thesis

Dimitris Papachristopoulos

Table of contents

Abstract

The Star Formation History (SFH) of a galaxy can offer many insights not only for the evolution and the future of the galaxy, but also for the evolution of the Universe. This is why there are various theoretical models trying to describe the SFH of galaxies. One of those models is the Delayed-Tau model, which approximates the Star Formation Rates (SFR) of galaxies as a function with a rising SFR at the beginning, until it reaches a peak at a time τ, unique for each galaxy, and then it drops at an exponential rate.

Haslbauer, Kroupa, and Jerabkova (2023a) argues that the Delayed-τ model is opposed to the Lilly-Madau plot ((Madau and Dickinson 2014a)), which plots the observed SFR's of galaxies with the corresponding redshifts (z) and calculates a cosmic SFR peak at $z \approx 2$. The way they calculated this inconsistency is by using observatory data for SFR and Stellar Masses [1] from the UNGC catalog (Karachentsev, Makarov, and Kaisina (2013), Karachentsev and Kaisina (2013)) for calculating the parameters (the timescale τ and the normalization constant A_{del}) of the model. This calculation for the galaxies of the Local Cosmological Volume (LCV), allows the investigation of the SFR throughout the life each galaxy and so we can find the expected time of peak of the SFR.

In this thesis project, we will try to calculate the same parameters, by using a bigger sample size and the method Markov Chain Monte Carlo, to examine if the inconsistencies of the model derive from the results of the previous analysis, or if it is an intrinsic problem of the model

Keywords: Galaxies, Galaxy Evolution, Star Formation History (SFH), Star Formation Rate (SFR), Delayed-τ, Local Cosmological Volume, Lilly-Madau Plot, Redshift, Markov Chain Monte Carlo (MCMC).

[1] They calculated the Stellar Masses by using a Mass to Light ratio of 0.6

Galaxy Morphology and Star-Forming Regions

Galaxy Ingridients

Galaxy Classification

Hubble-de Vacouler Classification

Dwarf Galaxies

Star-Formnig Regions

Star Formation History (SFH)

The SFH of a galaxy describes the evolution of its star formation rate over time. By selecting an appropriate model for SFH, we can analyze stellar production, predict periods of active or quiescent star formation, and determine when SFR stabilizes.

Understanding SFH models is crucial for interpreting internal and external processes affecting galaxies and identifying conditions for intense star formation in their early stages.Star Formation Rate

Star Formation Rate

The star formation rate (SFR) is defined as the total gas mass of a galaxy converted into stars over a specific time interval. It is typically expressed in solar masses per year ($M_\odot \cdot \mathrm{yr}^{-1}$).

The SFR varies significantly over time, and its integration over time provides the total stellar mass formed during the galaxy's history of star formation. Specifically:

where ζ accounts for mass loss, approximately $\zeta \approx 1.3$ (Kroupa et al. (2020)).

Estimating SFR from Spectra

SFR can be estimated using various photometric or spectroscopic methods based on the luminosity of at least one spectral band or the intensity of a spectral line. Different luminosities and intensities trace distinct emission mechanisms, offering insights into a galaxy's radiation sources. Below are common methods:

- **Hα Emission**: Traces the number of ionizing photons, assuming full usage and re-emission. These photons mainly originate from hot, massive stars (O-type stars, ~10 Myr). Dust can significantly affect observations.

- **Infrared (IR) Flux**: Assumes a fixed fraction of stellar radiation is absorbed by dust, re-emitted at infrared wavelengths, and enhances total IR radiation.
- **Radio Continuum Emission**: Strongly correlated with IR. Its origin is complex, involving synchrotron radiation from relativistic electrons and thermal Bremsstrahlung from hot gas.
- **Far-Ultraviolet (FUV) Flux**: Mainly emitted by young, hot stars (e.g., B-type stars, ~100 Myr). Dust presence can also significantly affect observations.
- **X-Ray Emission**: In star-forming galaxies, X-rays arise from high-mass binary systems (neutron star or black hole with massive stellar companion) and hot gas from supernovae, correlating with SFR up to redshift $z \sim 4$. X-rays are dust-insensitive, enabling accurate high-redshift observations.

SFR for different luminosities L_i can be calculated as:

$$\mathrm{SFR} = \mathcal{K}_i \times L_i \tag{1}$$

where $\mathcal{K}_i$ is a constant specific to each L_i (i = Hα, IR, radio, FUV, X). In our analysis, we lack radio and X-ray data.

For FUV and Hα observations, which are affected by dust, corrections or models accounting for dust absorption are applied. Generally:

Following Madau and Dickinson (2014b), this method may underestimate true SFRs, as different galaxy populations exhibit varying absorption mechanisms.

A more robust estimate of total SFR is:

where L_{FUV} is uncorrected for absorption.

Main Sequence Galaxies

The SFR and stellar mass of a galaxy are tightly correlated by the relationship:

$$\log(\mathrm{SFR}) = \alpha \log(M_*) + \beta$$

where $\alpha(t)$ and $\beta(t)$ depend on time and redshift z (Speagle et al. (2014)):

Star Formation History Models

Parameterized SFH models are commonly used, offering simplicity through a few parameters (Carnall et al. (2019)):

1. **Exponential Decline (Model)**:

   where τ is the timescale and $t_{\mathrm{sf}} = t - T_0$ is the star formation time.

2. **Delayed Exponential (Model)**:

   accounting for an initial rise in SFR before declining. Here, τ is the time to reach maximum SFR.

3. **Log-Normal Model**:

   with τ and T_0 as free parameters.

4. **Double Power Law**:

   where τ is the timescale, and α, β govern the SFR rise and fall.

Non-parametric models are also available, providing flexibility for galaxies with complex SFH patterns.

Delayed-τ Model

The delayed τ model is widely used for describing an initial starburst followed by a gradual decline in SFR. This places galaxies on the main sequence. It is particularly effective for massive galaxies (Haslbauer, Kroupa, and Jerabkova (2023b)). However, it assumes smooth SFR evolution and may overestimate peak SFR in high-redshift galaxies.

Using the delayed   model, we compute τ, t_{sf}, and normalization constant A_{del} with:

$$\mathrm{SFR}_0 = \mathrm{SFR}(t_{sf}) = A_{del} \frac{t_{sf}}{\tau^2} e^{-t_{sf}/\tau} \tag{2}$$

where SFR_0 is given in the catalogs.

Hubble Law

Redshift

Lookback time

Lilly-Madau Plot

Delayed-τ model

Computational Methods

Newton-Raphson

Markov Chain Monte Carlo

Prepering the Catalogs

UNGC HECATE join etc…

Catalog Completeness

Comparing the Catalogs

The “special” case of the Star Formation Rates

Calculating the parameters

According to pre-existing bibliography

Problems with the method

MCMC

Carnall, Adam C., Joel Leja, Benjamin D. Johnson, Ross J. McLure, James S. Dunlop, and Charlie Conroy. 2019. “How to Measure Galaxy Star Formation Histories. I. Parametric Models.” *The Astrophysical Journal* 873 (1): 44. https://doi.org/10.3847/1538-4357/ab04a2.

Haslbauer, Moritz, Pavel Kroupa, and Tereza Jerabkova. 2023b. "The Cosmological Star Formation History from the Local Cosmological Volume of Galaxies and Constraints on the Matter Homogeneity." *Monthly Notices of the Royal Astronomical Society* 524 (3): 3252–62. https://doi.org/10.1093/mnras/stad1986.

———. 2023a. "The Cosmological Star Formation History from the Local Cosmological Volume of Galaxies and Constraints on the Matter Homogeneity." *Monthly Notices of the Royal Astronomical Society* 524 (3): 3252–62. https://doi.org/10.1093/mnras/stad1986.

Karachentsev, Igor D., and Elena I. Kaisina. 2013. "STAR FORMATION PROPERTIES IN THE LOCAL VOLUME GALAXIES VIA H AND FAR-ULTRAVIOLET FLUXES." *The Astronomical Journal* 146 (3): 46. https://doi.org/10.1088/0004-6256/146/3/46.

Karachentsev, Igor D., Dmitry I. Makarov, and Elena I. Kaisina. 2013. "UPDATED NEARBY GALAXY CATALOG." *The Astronomical Journal* 145 (4): 101. https://doi.org/10.1088/0004-6256/145/4/101.

Kroupa, P, M Haslbauer, I Banik, S T Nagesh, and J Pflamm-Altenburg. 2020. "Constraints on the Star Formation Histories of Galaxies in the Local Cosmological Volume." *Monthly Notices of the Royal Astronomical Society* 497 (1): 37–43. https://doi.org/10.1093/mnras/staa1851.

Madau, Piero, and Mark Dickinson. 2014b. "Cosmic Star Formation History." *Annual Review of Astronomy and Astrophysics* 52 (1): 415–86. https://doi.org/10.1146/annurev-astro-081811-125615.

———. 2014a. "Cosmic Star Formation History." *Annual Review of Astronomy and Astrophysics* 52 (1): 415–86. https://doi.org/10.1146/annurev-astro-081811-125615.

Speagle, Joshua S., Charles L. Steinhardt, Peter L. Capak, and John D. Silverman. 2014. "A Highly Consistent Framework for the Evolution of the Star-Forming "Main Sequence" from z~0-6." *The Astrophysical Journal Supplement Series* 214 (2): 15. https://doi.org/10.1088/0067-0049/214/2/15.