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Synthesizer: Synthetic Observables For Modern Astronomy

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Software

- Review
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Summary

Synthesizer is a fast, flexible, modular, and extensible Python package that empowers astronomers to turn theoretical galaxy models into realistic synthetic observations - including spectra, photometry, images, and spectral cubes - with a focus on interchangeable modelling assumptions. By offloading computationally intensive tasks to threaded C++ extensions, Synthesizer delivers both simplicity and speed, enabling rapid forward-modelling workflows without requiring users to manage low-level data processing and computational details.

Statement of need

Comparing theoretical models of galaxy formation with observations traditionally relies on two main approaches, both translating theoretical models into the observer space (a technique known as forward modelling). The first uses computationally expensive dust radiative transfer codes (e.g. Camps & Baes, 2015; Jonsson, 2006; Narayanan et al., 2021); these codes are typically computationally expensive, prioritising fidelity. The second uses simpler, bespoke pipelines that sacrifice some physical fidelity to generate observables rapidly from large datasets (e.g. Fortuni et al., 2023; Marshall et al., 2025; Roper et al., 2022; Vijayan et al., 2020; Wilkins et al., 2020).

Simplified inverse modelling approaches, such as SED fitting (e.g. Brammer et al., 2008; Carnall et al., 2018; Johnson et al., 2021) work in the opposite direction, translating observables into intrinsic physical quantities. However, these methods can introduce biases and uncertainties from both observational effects and model assumptions. Compounding these uncertainties is the fact that converged inverse modelling techniques are costly in their own right, necessitating a simplified parameter space to ensure convergence in a reasonable time. Forward modelling is therefore becoming increasingly important not only for probing the validity of theoretical models, but also for quantifying the uncertainties in the modelling assumptions themselves.

However, existing forward modelling tools often lack the flexibility to explore modelling uncertainties, the usability and modularity to explore a wide range of modelling assumptions, and the performance necessary to explore a large parameter space and process modern-day large datasets. Furthermore, they frequently lack comprehensive documentation, hindering consistency, and reproducibility across a range of datasets.

Synthesizer addresses these shortcomings by offering:

- Flexibility: Anything that could be changed by the user is explicitly designed to be variable (for a quantitative model parameter) or exchangeable (for a qualitative modelling choice). This means that users can easily vary everything in a reproducible way, without needing to modify the core code.
- Performance: Computationally intensive operations are optimised by employing C extensions with OpenMP threading. Without this performance, the aforementioned flexibility is moot; only by coupling flexibility with the performance to utilise it can we explore large, high-dimensional parameter spaces in a reasonable time.
- Modularity: Synthesizer is object-oriented, with a focus on decoupled classes that can be specialised and then swapped out at will. This modularity, in conjunction with a reliance on templating and dependency injection (see Emission Models below), is what enables Synthesizer's flexibility, as well as its application to a diverse range of astrophysical problems in both forward and inverse modelling
- Extensibility: Extensive documentation and a clear API enable users to extend the package with their own calculations, parameterisations and subclasses. From the beginning, Synthesizer has been designed to be expanded to fit the needs of all users, even as astronomy and astrophysics evolve.

Synthesizer's design facilitates apples-to-apples comparisons between simulations and observations (e.g. Wilkins et al., 2025), permits exhaustive tests of the impact of parameter choices (e.g. Ho et al., 2024), enables the forward modelling of large datasets previously considered impractical (e.g. Lovell et al., 2024), and promotes open and reproducible science.

Implementation overview

Synthesizer is structured around a set of core abstractions. Here we give a brief outline of these abstractions and a link to the documentation for each.

- **Components**: Represent stars, gas, and black holes, encapsulating physical properties, and emission and emission generation methods. For more details, see the components documentation.
- **Galaxies**: Combine multiple components into a single object, allowing for cohesive calculations with all components, taking account of their interdependencies. For more details, see the galaxies documentation.
- **Emission Grids**: N-dimensional lookup tables of precomputed spectra and lines. Precomputed grids are available for stellar population synthesis models, including BC03 (Bruzual & Charlot, 2003), BPASS (Stanway & Eldridge, 2018), FSPS (Conroy et al. (2009), Conroy & Gunn (2010)), Maraston (Maraston (2005), Newman et al. (2025)), all reprocessed using Cloudy (Ferland et al., 1998). Grids of AGN emission can also be calculated and explored. Users can generate custom grids via the accompanying grid-generation package. For more details, see the grids documentation.
- **Emission Models**: Modular templates defining the process of producing emissions from components. These models can be used to extract, generate, transform, or combine emissions. These are the backbone of Synthesizer's flexibility and modularity. For more details, see the emission models documentation.

- **Emissions**: The output of combining components with an emission model. These emissions are either spectra stored in Sed objects, or line emissions stored in `LineCollection` objects.
- **Instruments**: Definitions of filters, resolutions, PSFs, and noise models to convert emissions into photometry, spectroscopy, images, and data cubes. For more details, see the instruments documentation and filters documentation.
- **Observables**: Containers for the output spectra with observational effects (Sed objects), photometry (`PhotometryCollection` objects), images (`Image` and `ImageCollection` objects), and spectral data cubes (`SpectralDataCube` objects).

Synthesizer is hosted on GitHub and is available on PyPI. The documentation is available through GitHub Pages.

Related packages

There are various other related packages which either perform similar tasks as Synthesizer or can be used in harmony with Synthesizer to create end-to-end workflows. We highlight a handful of these packages below.

- **Stellar population synthesis & Photoionisation**
  - **BC03** (Bruzual & Charlot, 2003): Classic stellar population synthesis code providing spectral energy distributions (SEDs) for single stellar populations with various initial mass functions (IMFs) and metallicities.
  - **FSPS** (Conroy et al., 2009; Conroy & Gunn, 2010): Stellar population synthesis code offering flexible isochrone-based spectral generation for a variety of IMFs and metallicities.
  - **BPASS** (Stanway & Eldridge, 2018): Models binary stellar populations with detailed spectral outputs, crucial for UV and nebular emission studies.
  - **Maraston** (Maraston, 2005): Provides high-resolution SEDs with alternative stellar evolution prescriptions, particularly useful for post-starburst galaxies.
  - **Cloudy** (Ferland et al., 1998): Photoionisation and spectral synthesis code for computing emission-line and continuum processes in gas under various physical conditions.
  - **MAPPINGS** (Dopita & Sutherland, 1996): An alternative photoionisation code for computing emission-line spectra from ionised gas, particularly useful for AGN and star-forming regions.
- **Monte Carlo radiative transfer**
  - **SKIRT** (Camps & Baes, 2015): 3D dust radiative-transfer engine supporting arbitrary geometries, multi-wavelength photon packets, and variance-reduction techniques for high-fidelity galaxy and torus models.
  - **Powderday** (Narayanan et al., 2021): Integrates FSPS, Hyperion (Robitaille, 2011), and yt (Turk et al., 2011) to perform Monte Carlo RT directly on hydrodynamic simulation outputs, automating grid preparation and execution.
- **Point spread function & instrument models**
  - **STPSF** (Perrin et al., 2014): Physical-optics simulator for JWST, Roman, and HST, modelling pupil masks, wavefront errors, and instrument-specific aberrations to generate realistic PSFs.
  - **GalSim** (Rowe et al., 2015): Versatile image-simulation toolkit offering analytic and empirical PSF models, shear and magnification operators, detector effects (e.g., charge diffusion), and realistic noise injection.
- **Pre- and post-processing utilities**
  - **Astropy** (Astropy Collaboration et al., 2022): Foundational library for astronomy,

providing FITS I/O, WCS transformations, units system, coordinate conversions, and utility functions for photometry and statistics.
    - **YT** (Turk et al., 2011): Analysis and visualisation toolkit for astrophysical simulations, supporting adaptive mesh refinement (AMR) data, particle data, and structured grids, with a focus on large-scale cosmological simulations.
    - **Astroquery** (Ginsburg et al., 2019): Python interfaces to VO services and mission archives (e.g., MAST, SIMBAD), enabling scripted retrieval of catalogues, images, and spectra.
    - **Dense Basis** (Iyer et al., 2019): A library for generating and manipulating dense basis functions tailored to SED fitting and SFHs, useful for efficiently representing complex SFHs.

- **Inverse modelling & SED fitting**
    - **EAZY** (Brammer et al., 2008): Fast photometric redshift and SED-fitting code using template-optimisation and Bayesian priors for parameter inference.
    - **BAGPIPES** (Carnall et al., 2018): Flexible Bayesian SED-fitting tool supporting complex star-formation histories, nebular emission, and dust attenuation curves.
    - **PROSPECTOR** (Johnson et al., 2021): Advanced inference framework combining MCMC and nested sampling for robust posterior estimation of stellar and dust parameters.

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