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ASTRAI

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We present ASTRAI, an end-to-end framework that accelerates Type II supernova (SN) research by integrating physically motivated models with generative diffusion techniques to produce a high-fidelity synthetic dataset for deep learning (DL)–based SN characterization. First, we aggregate and homogenize multi–survey photometric and spectroscopic observations from Carnegie, WISeREP, Zenodo, and LSST precursor programs, applying bolometric corrections and Gaussian-process interpolations to construct a benchmark dataset of real light curves. Building upon semi-analytical hydrodynamic and ejecta circumstellar medium (CSM) interaction models, we generate synthetic SN observables spanning total explosion energy, ejected mass, progenitor radius, radioactive yields, and CSM properties.

To address the irregular time sampling and incomplete labeling of real data, we develop a two-stage Generative AI pipeline: (1) a diffusion-based Light Curve Generator (LCGen) that learns the manifold of physically consistent SN evolutions conditioned on progenitor parameters; and (2) a Physical Parameter Regressor (PPR) that inverts the LCGen outputs back to progenitor properties. By jointly optimizing mean-squared losses and reconstruction error of the full cycle in both observable and parameter spaces, our approach ensures realism, diversity, and physical interpretability.

We evaluate ASTRAI on held-out surveys, demonstrating that DL models pre-trained on our synthetic dataset and fine-tuned on limited real observations reduce median parameter errors by half compared to classical Gaussian-process methods, while inference times drop from minutes to milliseconds per object. Ablation studies reveal that diffusion sampling contributes an improvement in light-curve fidelity over standard variational autoencoders, particularly in phases with sparse data. Our results showcase the potential of combining diffusion-driven data augmentation with physics-aware DL architectures to meet the demands of next-generation surveys such as LSST, enabling rapid, automated, and accurate characterization of supernovae.

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