Star formation histories of lensed $z \sim 1.5$–3 star-forming galaxies

Panos Sklias, Daniel Schaerer, Michel Zamojski,
Miroslava Dessauges-Zavadsky and the HLS team
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UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie
OBSERVATOIRE DE GENÈVE FONDÉ EN 1772

Introduction

We show how multi-wavelength, optical to IR/sub-mm and – when available – nebular emission observations can be used to constrain the star formation history (SFH) on a sample of strongly lensed galaxies identified by the *Herschel Lensing Survey* [1] or recently observed with *Herschel* independently, in the redshift range $z \sim 1.5$–3. Lensing allows us to explore the typical star-forming galaxies (LIRGs) of that epoch, contrary to the more extreme galaxies detected in blank fields (HyLIRGs).

Methods

We use an updated version of the *Hyperz* photometric code [2] to estimate the physical parameters of our sample and explore the impact of different parameters:

- SFHs:
  - exponentially declining $\tau = [0.05,3]$ Gyr
  - exponentially rising $\tau = [0.001,3]$ Gyr
  - constant (CSFR)
- extinction laws:
  - Calzetti [3], plus variant with stronger nebular extinction [4]
  - SMC [5]
- nebular emission

Assuming energy conservation (star light absorbed by dust and re-emitted in the IR), our various models predict the IR luminosity $L_{\rm IR}$ and are confronted to the observed $L_{\rm IR}$ (Fig. 2).

Using the calibration described in [6] we estimate the extinction A_V needed for our models to match the observed IR/UV ratio in order to make fits that are consistent with the observations (Table 2).

Conclusions

1. The SED models with nebular emission, declining SFH and the Calzetti extinction law are best suited for most of the sample. The SMC law seems suited though for cB58 and A68/nn4 (a very obscured intense starburst), that are the only ones for which we obtain young ages (<90 Myr) with this law.
2. In the case of the Cosmic Eye, we can safely exclude rising or CSFR SFHs, based on the comparison of the of the predicted emission with the observed spectrum (Fig. 3).
3. Thanks to lensing, the faintest galaxies we characterize extend the so called "main sequence" of star forming galaxies at $z \sim 2$ to below the 100 $M_\odot$ yr^{-1} regime.
4. The use of the observed $L_{\rm IR}/L_{\rm UV}$ ratio to constrain A_V proves very useful in breaking the age-extinction degeneracy that many of our red-sloped galaxies suffer from, and produces population models that are coherent with the observationally derived SFR estimates.

References

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SEDs, General Properties

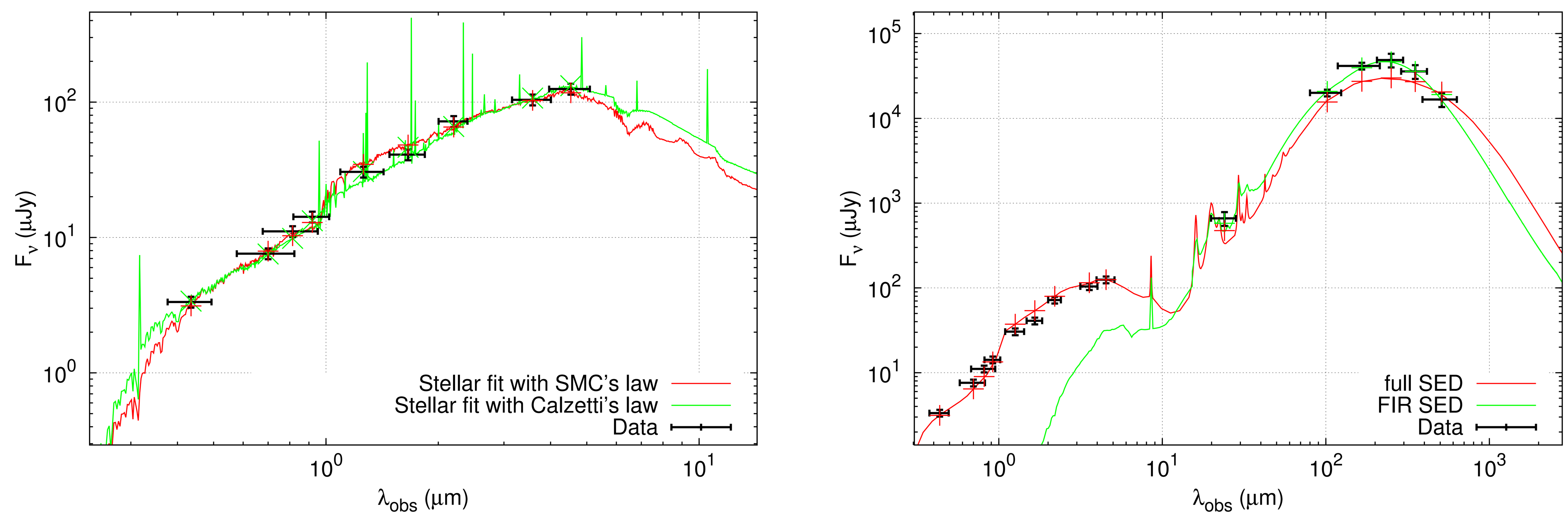

Figure 1: SED fits of one galaxy from our sample, A68/HLS115. For our analysis, we derive its physical parameters from independent fits to the stellar (left) and dust (right) components of the spectrum.

ID	$z_{\rm spec}$	μ	β	$L_{\rm UV} \times \mu$ [10^{12}L$_\odot$]	$L_{\rm IR} \times \mu$ [10^{12}L$_\odot$]	SFR$_{\rm IR}$ [M$_\odot$ yr^{-1}]	$T_{\rm dust}$ [K]
A68/C0	1.5854	30	$-0.42^{+0.5}_{-0.4}$	0.19 ± 0.02	3.55 ± 0.2	20.4 (19.2-21.5)	34.5
A68/h7	2.15	3	$-0.01^{+0.5}_{-1.0}$	0.22 ± 0.01	$5.49^{+0.26}_{-0.37}$	315 (294-330)	43.3
A68/HLS115	1.5859	15	$-0.31^{+0.55}_{-0.18}$	0.1 ± 0.01	$5.13^{+0.24}_{-0.23}$	59.0 (56.3-61.7)	37.5
A68/nn4	3.19	2.3	$2.57^{+1.3}_{-1.1}$	$0.014^{+0.001}_{-0.002}$	$15.8^{+0.4}_{-0.7}$	1184 (1132-1214)	54.9
MACS0451 N	2.013	49	$-1.40^{+0.12}_{-0.12}$	0.55 ± 0.01	$4.26^{+0.3}_{-0.28}$	15.0(14.0-16.0)	47.4
cB58	2.73	30	$-1.15^{+0.1}_{-0.1}$	$1.66^{+0.12}_{-0.07}$	9.12 ± 0.21	52.4 (51.2-53.6)	50.1
Cosmic Eye	3.07	28	$-1.41^{+0.13}_{-0.08}$	2.57 ± 0.06	$9.55^{+0.45}_{0.64}$	58.8 (54.9-61.6)	46.3

Table 1: Main observed and derived properties of our galaxies. μ is the magnification factor, β is the SED-inferred UV slope at 2000 Å. SFR$_{\rm IR}$ is obtained via the Kennicutt calibration [7], and $T_{\rm dust}$ from modified black body fits with an emissivity index of 1.5.

Stellar Population Properties and Star Formation Histories

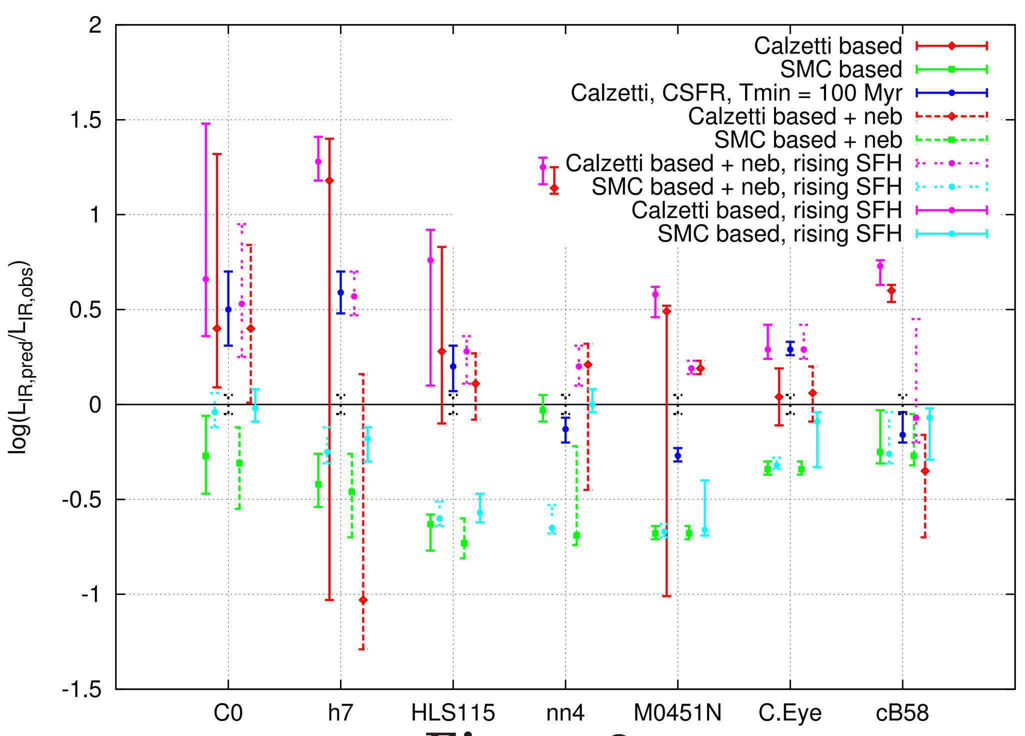

Figure 2

Left: Predicted over observed ratio for $L_{\rm IR}$ for the galaxies modeled and for the different stellar population scenarios we have explored. We can see that the SMC based predictions underpredict $L_{\rm IR}$ in almost all cases. The Calzetti based models, although more degenerate, match most of the objects observed $L_{\rm IR}$ within the 68% confidence range. The rising SFH models predict globally at least as much or more $L_{\rm IR}$ than their corresponding – in terms of extinction law – declining SFH ones, pushing in particular the Calzetti based models to overpredict the observed quantities. The effect is similar but smaller for the SMC based solutions, and allows a perfect match in the case of C0.

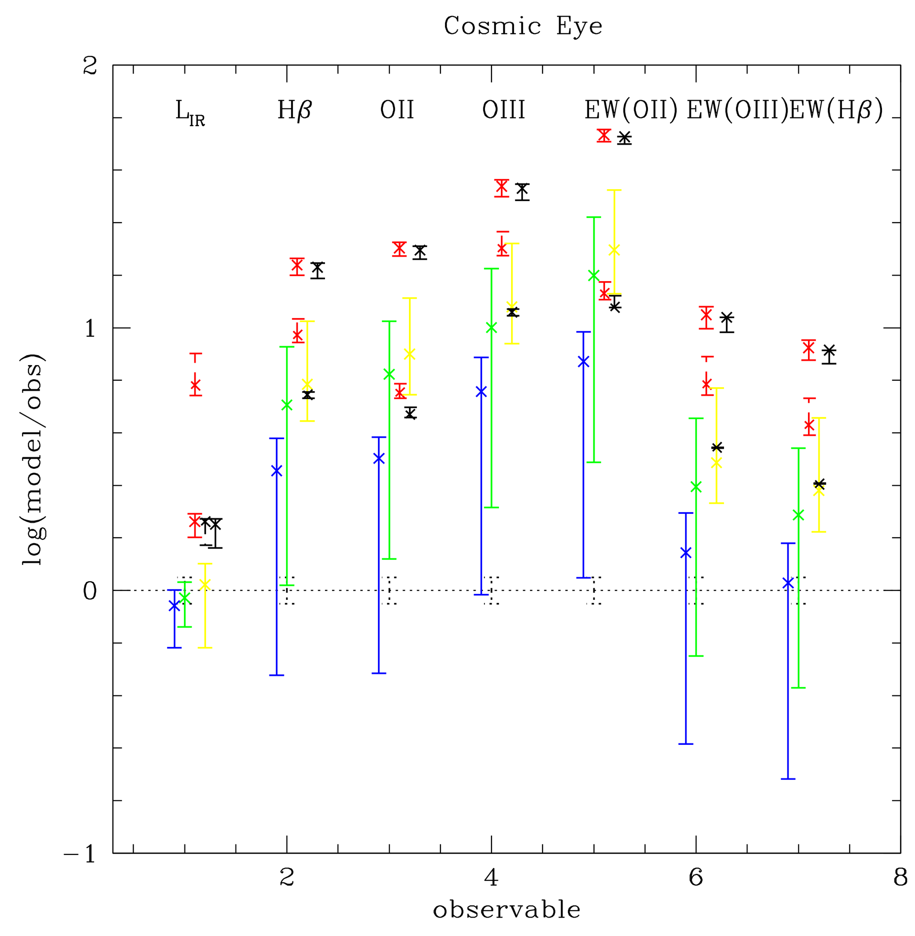

Figure 3

Right: Comparison of line properties for the Cosmic Eye, in particular the fluxes and equivalent width for Hβ, [O II] λ3727, and [O III] $\lambda\lambda$4959,5007. Colors correspond to models with different SFHs (green: exponentially declining, and yellow: delayed SFHs; black: CSFR; red: exponentially rising; blue: exponentially declining with higher nebular extinction [4]; red and black dashed: respectively rising and CSFR for that same extinction). The declining model with the stronger nebular extinction is the only one matching the observations at the 68% confidence level, this together with the other properties we derive (Table 2) are consistent with the Eye being a post-starburst.
The same analysis was conducted for cB58, and most models were able to reproduce the observed line properties, without one having a clear advantage. This is thought to be due to the very young age and little extinction the models have preferred, thus leaving little room for differentiation.

ID	A_V	Age t [Gyr]	t/τ	$M_\star$ [10^{10}M$_\odot$]	SFR$_{\rm SED}$[M$_\odot$ yr^{-1}]
A68/C0	1.1	1.01(0.25-1.7)	2.03 (0.67-3.64)	3.4 (2.3-4.5)	15.5 (8.8-21.2)
A68/h7	1.26	0.25 (0.18-0.25)	3.63 (3.61-3.63)	26.1 (19.6-27.7)	129.2 (123.5-134.9)
A68/HLS115	1.58	0.13 (0.09-0.13)	1.83 (1.81-2.5)	1.37 (1.03-1.65)	42.45 (32.3-46.9)
A68/nn4*	2.17	0.033 (0.033-0.036)	0.66 (0.66-0.72)	5.6 (5.2-6.0)	1243 (1176-1314)
MACS0451	0.63	0.13 (0.13-0.18)	1.28 (0.6-1.28)	0.49 (0.49-0.52)	22.3 (22.1-24.9)
cB58	0.7	0.13 (0.13-0.13)	0.13 (0-0.43)	0.75 (0.71-0.81)	63.2 (58.3-67.3)
Cosmic Eye	0.58	0.18 (0.18-0.18)	2.58 (2.58-2.58)	4.0 (3.9-4.1)	56.1 (55.2-57.2)

Table 2: Physical parameters derived from the energy conserving models. A_V is fixed by the observed IR/UV ratio. All models are Calzetti based except for very obscured starburst A68/nn4 that is made with the SMC law. t/τ is the age over timescale of the decreasing SFR, and is indicative of whether we have a starburst (t/τ < 1) or a post-starburst (t/τ > 1).