ICTP PWF Bangladesh: Summer Internship Program

Determine the total magnified stellar mass and star formation history of the Sparkler galaxy

by

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October, 2025

Content

1. Introduction

The *Sparkler Galaxy* is a highly magnified, distant system located approximately 9 billion light-years away, first reported by Golubchik et al. (2022). Surrounding the galaxy is a collection of relatively bright, point-like sources (AB ≈ 27 mag) known as *"sparkles."* Previous studies (Mowla & Iyer et al. 2022; Claeyssens et al. 2023) suggest that these sparkles are likely ancient globular clusters (GCs). Interestingly, star clusters in other lensed galaxies within the same field do not exhibit such an old stellar population (Claeyssens et al. 2023; Vanzella et al. 2022). However, these conclusions were derived primarily from photometric data, which are often subject to significant parameter uncertainties. Therefore, alternative interpretations—such as younger stellar clusters or even ultra-compact satellite galaxies—remain plausible.

Recently obtained JWST/NIRSpec IFU PRISM+G140M observations offer deeper spectroscopic insight that can help distinguish between these scenarios and enable a detailed analysis of the Sparkler's main body. In this internship, my focus is on learning to work with photometric data and performing SED fitting using the Dense Basis framework. The SED fit of the galaxy's main body provides constraints on key physical properties, including stellar mass, stellar age, star formation history (SFH), dust attenuation, metallicity, and redshift.

This report is organized as follows: Section 2 describes the available data and the subset used for SED fitting, while Section 3 outlines the process of constructing the RGB image. Sections 4 and 5 present the photometry extraction and SED fitting procedures in detail, and finally, Section 6 discusses the resulting physical properties of the Sparkler Galaxy.

2. Data

The Sparkler has extensive multi-wavelength coverage, including previous JWST/NIRCam imaging (F090W, F150W, F200W, F277W, F356W, F444W), shallow NIRISS wide-field spectroscopy (F115W, F200W), and MIRI imaging (F770W, F1000W, F1500W, F1800W). The newly obtained NIRSpec/IFU PRISM+G140M data provide deeper spectroscopic information, enabling significant improvements in constraining the galaxy's physical properties. In particular, the PRISM data, combined with the G140M absorption lines, help break the age–metallicity degeneracy, allowing a more precise characterization of both the sparkles and the host galaxy.

The work presented in this report utilizes only the photometric observations from JWST/NIRCam imaging (F090W, F150W, F200W, F277W, F356W, F444W).

3. RGB Image Making

Data processing for this work began with the reduced (noise-removed) images in six bands (F090W, F150W, F200W, F277W, F356W, F444W). The background of each image was estimated and subtracted using the **SigmaClip** function from *Astropy* and the **MedianBackground** and **Background2D** functions from *Photutils*. Segmentation was performed on the F444W image using the **detect_sources** and **deblend_sources** functions from *Photutils*. Based on the resulting catalogue, a mask was created and applied to all other bands. After masking, cutouts were made to generate an RGB image and for further photometric analysis. The RGB image was produced using the **make_lupton_rgb** function from *Astropy*, with appropriate tuning of the color-scaling parameters.

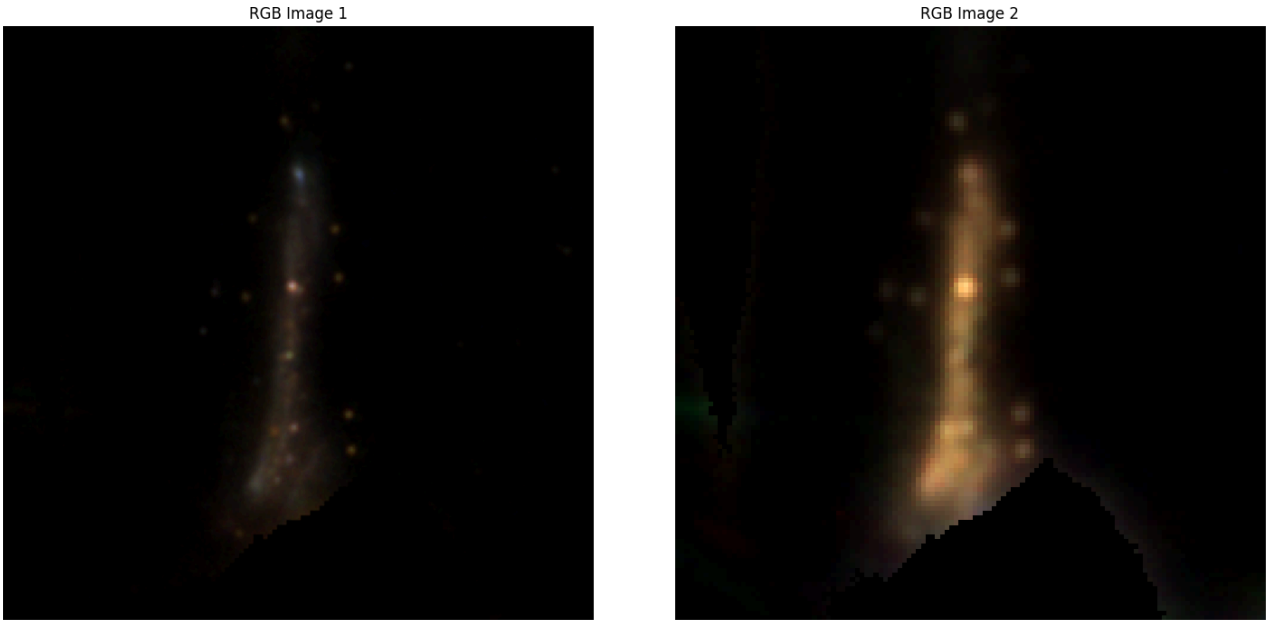

Figure 1: RGB Image 1 is a combination of three filters — F090W, F150W, and F200W — while RGB Image 2 is composed of the other three filters — F277W, F356W, and F444W.

4. Photometry

Each filter has its own point spread function (PSF); therefore, before estimating the flux in each filter, it is preferable to match their PSFs. To achieve this, convolution kernels for PSF matching (to the F444W band) were obtained from the JWST UNCOVER project, and convolution was performed accordingly. An elliptical aperture encompassing the entire Sparkler galaxy, with minimal contamination from nearby sources, was then applied. The measured flux values were **3366.152, 5350.669, 5475.769, 6603.653, 6781.379,** and **6763.321**, corresponding sequentially to the filters **F090W, F150W, F200W, F277W, F356W,** and **F444W**, respectively.

5. SED Fitting

To fit the SED, I used the Dense Basis, a Bayesian spectral energy distribution (SED) fitting framework designed to infer the physical properties of galaxies—such as stellar mass, star formation rate (SFR), dust attenuation, metallicity, and redshift—from multi-wavelength photometric data. It uses a library (or atlas) of model SEDs generated from parameterized star formation histories (SFHs), metallicities, and dust laws, computed through stellar population synthesis models. The method employs a precomputed grid of models and evaluates the likelihood of each model given the observed photometry and uncertainties. By marginalizing over the model parameters, Dense Basis provides posterior probability distributions for each physical property. Its flexibility allows users to define custom priors, control the complexity of the SFH, and constrain redshift either as a fixed or free parameter.

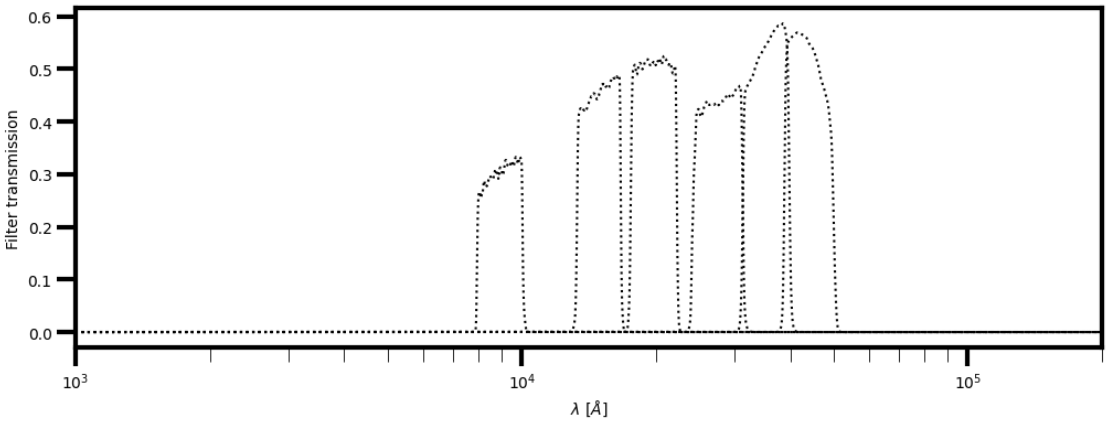

Figure 2: Throughputs of the six filters used in this report.

The throughputs of six filters were first provided to define the photometric response of the system. Then, physically motivated priors were set for the SED parameters to generate the atlas—a library of model spectra covering a wide range of possible galaxy properties. After the atlas generation, the observed flux values in the six filters (converted to units of microJy) were passed to the sedfit function for fitting. These priors ensure that the fitting process explores a realistic and physically constrained parameter space while maintaining enough flexibility to capture the intrinsic spectral characteristics of the galaxy. [All the notebooks are available in this git repository: Sparkler]

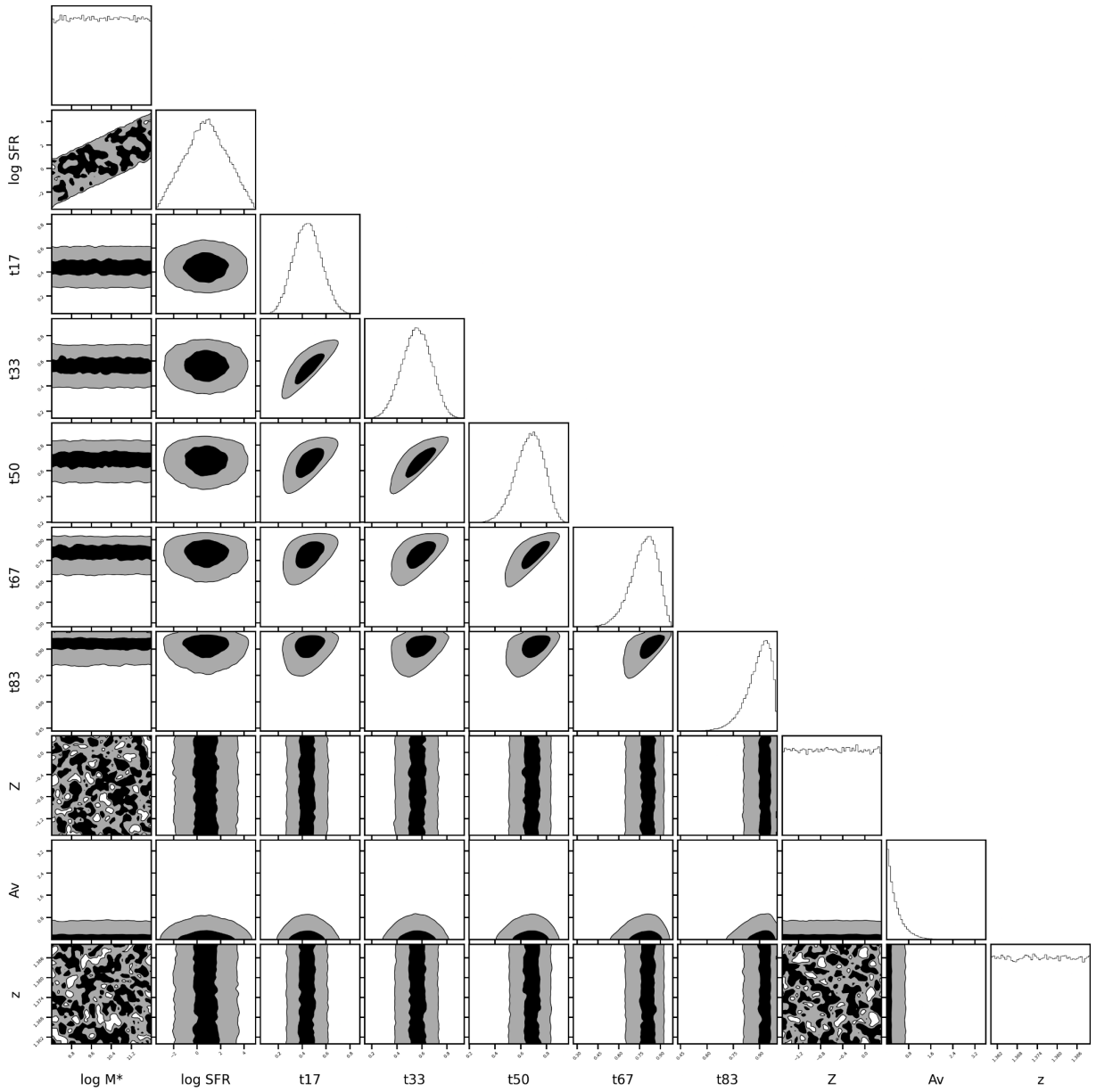

Figure 3: Corner plot showing the adopted prior distributions for the SED fitting parameters used in *Dense Basis*. The priors include stellar mass, star formation history (with five time bins), specific star formation rate (sSFR), metallicity, dust attenuation (AV), and redshift.

6. Results

The SED fitting of the Sparkler Galaxy was performed using the Dense Basis framework, yielding posterior estimates for key physical parameters of the galaxy. The median values (with error values) are as follows:

Parameter	Description	Best-fit Value
log(M★/M⊙)	Stellar mass	$10.13^{+0.05}_{-0.06}$
log(SFR/M⊙ yr⁻¹)	Star formation rate	$1.09^{+0.10}_{-0.16}$
A_V (mag)	Dust attenuation	$0.18^{+0.15}_{-0.13}$
log(Z/Z⊙)	Metallicity	$-0.15^{+0.21}_{-0.26}$
z	Redshift	$1.376^{+0.009}_{-0.010}$

These results indicate that the Sparkler is a moderately massive galaxy ($M\bigstar \approx 1.3 \times 10^{10}\ M\odot$) with a relatively high star formation rate (~12 $M\odot\ yr^{-1}$), consistent with a star-forming system at $z \approx 1.38$. The low dust attenuation ($A_V \approx 0.2$ mag) suggests that the galaxy is only mildly obscured, and the sub-solar metallicity ($Z \approx 0.7\ Z\odot$) implies an evolving stellar population that is still building up its chemical content.

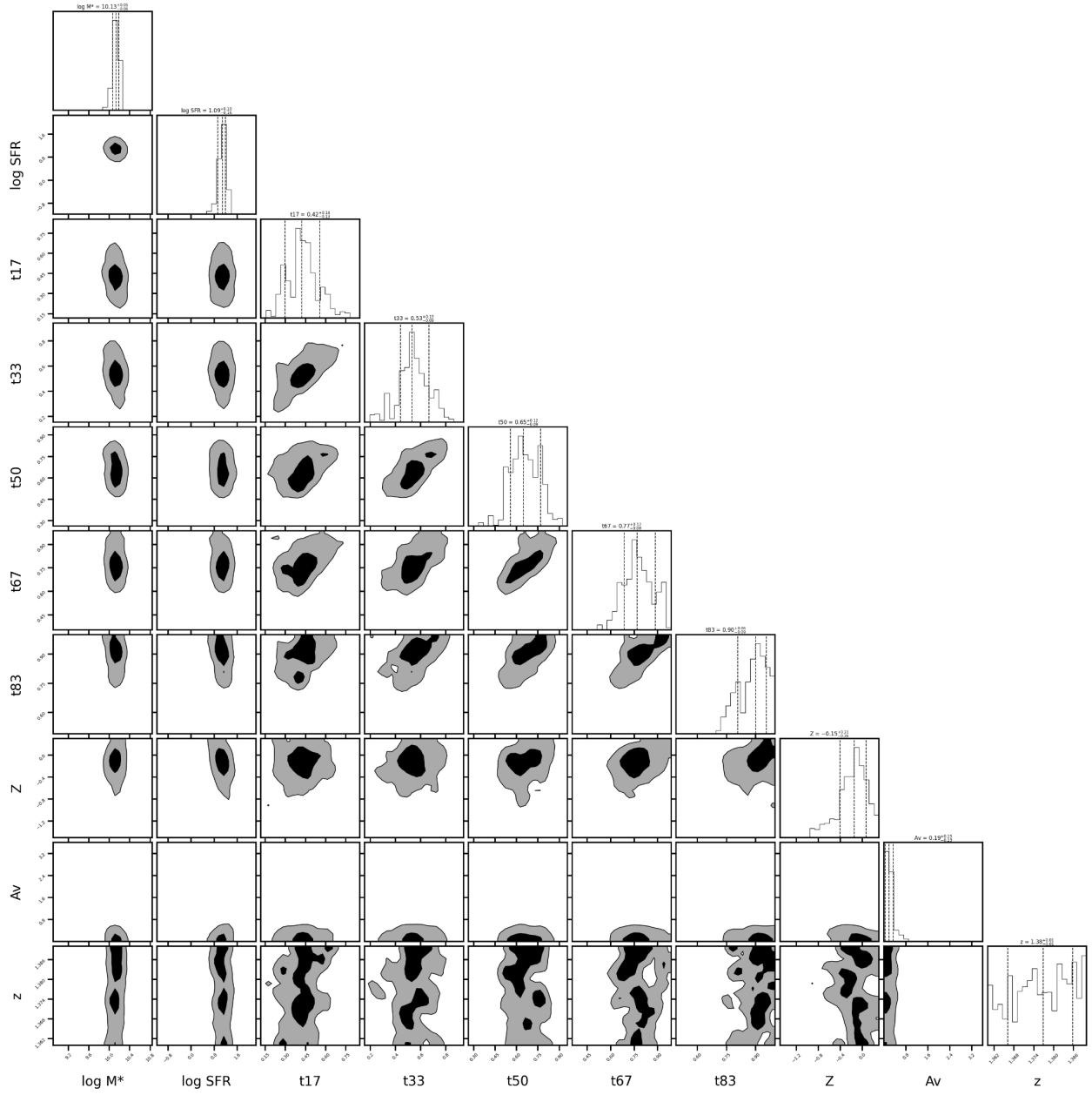

Figure 4: Corner plot showing the posterior distributions of the fitted physical parameters (stellar mass, SFR, dust attenuation, metallicity, and redshift) from the Dense Basis SED fitting. The contours represent the 1σ and 2σ confidence intervals for each parameter pair.

The derived **star formation history (SFH)**, presented in **Figure 5**, shows that the Sparkler experienced a relatively continuous star formation over the past several billion years, with sustained activity in recent epochs. This supports the interpretation that the Sparkler is still actively forming stars at $z \approx 1.38$.

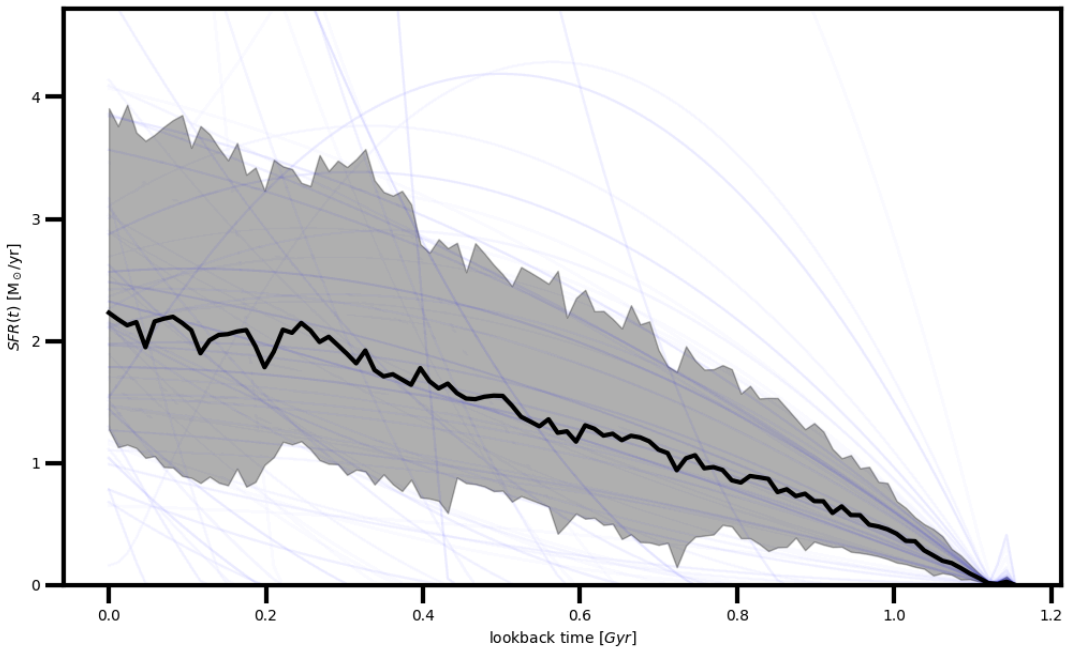

Figure 5: Star formation rate (SFR) as a function of lookback time derived from the Dense Basis fit. The plot suggests a gradually declining but persistent star formation activity in the galaxy.

The model SED fit to the observed photometry is shown in **Figure 6**, demonstrating an excellent agreement between the observed fluxes and the best-fit model across all six filters.

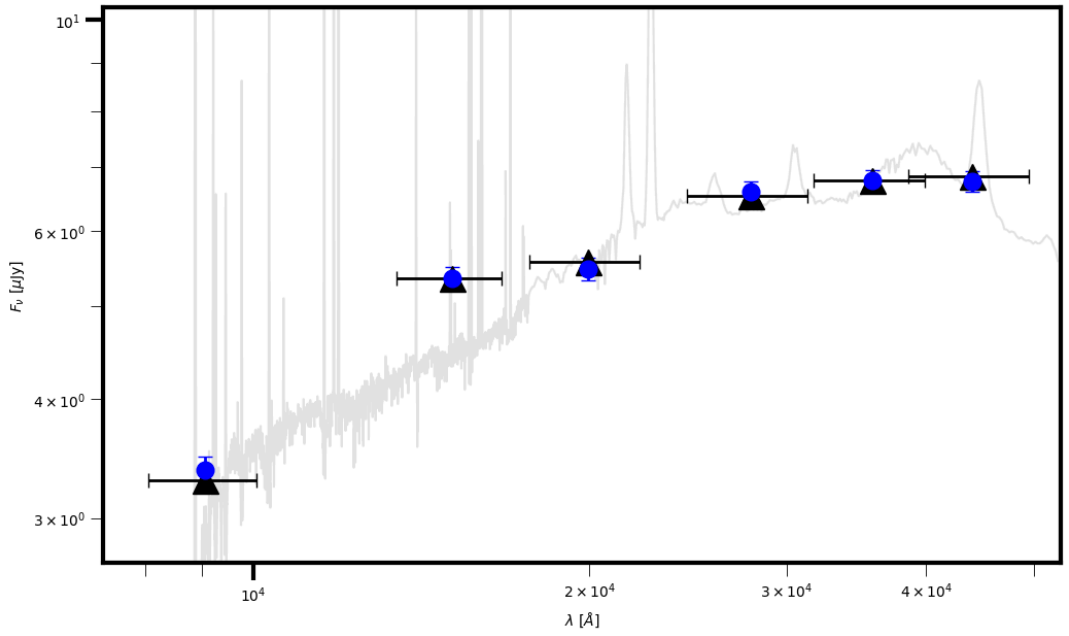

Figure 6: Best-fit spectral energy distribution (SED) of the Sparkler Galaxy obtained with Dense Basis. The black points represent the observed photometric fluxes with uncertainties, and the blue curve shows the best-fit model spectrum. The colored squares indicate the model-predicted fluxes in each filter band.

7. References

1. Golubchik, M., et al. 2022, ApJL, 938, 14
2. Mowla & Iyer, M., et al. 2022, ApJL, 937, L35
3. Claeyssens, A., et al. 2023, MNRAS, 520, 2180-2203
4. Vanzella, E., et al. 2022, ApJL, 940, L53

8. **Worklog:** Summary of Tasks and Meeting Attendance

Week	Attendance	Goal/Issues	Progress
Jul 15, 2025	Yes	-	We got introduced to each other and discussed the plan for the next 3 months.
Jul 16, 2025	No	**Due to sudden rescheduling, I had to watch the recording.**	Discussed the plan for the next 3 months.
Jul 29, 2025	Yes	**SED Fittting w/ Dr. Iyer**	Read the SED paper
Aug 12, 2025	Yes	Tutorials on making cutout, creating RGB images, masks, photometry, and SED fitting	Made a cutout of the Sperkler Galaxy and created two RGB images. RGB1: F090W, F150W, F200W RGB2: F277W, F356W, F444W
Aug 19, 2025	Yes	Tutorials on making cutout, creating RGB images, masks, photometry, and SED fitting	Performed the photometry using the Photutils package. Also created masks from the segmentation map.
Aug 26, 2025	Yes	Tutorials on making cutout, creating RGB images, masks, photometry, and SED fitting	Created one mask for all filters. And tried to estimate the fluxes in all filters with photutils segmentation. Completed the practices of dense basis: The GP-SFH module.
Sep 15, 2025	Yes	Tutorials on making cutout, creating RGB images, masks, photometry, and SED fitting	Set up an environment in the linux system with fsps and completed the full SED fitting tutorial of Dense Basis.
Sep 29, 2025	Yes	SED fitting	Flux estimation was done with an astropy aperture feature.
Oct 22, 2025	Yes	Discuss the Dense Basis outputs	Fitted the SED model to the photometry data, but the stellar mass estimation was not good. So, I need to work on that.
Oct 30, 2025 End of Internship		Report due.	Discussed the Dense Basis results and submitted the internship report.

9. Reflection

This internship has been an incredible opportunity for me to connect with Dr. Lamiya Mowla and gain hands-on experience in astrophysical research. It has provided me with valuable exposure to real scientific data analysis and the use of advanced tools like Dense Basis to study galaxy properties. I am truly grateful for this experience, as it has not only strengthened my research skills but also paved the way for my future — I will be continuing to work under Dr. Mowla's supervision as a Graduate Research Assistant. I believe this initiative offers an important platform for students from Bangladesh to engage with cutting-edge international research, and such opportunities should be continued every year to inspire and empower the next generation of young researchers.

Approval

The internship report titled “Determine the total magnified stellar mass and star formation history of the Sparkler galaxy” submitted by Ahmad Al-Imtiaz, a participant of the ICTP PWF: Physics for Bangladesh Online Summer Internship, has been found satisfactory in partial fulfillment of the requirements of the internship program. The internship was conducted under the supervision of **Lamiya Mowla** during the period **15 July 2025** to **15 October 2025**.

Supervisor

Lamiya Mowla

Wellesley College, MA, USA.