Exploration of Nonlinear Time-Series Features for Astronomical Light Curve Classification

Jiri Roman Moronga[1], Jan Novotny[1], Karel Adamek[1]

[1]Institute of Physics in Opava, Silesian University in Opava

SILESIAN UNIVERSITY
INSTITUTE OF PHYSICS IN OPAVA

Introduction

- The PLAsTiCC (Photometric LSST Astronomical Time-Series Classification Challenge) aims to classify simulated astronomical transients for future surveys
- **Challenge:** Extract informative features from irregularly sampled, noisy, multi-band light curves

Motivation

Research Question:
Can state space reconstruction provide complementary information for light curve classification?

- Time delay embedding captures dynamical structure
- Hypothesis: Features extracted from phase space add complementary information to standard features

Data & Preprocessing

Dataset:

- PLAsTiCC Kaggle challenge dataset
- Multiple astronomical transient classes
- Irregularly sampled, multi-band photometry
- Train samples - 595006, test samples - 3492890
- Only classes in training set were predicted

Data Preprocessing:

- Boone (2019) data augmentation and interpolation methodology [1]
- Gaussian Process (GP) 2D interpolation per band
- Training set augmentation to match test set statistics

Time Delay Embedding

State Space Reconstruction:

- Apply Takens' embedding theorem
- Reconstruct phase space from time series
- Extract nonlinear and geometrical features

Method:

$$\mathbf{x_i}(t) = [x_i(t), x_i(t+\tau), x_i(t+2\tau), ..., x_i(t+(d-1)\tau)],$$

where $x_i(t)$ is a light curve signal measure in time t and in i-th passband, τ is time delay, d is embedding dimension and $\mathbf{x_i}(t)$ is embedded vector in i-th passband's phase space. The union of the phase spaces creates joint phase space whose elements are $\mathbf{x}(t)$.

Novel Phase Space Features

Ring Radius per passband:

$$R_i = \frac{1}{N_i} \sum_{k=1}^{N_i} \|\mathbf{x_i}^{(k)} - \mathbf{c_i}\|$$

where $\mathbf{c_i} = \frac{1}{N_i} \sum_k \mathbf{x_i}^{(k)}$ is the centroid.

Ring Radii Standard Deviation:

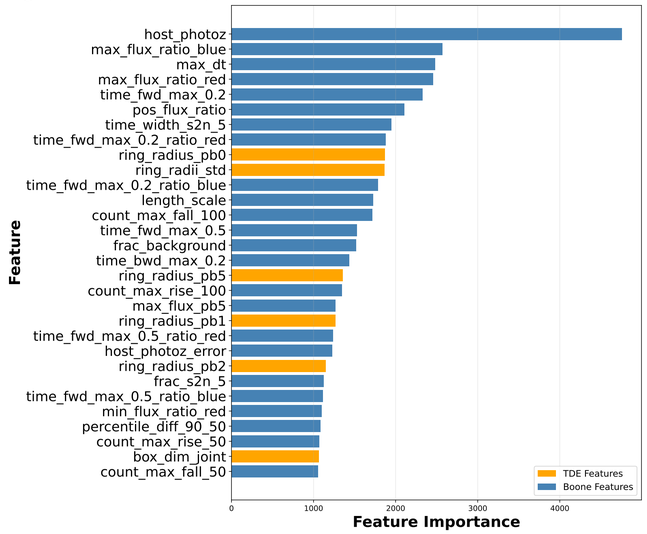
$$\sigma_R = \sqrt{\frac{1}{6} \sum_{i=1}^{6} (R_i - \bar{R})^2}$$

Ring Ordering: Order passbands by R_i: smallest to largest radius

Additional features:

- Fractal dimension (box-counting)
- Per-passband and joint phase space metrics

Figure 1: Top 30 most important features from selected Boone + TDE features model



Classification Framework

- Classifier: LightGBM
- 4 model variants tested
- Cross-validation on training set
- Evaluation on held-out test set

Feature Combinations

- Boone's features only (baseline)
- Time delay embedding (TDE) features only
- All Boone's and all TDE features
- Selected Boone's and TDE features

Results

Performance comparison (weighted multi-log loss [2]):

Model	Score
Boone's features	0.5616
TDE features only	0.6397
Boone + TDE features	0.5617
Selected Boone + TDE	**0.5604**

Top 5 Kaggle leaderboard models (evaluated on all classes):

Team / Method	Public score
Kyle Boone	0.68503
Mike & Silogram	0.69933
Major Tom	0.70016
AhmetErdem	0.70423
SKZ Lost in Translation	0.75229

Note: Our scores are computed only on training-set classes. Improving predictions on these classes enhances overall performance, as probabilities are normalized across all classes (softmax), benefiting rare or unseen classes in full PLAsTiCC evaluation.

Conclusions & Future Work

Conclusions:

- TDE features capture complementary dynamical information

Future Work:

- Create more informative features
- Explore deep learning on phase space representations

References

[1] Boone, K. (2019). Avocado: Photometric classification of astronomical transients with gaussian process augmentation. *The Astronomical Journal*, 158(6), 257. arXiv:1907.04690

[2] Hložek, R., et al. (2020). Results of the Photometric LSST Astronomical Time-series Classification Challenge (PLAsTiCC). arXiv:2012.12392

Light Curve Examples and Corresponding Phase Space Reconstructions

Figure 2: GP-interpolated light curve of Object A

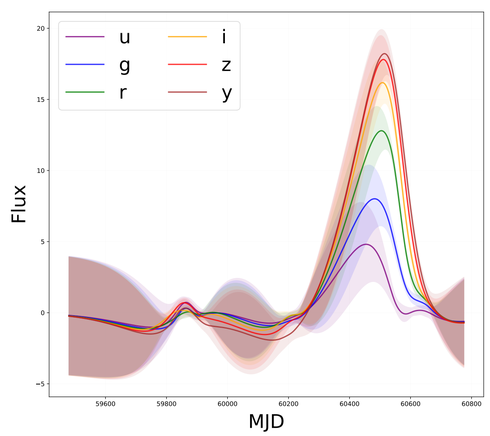


Figure 3: TDE-reconstructed phase space of Object A

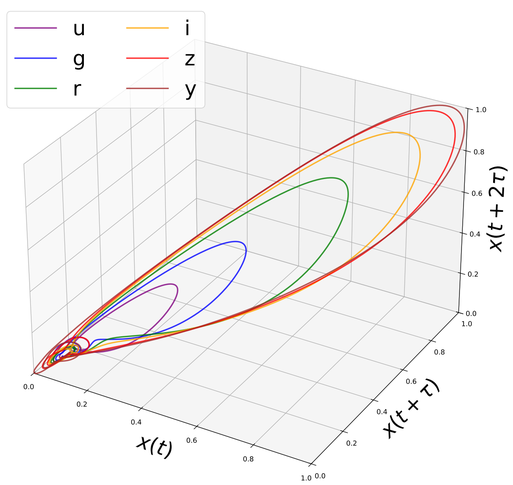


Figure 4: GP-interpolated light curve of Object B

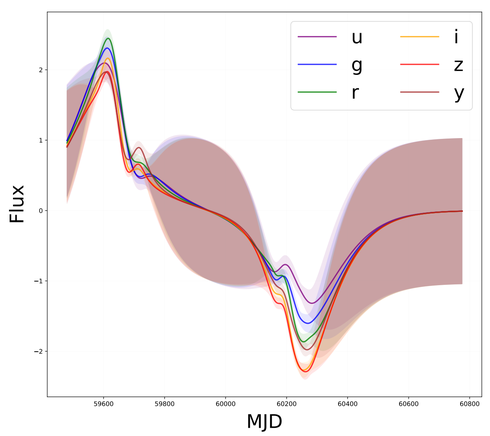


Figure 5: TDE-reconstructed phase space of Object B