(Q(H)) when log(t/yr) $\geq$ 6.7.

The raise of Q(H) is caused by the fact that binary interactions increment the UV spectrum at the corresponding ages. In Fig. 3 we give the stellar and nebular spectra of the Burst galaxy type (SP) at an age of log(t/yr)=7.5 for both Models A-MS79 and B-MS79. From it we see that binary interactions not only raise the stellar spectrum in the UV band, but also raise the nebular continuum (by an amount of ~2 dex).

The higher UV spectrum is caused by more hotter stars produced by binary interactions. In Fig. 4 we give the distribution of stars in log$T_{\text{eff}}$-logg plane for Bursts (SPs) at an age of log(t/yr) = 7.2 for Models A-MS79 and B-MS79. From the left panel, we can see that binary interactions (i.e., Model A-MS79) indeed produce some hotter helium stars ($logT_{\text{eff}} \sim 4.9$ and log g $\sim 5.8$). These helium stars are originated from those binary systems, for which the primaries have evolved from the giant branch (GB, core-helium-burning) phase to the helium main-sequence (HeMS) phase due to the mass loss of the primaries. In Fig. 5 we give the evolution of such a binary system from zero age main sequence (ZAMS) to the end of helium burning in the log$T_{\text{eff}}$-log L plane. From it we see that the primary would evolve from GB to HeMS phase due to the mass loss, and the luminosity of the secondary increases rapidly due to the mass increase. In general, these binary systems have rela-
Table 5. Conversion coefficients between SFR and $L_{2800}$ (i.e., $i = 2$ in Eqs. [16] and [17]) for all models except for Models Cr-Cha03, Cr-S55, E-K01 and E-S55.

| Model     | Eq. [16] (C$^2_{2800}$, $\sigma_{2800}$) | Eq. [17] (A$^2_{2800}$, $\sigma'_{2800}$) |
|-----------|--------------------------------------|-----------------------------------------|
| A-MS79    | -28.0227, 0.0674                      | -29.2780, 1.0701                       |
| B-MS79    | -27.9737, 0.0714                      | -29.2873, 1.0735                       |
| A-S55     | -27.7947, 0.0984                      | -29.6921, 1.1073                       |
| B-S55     | -27.7221, 0.1031                      | -29.7416, 1.1115                       |
| C-Cha03   | -28.0637, 0.0538                      | -28.9987, 1.0534                       |
| C-S55     | -27.8717, 0.0594                      | -28.9053, 1.0597                       |
| D-MS79    | -28.0625, 0.0539                      | -28.9996, 1.0535                       |
| F-K93′    | -27.7540, 0.0759                      | -29.1760, 1.0805                       |
| F-S55     | -28.8251, 0.0459                      | -28.6379, 1.0458                       |
| G-K93′    | -27.9478, 0.1704                      | -30.5344, 1.1465                       |
| G-S55     | -27.9483, 0.0963                      | -29.1312, 1.0670                       |

As shown in Table 5, the fitting coefficients for Models A-MS79 and B-MS79 are smaller than those for Models A-MS79 and B-MS79. The differences between Model A-MS79 and Model B-MS79 are significant for all galaxy types at all ages. Therefore, binary interactions would not affect significantly the SFR-Log($L_{2800}$) relations.

4.2 SFR vs. $L_{1500}$ and SFR vs. $L_{2800}$

In Fig. 4, we give the relations between log(SFR) and the logarithmic UV-luminosities at 1500 and 2800 Å of A, S0-Sd types of galaxies for Models A-MS79 and B-MS79, also give the results of K98, MPD98 and G10. The results of MPD98 are obtained by using S55 with $\alpha = -2.35$ and Scalo (1988) IMF.

From the left and right panels of Fig. 4, we see that the differences in the SFR-L$^{1500}_{1500}$ and SFR-L$^{2800}_{2800}$ relations between Models A-MS79 and B-MS79 are small. By comparing the SFR of K98, MPD98 and G10 at given $L_{1500}$ or $L_{2800}$, we find that the log(SFR) increase from G10, Models A-MS79/B-MS79, MPD98-S55, K98 and MPD98-Scalo in turn (i.e., SFR$^{G10}_{1500}$ > SFR$^{A-MS79/B-MS79}_{1500}$ > SFR$^{MPD98-S55}_{1500}$ > SFR$^{K98}_{1500}$ > SFR$^{MPD98-S55}_{1500}$), the differences between SFR$^{MPD98-S55}_{1500}$ and K98 are small, and the results lie between G10 and MPD98-S55.

The reason that binary interactions do not affect SFR at given $L_{1500}$ or $L_{2800}$ can be seen from Fig. 1, in which we give the evolutions of $L_{1500}$ and $L_{2800}$ of Burst, E, S0-Sd and Sd types of galaxies for Models A-MS79 and B-MS79. First, from the left panel of Fig. 1, we see that the $L_{1500}$ of Model A-MS79 is greater than that of Model B-MS79 only for Bursts at ages of log(t/yr) $\sim$ 9 (the maximal difference is $\sim$1 dex at an age of 1 Gyr). For the other galaxy types, the difference in the $L_{1500}$ is small. The reason for this is that the contribution of the SP with an age of $\sim$1 Gyr to the ISEDs is smaller for E, S0-Sd galaxies according to

$$F(t) = \int_0^t \psi(t - t') f_{SP}(t') dt',$$

where $F(t)$ is the galaxy spectrum at time $t$, $\psi(t - t')$ is the SFR at $t - t'$ (see Eq. [1]) and $f_{SP}(t')$ is the flux of SP with an age of $t'$. In addition, from the right panel we see that the difference in the $L_{2800}$ between Models A-MS79 and B-MS79 is insignificant for all galaxy types at all ages. Therefore, binary interactions would not affect significantly the SFR-L$^{1500}_{1500}$ and SFR-L$^{2800}_{2800}$ relations.

Also, we fit the log(SFR)-log($L_{1500}$) and log(SFR)-log($L_{2800}$) relations by using the expressions

$$\log SFR_{i, UV} = \log L_{i, UV} + C_{i, UV},$$

and

$$\log SFR_{i, UV} = A_{i, UV} \times \log L_{i, UV} + C'_{i, UV},$$

where $i=1$ denotes the wavelength $\lambda = 1500$ Å, $i=2$ means $\lambda = 2800$ Å, and SFR$^{i, UV}_{i, UV}$ means that it is from the $i$-th UV luminosity $L_{i, UV}$. The fitting coefficients between log(SFR) and log($L_{1500}$) ($C_{i, UV}, C'_{i, UV}$) and rms ($\sigma_{i, UV}, \sigma'_{i, UV}$) are given in Table 4, and those between log(SFR) and log($L_{2800}$) are given in Table 4.

4.3 SFR vs. L$^{[OII]}$

The luminosity of the [OII]$\lambda$3727Å forbidden-line doublet, $L_{i,[OII]}$, is indirectly related to the ionizing luminosity. Often it is obtained by using the ratio of $L_{i,[OII]}/L_{H\alpha}$, which is obtained empirically. In the work of K98 $L_{i,[OII]}/L_{H\alpha}$ is 0.45, in the work of H03 it is 0.23, in the work of G10 the value is 0.5, and in the PEGASE code the value is 3.01/2.915. In this work we use the value of 0.23 used by H03 to obtain $L_{i,[OII]}$. Because the fixed $L_{i,[OII]}/L_{H\alpha}$ ratio is used, the plot of SFR-L$^{[OII]}$ is similar to Fig. 1. At a given SFR, the log($L_{i,[OII]}$) is smaller than log($L_{H\alpha}$) by an amount of log(1/0.23), i.e., the calibration curve moves upwards by log(1/0.23). Therefore we do not give the plot of SFR-L$^{[OII]}$ relation. Combining the conclusion made in Section 4.2, we know that binary interactions make the log(SFR) increase in terms of $L_{i,[OII]}$ by about 0.2 dex at a given $L_{i,[OII]}$. Also, we give a fitting relation between SFR and $L_{i,[OII]}$ by the following two forms:

$$F(t) = \int_0^t \psi(t - t') f_{SP}(t') dt',$$

where $F(t)$ is the galaxy spectrum at time $t$, $\psi(t - t')$ is the SFR at $t - t'$ (see Eq. [1]) and $f_{SP}(t')$ is the flux of SP with an age of $t'$. In addition, from the right panel we see that the difference in the $L_{2800}$ between Models A-MS79 and B-MS79 is insignificant for all galaxy types at all ages. Therefore, binary interactions would not affect significantly the SFR-L$^{1500}_{1500}$ and SFR-L$^{2800}_{2800}$ relations.

Also, we fit the log(SFR)-log($L_{1500}$) and log(SFR)-log($L_{2800}$) relations by using the expressions

$$\log SFR_{i, UV} = \log L_{i, UV} + C_{i, UV},$$

and

$$\log SFR_{i, UV} = A_{i, UV} \times \log L_{i, UV} + C'_{i, UV},$$

where $i=1$ denotes the wavelength $\lambda = 1500$ Å, $i=2$ means $\lambda = 2800$ Å, and SFR$^{i, UV}_{i, UV}$ means that it is from the $i$-th UV luminosity $L_{i, UV}$. The fitting coefficients between log(SFR) and log($L_{1500}$) ($C_{i, UV}, C'_{i, UV}$) and rms ($\sigma_{i, UV}, \sigma'_{i, UV}$) are given in Table 4, and those between log(SFR) and log($L_{2800}$) are given in Table 4.
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\[ \log \left( \frac{SFR_{[\text{OII}]} (\text{M}_\odot \text{yr}^{-1})}{L_{[\text{OII}]} \text{(ergs s}^{-1})} \right) = \log \left( \frac{L_{[\text{OII}]} \text{(ergs s}^{-1})}{L_{\text{H} \alpha}} \right) + C_{[\text{OII}]} \] (18)

and

\[ \log \left( \frac{SFR_{[\text{OII}]} (\text{M}_\odot \text{yr}^{-1})}{L_{[\text{OII}]} \text{(ergs s}^{-1})} \right) = A_{[\text{OII}]} \times \log \left( \frac{L_{[\text{OII}]} \text{(ergs s}^{-1})}{L_{\text{H} \alpha}} \right) + C'_{[\text{OII}]} \] (19)

Because the fixed \( L_{[\text{OII}]} / L_{\text{H} \alpha} \) ratio is used, the fitting coefficient \( A_{[\text{OII}]} = A_{[\text{H} \alpha]} \), \( C_{[\text{OII}]} = C_{\text{H} \alpha} - \log(0.23) \) and \( C'_{[\text{OII}]} = C'_{\text{H} \alpha} - \log(0.23) \) (cf. Eqs. 13-14). The actual numbers can immediately be computed from the values in Table 3.

4.4 SFR vs. \( L_{\text{FIR}} \)

In the computations of the above three SFR diagnostics (Section 4), the calibration factors are from those models with an exponentially decreasing SFR (i.e., Eq. 9), while the calibration between SFR and FIR luminosity is from the models with constant SFR under the assumption of the bolometric luminosity \( L_{\text{BOL}} = L_{\text{FIR}} \).

In Fig. 9 we give the \( L_{\text{FIR}} \) evolution of Irr galaxies (i.e., models with constant SFR) for Models A-MS79 and B-MS79. Also shown are the results of K98. In all cases the total mass of the model galaxy is normalized to 1 M_\odot. From this figure we see that the difference in the \( L_{\text{FIR}} \) evolution between Models A-MS79 and B-MS79 is small, that is to say, binary interactions almost do not vary the conversion factor between SFR and \( L_{\text{FIR}} \).

5 OTHER FACTORS ON SFR CALIBRATIONS

The calibrations between SFR and \( L_{\text{H} \alpha} \), \( L_{1500} \), \( L_{2800} \), \( L_{[\text{OII}]} \) and \( L_{\text{FIR}} \), which have been given in Section 4, can be affected by the adoption of different EPS models, IMF and the assumption of gas recyle. In this section, we will discuss the effects of these factors on the above mentioned SFR calibrations by introducing the Models A-S55, B-S55, ..., G-K93' and G-S55. For these models, the \( L_{\text{H} \alpha} \), \( L_{1500} \), \( L_{2800} \), \( L_{[\text{OII}]} \) and \( L_{\text{FIR}} \) are calculated, and the calibration factors are presented in Tables 3, 4 and 5, respectively.

5.1 The effect of IMF

To analyse the effect of IMF on these calibrations, the results of Models A-S55 and B-S55 are needed to be combined with those of Models A-MS79 and B-MS79 (Section 4). Models A-S55 and B-S55 are built by using the IMF and the assumption that the masses of the two component stars in a binary system are uncorrelated.

5.1.1 IMF on SFR vs. \( L_{\text{H} \alpha} \)

In Fig. 10 we give the comparison in the SFR-\( L_{\text{H} \alpha} \) relation among Models A-MS79, A-S55, B-MS79 and B-S55. Also shown are the results of K98 and B04.

By comparing the SFR-\( L_{\text{H} \alpha} \) relation between Models A-MS79 and A-S55, and that between Models B-MS79 and
B-S55, we see that the log($L_{H\alpha}$) of Model A-S55 is smaller than that of Model A-MS79 by an amount of 0.4 dex, and that the prediction for Model B-S55 is smaller by $\sim 0.2$ dex than that of Model B-MS79 for a given log(SFR). This is partly caused by the fact that Models A/B-S55 produce less massive-stars (see Fig. 11) and less $Q(H)$ (see Fig. 12). In Fig. 11 we present a comparison of the IMF between Models A/B-MS79 and A/B-S55, where the S55 and MS79 IMFs are obtained by using the EFT’s approximation (i.e., Eqs. 1 and 4) and are different from those given by Eqs. 2 and 5. In Fig. 12 we present the $Q(H)$ evolution of all galaxy types for Models A-MS79, B-MS79, A-S55 and B-S55, respectively. From them we indeed see that the number of massive stars and therefore $Q(H)$ at early ages of Bursts for Models A/B-S55 is less than those for Models A/B-MS79.

Moreover, by comparing the result between Models A-S55 and B-S55 we find that the difference in the SFR-$L_{H\alpha}$ relation between them is small, which is significantly different from that between Models A-MS79 and B-MS79. The difference in the SFR-$L_{H\alpha}$ relation between Models A-MS79 and B-MS79 is caused by the difference in the $Q(H)$ of Bursts in the age range $6.7 \lesssim \log t/yr \lesssim 8.4$, while the difference in the $Q(H)$ between Models A-S55 and B-S55 is small for Bursts at all ages (see Fig. 12). Why Model A-S55 could not produce more $Q(H)$ than Model B-S55, like Model A-MS79?

This is because less hotter helium stars ($\log T_{\text{eff}} \sim 4.9$ and logg $\sim 5.8$) could be produced in the range $6.7 \lesssim \log t/yr \lesssim 8.4$ for Model A-S55 (see the right panel of Fig. 12 and the comparison with the corresponding left-right panel). We can understand it from the discussion in Section 4.1 and from Figs. 11 and 13. First, from the discussion in the Section 4.1 we know that those hotter helium stars (present in the left panel of Fig. 4) evolve from those initial binary systems with the relatively large primary-mass ($M_1$), large mass-ratio ($q$) and small orbital separation. Then, from Fig. 11 we know that the number of massive primary-stars becomes to be less for Model A-S55. Furthermore, from Fig. 13 we know that the number of binary systems with relatively large $M_1$ and large $q$ becomes to be less for Model A-S55. In Fig. 13 we give the the number of binary systems in the primary-mass range $M_1 \rightarrow M_1 + dM_1$ and the mass-ratio range $q \rightarrow q + dq$ for Models A/B-MS79 and A/B-S55. The results of using the S55 IMF and assuming that the masses of the two component stars are correlated (the same
Figure 13. The number of binary systems in the ranges $M_1 \rightarrow M_1 + dM_1$ and $q \rightarrow q + dq$ (dy=0.02) per million binary systems $(dN)$ for Models A/B-MS79 (red) and A/B-S55 (cyan). The grey circles denote the grid $(M_1, q)$, and the distance from grid to the right point denotes the number of binary systems. For comparison, we also give the results of using the S55 IMF and the assumption that the masses of the two component stars are correlated (blue).

as that in Models A/B-MS79) are also represented. For the sake of clarity, in Fig. 13 we only give the number of binaries with the primary-mass $8 \leq M_1 \leq 45 M_\odot$. These binaries are likely to evolve into hotter helium stars in the range $6.7 \lesssim \log t/yr \lesssim 8.4$, and the MS lifetimes of single stars with the upper and lower masses $(8 \& 45 M_\odot)$ approximately correspond to the ages of $\log t/yr=6.7$ and $8.4$ (the MS lifetime of $M = 3.5 M_\odot$ is $\log t=8.4$, the MS lifetime of star with $M = 38 M_\odot$ is $\log t=6.7$ at solar metallicity). From it we see that the number of binary systems with larger $M_1$ and $q$ is less for Model A-S55. Thus Model A-S55 could not produce more hotter helium stars and Q(H). Moreover, from Fig. 13 we also see that the number of binaries with larger $M_1$ and $q$ of Model A-MS79 is similar to that by using S55 IMF and assuming that the masses of the two component stars are correlated. Therefore, the real reason why Model A-S55 could not produce hotter helium stars is the assumption about the masses of two component stars in binary systems.

From the above discussion, we conclude that the SFR vs. $L_{H\alpha}$ calibration is affected not only by the adoption of the different IMF, but also by the assumption about the masses of the component stars in binary systems.

5.1.2 IMF on SFR vs. $L_{1500}$ and $L_{2800}$

In Fig. 14 we give the comparisons in the SFR-$L_{1500}$ and SFR-$L_{2800}$ relations among Models A-MS79, A-S55, B-MS79 and B-S55. Also shown are the results of K98, MPD98 and G10.

By comparisons, we find that the log($L_{1500}$) and log($L_{2800}$) of Models A/B-S55 are smaller than the corresponding ones of Models A/B-MS79 by about 0.2 dex at a given log(SFR), the conversion curves move upwards from the lines of K98 and MPD98-S55. For the reason we provided in Section 5.1.1 (less massive stars), and from the results displayed in Fig. 15 (which represents the UV luminosities for all galaxy types predicted by the Models A-MS79, B-MS79, A-S55 and B-S55). We see that the $L_{1500}$ and $L_{2800}$ of Models A/B-S55 are smaller than the corresponding ones for Models A/B-MS79 at all ages for Bursts, leading to smaller $L_{1500}$ and $L_{2800}$ for E, S0-Sd galaxies and therefore larger conversion factors between SFR and $L_{1500}$ and between SFR and $L_{2800}$.

From the left panel of Fig. 14 we see that the difference in the SFR-$L_{1500}$ relation between Models A-S55 and B-S55 is small, which is similar to the case of using MS79 IMF (see Fig. 7). The reason is the same given in the discussion presented in the 3rd paragraph of Section 5.2, i.e., the SFR conversion between Models A-S55 is smaller than that of B-S55 only for Bursts in the age range $8.75 \lesssim \log t/yr \lesssim 9.2$, and the maximal difference between them is $\sim 0.2$ dex (also see the left panel of Fig. 15). This would not affect significantly the $L_{1500}$ of E, S0-Sd galaxies. Therefore IMF would not affect significantly the SFR vs. $L_{1500}$ conversion.

Moreover, from the right panel of Fig. 14 we see that the difference in the SFR-$L_{2800}$ relation between Models A-S55 and B-S55 is also small. This is because that IMF does not affect the $L_{2800}$ for Bursts at all ages.

5.1.3 IMF on SFR vs. $L_{\alpha}[OII]$

Because we use the fixed $L_{\alpha}[OII]/L_{H\alpha}$ ratio, the effect of IMF on the SFR vs. $L_{\alpha}[OII]$ conversion is the same as that on the SFR vs. $L_{H\alpha}$ conversion, i.e., the conversion factor between SFR and $L_{\alpha}[OII]$ of Model A-S55 is larger than that of Model A-MS79 by $\sim 0.2$ dex, the conversion factor of Model B-S55 is larger than that of Model B-MS79 by $\sim 0.2$ dex, and the difference in the SFR vs. $L_{\alpha}[OII]$ conversion between Models A-S55 and B-S55 is small.

5.1.4 IMF on SFR vs. $L_{FIR}$

In Fig. 16 we give the $L_{FIR}$ evolution of Irr galaxies for Models A-S55 and B-S55. From it we see that the $L_{FIR}$ of Models A/B-S55 is lower than that of Models A/B-MS79 by an amount of $\sim 0.2$ dex. Therefore, the conversion factor between SFR and $L_{FIR}$ of Models A/B-S55 is larger than that of Models A/B-MS79 by an amount of $\sim 0.2$ dex.

5.2 The effect of gas-recycle assumption

In this part we use the Models C and Cr to discuss the effect of gas-recycle assumption on these SFR calibrations. In Models C and Cr the value of $\alpha$ (see Eq. 8) is set to 0 and 1, respectively, i.e., in Model C the gas can not be recycled into new star formation, while in Model Cr it can.

In Fig. 15 we give the calibration between SFR and $L_{H\alpha}$ for Models C-Cha03, C-S55, Cr-Cha03 and Cr-S55 (left and right are for Models C and Cr, respectively). By comparison, we see that log(SFR) does not vary linearly with log($L_{H\alpha}$) within a certain SFR (age) range for E, S0-Sd types of galaxies when considering the gas-recycle assumption (i.e., Models Cr-Cha03/S55), and that log($L_{H\alpha}$) of Models Cr-Cha03/S55 is greater than that of Models C-Cha03/S55 at a given log(SFR) (easily seen by comparing with the line
of B04). This is because the inclusion of the gas-recycle assumption produces more $Q(H)$ and larger $L_{\text{H}_\alpha}$. In Fig. [17] we give the evolution of $Q(H)$ of Sd-type galaxies for Models C-Cha03 and Cr-Cha03.

Moreover, from Fig. [16] we see that the difference in the log($SFR$)-log($L_{\text{H}_\alpha}$) relation between Models C and Cr increases with decreasing SFR (increasing age). For example, the line of Model C-Cha03 overlaps that of B04 at log($SFR$) $\sim -11$, while that of Cr-Cha03 is shifted to the right of the line of B04 ($\sim 0.1$ dex). The reason for this is that the difference in the $Q(H)$ increases with age (see Fig. [17]).

For the $L_{\text{1500}}$ and $L_{\text{2800}}$, the situation is similar to that of $L_{\text{H}_\alpha}$. For the sake of size, we do not give the plots for them in this paper. The inclusion of gas-recycle assumption can lower the derived $SFR$ in terms of $L_{\text{i}, \text{UV}}$ by an amount of 0.05 dex at log($SFR$) $\sim -12$.

For the $L_{\text{[OII]}}$, the situation is similar to that of $L_{\text{H}_\alpha}$. For the sake of size, we do not give the plots for them in this paper. The inclusion of gas-recycle assumption can lower the derived $SFR$ in terms of $L_{\text{UV}}$ by an amount of 0.05 dex at log($SFR$) $\sim -12$.

5.3 The effect of EPS models

We use all Models, except for the set of Model Cr, to analyse the adoption of different EPS models on these $SFR$ calibrations. These models use the EPS models of $\text{Yunman GESSEL98}$, $\text{BC03}$, $\text{PopSTAR}$, $\text{Starburst99}$ and $\text{PEGASE}$, respectively.

To decrease the influence of IMF, we divide the comparisons into two groups. One group uses the S55 IMF and another group uses NON-S55 (including K01, K93', MS79 and Cha03) IMF. Moreover, we only compare our results with those studies by using the same (similar) IMF.

5.3.1 EPS models on $SFR$ vs. $L_{\text{H}_\alpha}$

In Fig. [18] we give the comparison in the $SFR-L_{\text{H}_\alpha}$ relation for all models by using S55 and NON-S55 IMFs.

At first, from the left panel of Fig. [18] we see that Models A-S55, B-S55 ($\text{Yunman}$) and F-S55 ($\text{Starburst99}$) give the similar $SFR-L_{\text{H}_\alpha}$ calibration and the corresponding curves lie above the line of K98. The calibration curve of Model E-S55' ($\text{PopSTAR}$) locates below the line of K98 and is the lowest one; the calibration curve of Model C-S55 ($\text{BC03}$) is
Figure 18. Similar to Fig. 1. Left panel is for all Models using S55 IMF (including A-S55, B-S55, C-S55, E-S55', F-S55 and G-S55). Right panel is for all Models using NON-S55 IMFs (including A-MS79, B-MS79, C-Cha03, D-MS79, E-K01, F-K93' and G-K93').

Figure 20. Similar to Fig. 7. Left and right panels correspond to $L_{1500}$ and $L_{2800}$, respectively. Top panels represent all the models using S55 IMF (including A-S55, B-S55, C-S55, E-S55', F-S55 and G-S55). Bottom panels show all the models using NON-S55 IMFs (including A-MS79, B-MS79, C-Cha03, D-MS79, E-K01, F-K93' and G-K93').

close to that of K98; and the calibration curve of Model G-S55 (PEGASE) lie between Models C-S55 and E-S55' and does not display a linear calibration relation. The difference in the SFR vs. $L_{H\alpha}$ calibration caused by the adoption of different EPS models can reach $\sim 0.7$ dex when using the S55 IMF.

From the right panel of Fig. 18, we see that the calibration curves of Models C-Cha03 (PEGASE) together with D-MS79 (GISELSE) overlap the line of B04, and the calibration
5.3.2 EPS models on SFR vs. L_{1500} and SFR vs. L_{2800}

In Fig. 21, we give the comparisons in the SFR vs. L_{1500} and SFR vs. L_{2800} relations for all models except for the set of Model E (PopStar), for which the ISEDs are not provided. Top and bottom panels are for the results based on S55 and NON-S55 (including K01, K93’, MS79 and Cha03) IMFs, respectively.

At first, from the top panel of Fig. 21, we see that the SFR vs. L_{1500} and SFR vs. L_{2800} conversion factors of all models with S55 IMF (A-S55, B-S55, C-S55, F-S55 and G-S55) are similar to those of K98 and MPD98-S55 (i.e., the results with the S55 IMF). The differences in the SFR vs. L_{1500} and SFR vs. L_{2800} conversion factors, caused by the adoption of different EPS models, are less than ~0.3 dex when using the S55 IMF.

From the bottom panels of Fig. 21, we see that all models with NON-S55 IMF (A-MS79, B-MS79, C-Cha03, D-MS79, F-K93’ and G-K93’) give small differences in the SFR vs. L_{1500} and SFR vs. L_{2800} conversion factors, caused by the adoption of different EPS models, can reach ~0.2 dex when using NON-S55 IMF. This is partly caused by the difference in the IMF.

5.3.3 EPS models on SFR vs. L_{[OII]}

The effect of EPS models on the SFR vs. L_{[OII]} relation is the same as that on the SFR vs. L_{Hα} relation, i.e., the differences in the SFR vs. L_{[OII]} conversion factor can reach ~0.7 dex when using the S55 IMF, and ~0.9 dex when using the NON-S55 IMF.

5.3.4 EPS models on SFR vs. L_{FIR}

In Fig. 21, we give the L_{FIR} evolution of Irr-type galaxies (i.e., models with const SFR) when using the S55 and NON-S55 IMFs for all models except for the set of Model E (PopStar). From this figure we see that the difference in the EPS models can cause the difference of 0.4 dex in the SFR vs. L_{FIR} conversion factor when using the S55 IMF, and the difference of 0.8 dex when using the NON-S55 IMF.

6 SUMMARY

We use the ghuman EPS models with and without binary interactions to present the luminosities of the Hα recombination line, the [OII]λ3727 forbidden-line doublet, the UV (at 1500 and 2800 Å) and the FIR continuum for Burst, E, S0, Sa-Sd and Irr galaxies, and present the calibrations of SFR in terms of these diagnostics.

By comparison, we find that binary interactions lower the SFR vs. L_{Hα} and SFR vs. L_{[OII]} conversion factors by ~0.2 dex, and do not significantly vary the SFR vs. L_{1,UV} (at 1500 and 2800 Å) and SFR vs. L_{FIR} calibrations.

We also consider the effects of IMF, the gas-recycle assumption and EPS models on these calibrations. By comparison, we find that the SFR vs. L_{Hα} and SFR vs. L_{[OII]} conversion factors of Models A/B-S55 are larger by 0.4 and 0.2 dex than the corresponding ones of Models A/B-MS79, and that the SFR vs. L_{1,UV} and SFR vs. L_{FIR} conversion factors are larger by 0.2 dex. By comparing the results between Models C and Cr, we find that the inclusion of gas-recycle assumption only lowers the SFR calibrations at faint SFR. Also we use the other EPS models (B03, GISSEL98, PopStar, PEGASE and STARBURST99) to obtain these SFR calibrations. By comparison, we find that the differences in the SFR (L_{Hα}) and SFR (L_{[OII]}) calibrations reach ~0.7 and 0.9 dex, the difference in the SFR (L_{FIR}) calibration reaches

Figure 21. Similar to Fig. 9, left panel represents all the models using S55 IMF (including A-S55, B-S55, C-S55, E-S55’, F-S55 and G-S55). Right panel shows all the models using NON-S55 IMFs (including A-MS79, B-MS79, C-Cha03, D-MS79, E-K01, F-K93’ and G-K93’).
0.4 and 0.8 dex, and the differences in the SFR($L_{i,UV}$) calibration reach 0.3 and 0.2 dex when using S55 and NON-S55 (partly caused by the difference in the IMF) IMFs, respectively.

At last, in this paper we give the conversion coefficients between SFR and these diagnostics for all models. In this paper we have only considered the effects of binary interactions for solar metallicity galaxies - more detailed studies will be given.

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REFERENCES

Aller L. H., 1984, ASSL, 112
Bressan A., Granato G. & Silva L., 1998, A&A, 332, 135
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Bruzual G. & Charlot S., 2003, MNRAS, 344, 1000 [BC03]
Chabrier G., 2003, PASP, 115, 763
Clegg R. E. S. & Middlemass D., 1987, MNRAS, 228, 759
Eggleton P. P., 1971, MNRAS, 151, 351
Eggleton P. P., 1972, MNRAS, 156, 361
Eggleton P. P., 1973, MNRAS, 163, 279
Eggleton P. P., Fitchett M. J. & Tout C. A., 1989, ApJ, 347, 998
Ferland G. J., 1980, PASP, 92, 596
Fioc M. & Rocca-Volmerange B., 1997, A&A, 326, 950
[HUBBLE]
Fioc M. & Rocca-Volmerange B., 1999, [astro-ph/9912179]
García-Vargas M., Molla M. & Bressan A., 1998, A&AS, 130, 513
Gilbank D. G., Baldry I. K., Balogh M. L., Glazebrook K., Bower R. G., 2010, MNRAS, 405, 2594
Goldberg D., Mazeh T., 1994, A&A, 282, 801
Han Z., Podsiajowski Ph. & Eggleton P. P., 1995, MNRAS, 272, 800
Hopkins A. M., Miller C. J., Nichol R. C., Connolly A. J., Bernardi M., Gómez P. L., Goto T., Tremonti C. A., Brinchmann J., Ivezic Ž, Lamb D. Q., 2003, ApJ, 599, 971
Huang S. & Gu Q., 2009, MNRAS, 398, 1651
Hurley J. R., Pols O. R. & Tout C. A., 2000, MNRAS, 315, 543
Hurley J. R., Tout C. A. & Pols, O. R., 2002, MNRAS, 329, 897
Kennicutt R. C., 1998, ARAA, 36, 189
Kennicutt R. C., Tamblyn P. & Congdon C. E., 1994, ApJ, 435, 22
Kroupa P., Tout C. A. & Gilmore G., 1993, MNRAS, 262, 545
Kroupa P., Aarseth S. & Hurley J., 2001, MNRAS, 321, 699,
Le Borgne J. F., et al. 2003, A& A, 402, 433
Leitherer C. & Heckman T. M., 1995, ApJS, 96, 9
Leitherer C., Schaerer D., Goldader J. D., González Delgado R. M., Robert C., Rube D. F., de Mello D. F., Devost D., Heckman T. M., 1999, ApJS, 123, 3 (STAR-BURST99)
Leitherer C., Ortiz Otálvaro P., Bresolin F., Kudritzki R., Lo Faro B., Pauldrach A., Pettini M., Rix S., 2010, ApJS, 189, 309
Lejeune Th., Cuisinier F. & Buser R., 1997, A&AS, 125, 229
Lejeune Th., Cuisinier F. & Buser R., 1998, A&AS, 130, 65
Maeder A. & Meynet G., 1989, A&A, 210, 155
Maeder A. & Meynet G., 1991, A&AS, 89, 451
Martín-Manjón M., García-Vargas M., Mollá M., Díaz A., 2010, MNRAS, 403, 2012
Mateus A., Sodré L., Cid Fernandes R., Stasińska G., 2007, MNRAS, 374, 1457
Mazeh T., Goldberg D., Duquennoy A. & Mayor M., 1992, ApJ, 401, 265
Miller G. E. & Scalo J. M., 1979, ApJS, 41, 513
Mollá M., García-Vargas M. L. & Bressan A., 2009, MNRAS, 398, 451 (PopSTAR)
Osterbrock D. E., 1989, Astrophysics of gaseous nebulae and active galactic nuclei. Univ. Sci. Books, Mill Valley, CA
Pols O. R., Schröder K. P., Hurley J. R., Tout C. A., Eggleton P. H., 1998, MNRAS, 298, 525
Pickles A. J., 1998, PASP, 110, 863
Salpeter E. E., 1955, ApJS, 121, 161
Scalo J. M., 1986, Fundam. Cosmic Phys., 11, 1
Schaerer D., 1999, [arXiv:astro-ph/9906014v2]
Shi L., Gu Q. & Peng Z., 2006, A&A, 450, 15
Tremonti C. A., Heckman T. M., Kauffmann G., Brinchmann J., Charlot S., White S. D. M., Seibert M., Peng E. W., Schlegel D. J., Uomoto A., et al., 2004, ApJ, 613, 898
Vázquez G. A. & Leitherer C., 2005, ApJ, 621, 695
Zhang F., Han Z., Li L., Hurley, J. R., 2002, MNRAS, 334, 883
Zhang F., Han Z., Li L., Hurley, J. R., 2004, A&A, 415, 117
Zhang F., Han Z., Li L., Hurley, J. R., 2005, MNRAS, 357, 1088
Zhang F., Han Z., Li L., Shan H., Zhang Y., 2010, MNRAS, 408, 1283

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