Website with interactive visualization of multivariate astronomical time series

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Abstract

Light curves represent astronomical time series of flux measured across one or more photometric bands. With the rapid growth of large-scale sky surveys, time-domain astronomy has become an essential area of modern astrophysical research. Interactive visualization of extensive light-curve datasets plays a key role in exploring transient phenomena and in planning large follow-up campaigns. In this work, we introduce two web-based platforms designed for interactive light-curve visualization: Fulu, for transient event studies, and VALC, for investigations of low-mass active galactic nuclei (AGNs). These tools provide a user-friendly interface for examining, comparing, and interpreting vast collections of astronomical light curves, supporting scientific discovery.

Keywords: *methods: miscellaneous, virtual observatory tools.*

1. Motivation

Interactive visualization of multivariate time series in astronomy, specifically light curves of astrophysical sources, is an important and often missing component of wide-field sky surveys and also of smaller, focused astronomical databases. Keeping this in mind, we developed the website[1] for light curve visualization and exploration. Our platform allows users to explore and visualize the results of Fulu neural network approximation and variability analyzer for light curves (VALC) algorithms applied to real observational samples, offering object-by-object insights into time-domain behavior. In this paper, we present the website's architecture, core functionality, and its scientific applications, demonstrating how it facilitates efficient analysis and interpretation of complex light-curve data.

1.1. FULU

Fulu (Demianenko et al., 2023b) is a Python package that provides ready-to-use neural network and Gaussian processes (GP; Williams & Rasmussen, 1995) approximation methods for multiband light curves with uneven time steps, accessing approximation both through time and passband. Implemented methods (Bayesian neural network (Blundell et al., 2015), normalizing flows (Rezende & Mohamed, 2015, Tabak & Turner, 2013), multilayer perceptions (Rumelhart et al., 1986) with one and two hidden layers, GP) predict the observations and their errors in several photometric bands. The models require at least 10 points within one light curve for fair performance. The tests on the Zwicky Transient Facility (ZTF; Masci et al., 2019) Bright Transient Survey (BTS; Fremling et al., 2020, Perley et al., 2020) light curves based on Fulu showed that neural network models are a reasonable alternative to GP and also take less computational time than the widely-used GP with different covariance matrices (Demianenko et al., 2023c). Both PLAsTiCC Legacy

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[1]https://lc-dev.voxastro.org

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Survey of Space and Time (LSST; Hambleton et al., 2023) simulated (Hložek et al., 2023) and real ZTF BTS datasets were validated by regression metrics, quality metrics of observations predicted by the models, as well as the quality of subsequent classification and peak estimation (Demianenko et al., 2023a,b, Samorodova et al., 2024).

We present the FULU webpage[2] with the BTS ZTF sample of neural network and GP approximated transient light curves, with estimated peak time and magnitude.

1.2. VALC

Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al., 2018) Forced Photometry service (AFPS; Shingles et al., 2021, Smith et al., 2020) provides PSF-photometry at different images adopting the algorithm TPHOT (Sonnett et al., 2013, Tonry, 2011). The ZTF Forced Photometry service (ZFPS Masci et al., 2023) produces *statistically optimal* PSF-photometry at different imaging (ZOGY; Zackay et al., 2016) and the adoption of it for aperture photometry. Such light curves enable us to investigate the variability amplitudes of active galactic nuclei (AGN), eliminating the host galaxy contribution. However, even in the case of the ZOGY, we still observe artificial variability contributions in ZFPS, the exact source of which has not yet been identified. Demianenko et al. (2022, 2024) developed a post-processing algorithm for the artificial variability elimination in ZFPS light curves using non-variable stars, then applied it to ∼1900 low-mass AGN candidates up to $2 \times 10^6\ M_\odot$ selected by broad optical emission lines using SDSS DR7 spectra (Chilingarian et al., 2017, 2018).

We developed a VALC webpage[3] with ZTF and ATLAS Forced Photometry light curves and main parameters of these objects.

2. Architecture and functionality

The website features visualizations that utilize PLOTLY (Inc., 2015) to display interactive graphics. On the server side, the system is implemented as a Python application using the FASTAPI (Ramírez, 2018) framework. Data are stored as JSON (Crockford, 2006) objects in MongoDB (MongoDB, 2009). All components of the system, including the frontend, backend, and database, are encapsulated within Docker (Merkel, 2014) containers. Figure 1(a) shows process interactions between the user, frontend, API, and MongoDB arranged in a time sequence. The system architecture is shown in Figure 1(b).

Such an architecture was chosen for its simplicity and ease of maintenance. Docker containers enable full system deployment on any server with a few commands. FastAPI, with its strong typing support, provides strict control over data models while maintaining high development speed in Python. The client is separated from the backend, allowing for future migration to another frontend technology without affecting the backend - a step we plan to take as the current frontend becomes harder to maintain. Since the system does not involve complex data filtering logic, a document-oriented database such as MongoDB was found to be a suitable solution.

Data ingestion to the website occurs in two stages. First, the raw data are processed locally using the FULU and VALC algorithms discussed in the following sections. Then, a dedicated script uploads the results through the service API, mapping them into internal data structures and storing them in the database. This approach enables rapid iteration over algorithm versions and allows updates without redeploying the service itself. However, as discussed below, this scheme becomes less suitable for our future development plans, and we outline the planned improvements in Section 4.

The VALC page shows the list of objects from the ∼1900 low-mass AGN sample. The search is available, and in case of partial name input, it shows subsamples that satisfy this part of the IAU name of the object. The page of a particularly chosen object shows equatorial coordinates `ra` and `dec`; black hole mass measured using the broad Hα component in SDSS (`MBH_SDSS`), MagE (`MBH_MagE`), ESI (`MBH_ESI`), and SALT RSS (`MBH_SALT`) spectra, with numeration if available several spectra from the same instrument (Goradzhanov et al., 2022, 2024a); `source` of X-ray detection, photon index `Gamma`, hydrogen column density `NH` and X-ray luminosity `L_X` from the X-ray power-law with photoelectric absorption fit, if any (Toptun et al., 2022); `rcsed` - the link with coordinate search in the development version of the RCSEDv2[4] catalog (Chilingarian et al., 2024, Goradzhanov et al., 2024b, Kasparova et al., 2024, Klochkov et al., 2024, Rubtsov et al., 2024,

[2] https://lc-dev.voxastro.org/fulu.html
[3] https://lc-dev.voxastro.org/valc.html
[4] https://dev-rcsed2.voxastro.org/

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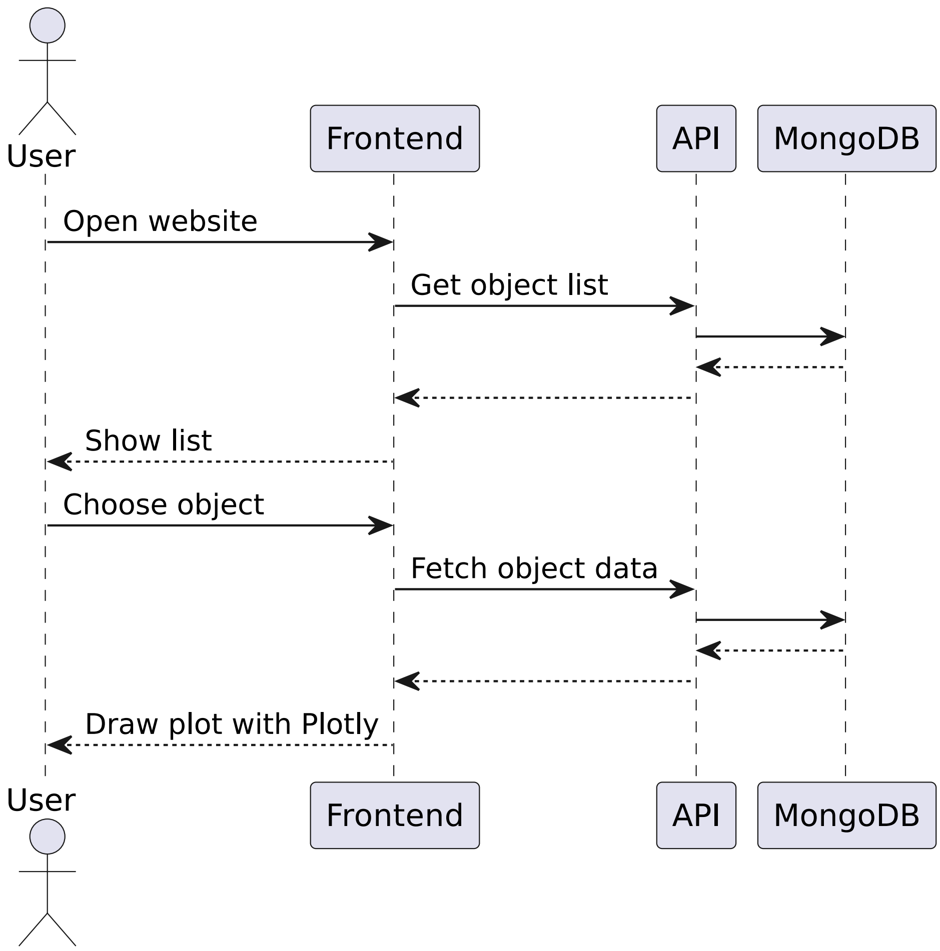
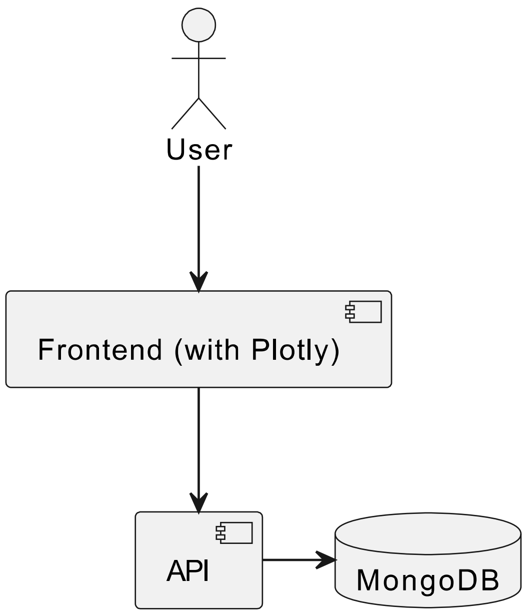


(a)



(b)

Figure 1. (a) Sequence diagram illustrating the data flow between the user, frontend, API, and MongoDB when displaying and plotting object data using Plotly. (b) Component diagram illustrating simple architecture of the system.

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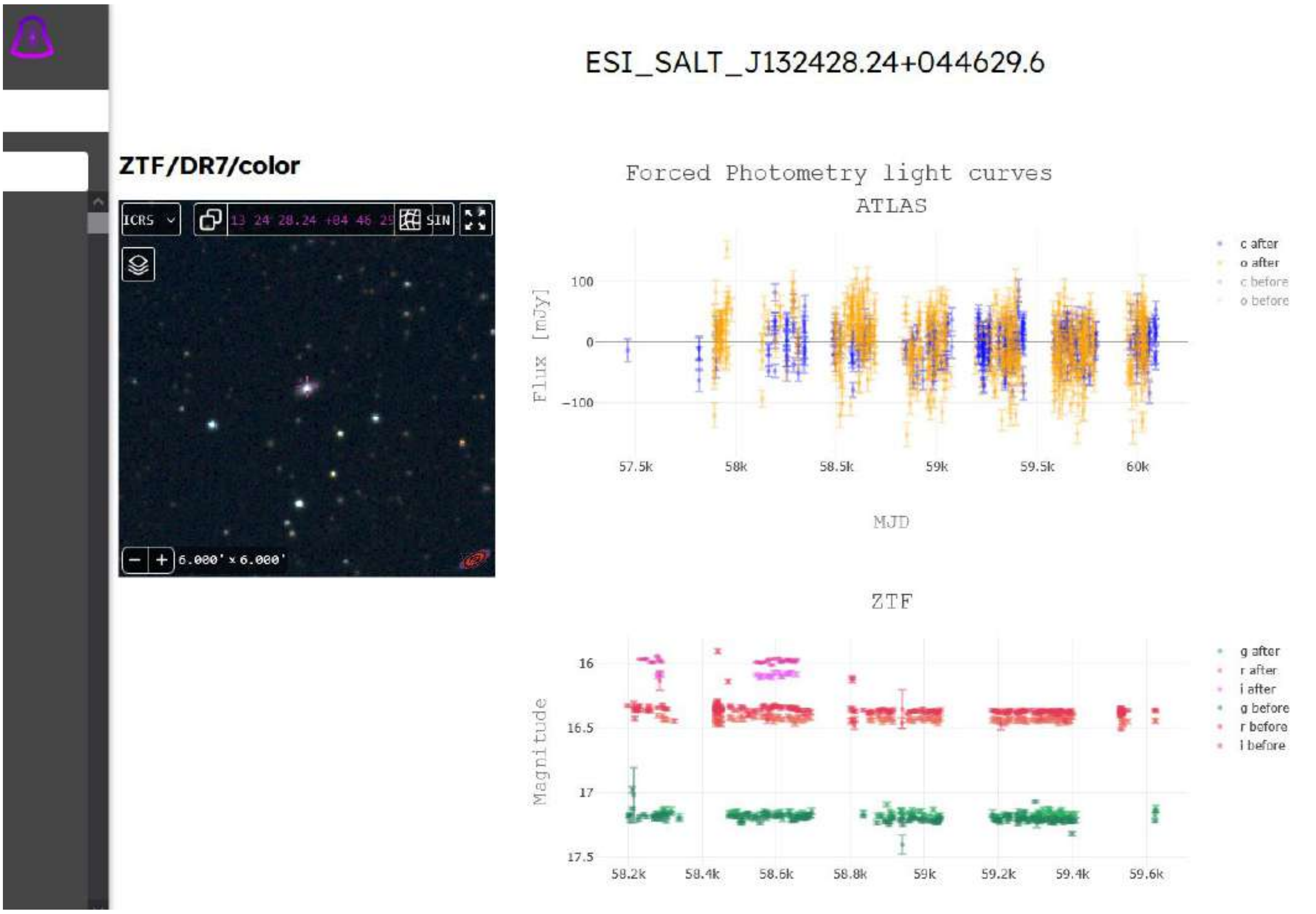

Figure 2. Interface example of the low-mass AGN light curves visualization at the VALC page.

Toptun et al., 2024). All other fields are introduced for internal use within the VOxAstro team. The light curves from AFPS and ZFPS are shown both before/after post-processing. The post-processing for ZFPS light curves includes zero-point and color correction, filtering following ZTF guidelines, and subtraction of the median star from the image (Demianenko et al., 2024). We show the Aladin-lite interactive image viewer (Boch, 2014) of the ZTF catalog to indicate whether a target is within the ZTF sample. ZFPS light curves are visualized in $\{g, r, i\}$ passbands if any of the points were available after post-processing. The color correction term effectively converts ZTF magnitudes to the Pan-STARRS1 (PS1; Chambers et al., 2016) magnitudes. Therefore, the shift between 'before' and 'after' light curves is present. AFPS light curves underwent only median reference star subtraction and represent flux in $\{o, c\}$ passbands. Figure 2 shows an example of the VALC webpage interface.

The Fulu page shows a list of events from the BTS ZTF. The search by ZTF alert ID or part of this ID is also available. The page of the object represents the ZTF light curve in $\{g, r\}$ passbands, as well as peak parameters: (`MJD_sum` - Modified Julian Date (MJD) of the peak, estimated from the sum of both filters light curve; `magnitude_sum` - apparent magnitude of the peak calculated from the same cumulative light curve; `flux` - peak flux in mJy of the same cumulative light curve; `magnitude_g`(`magnitude_r`) - peak apparent magnitude in $g(r)$ passband light curve; `flux_g`(`flux_r`) - peak flux in mJy; `MJD_g`(`MJD_r`) - MJD of the $g(r)$ peak in the assumption that we have one peak. Figure 3 shows an example of the Fulu webpage interface.

The open-source code in the GitHub repository [5] facilitates the implementation of a similar approach in other projects and publications within the scientific community.

3. Results

The Fulu page presents results of BTS ZTF light curves approximation by neural networks and GP (Demianenko et al., 2023a,b). The VALC page of the website is used within the VOxAstro team

[5] https://github.com/salamantos/FLEX

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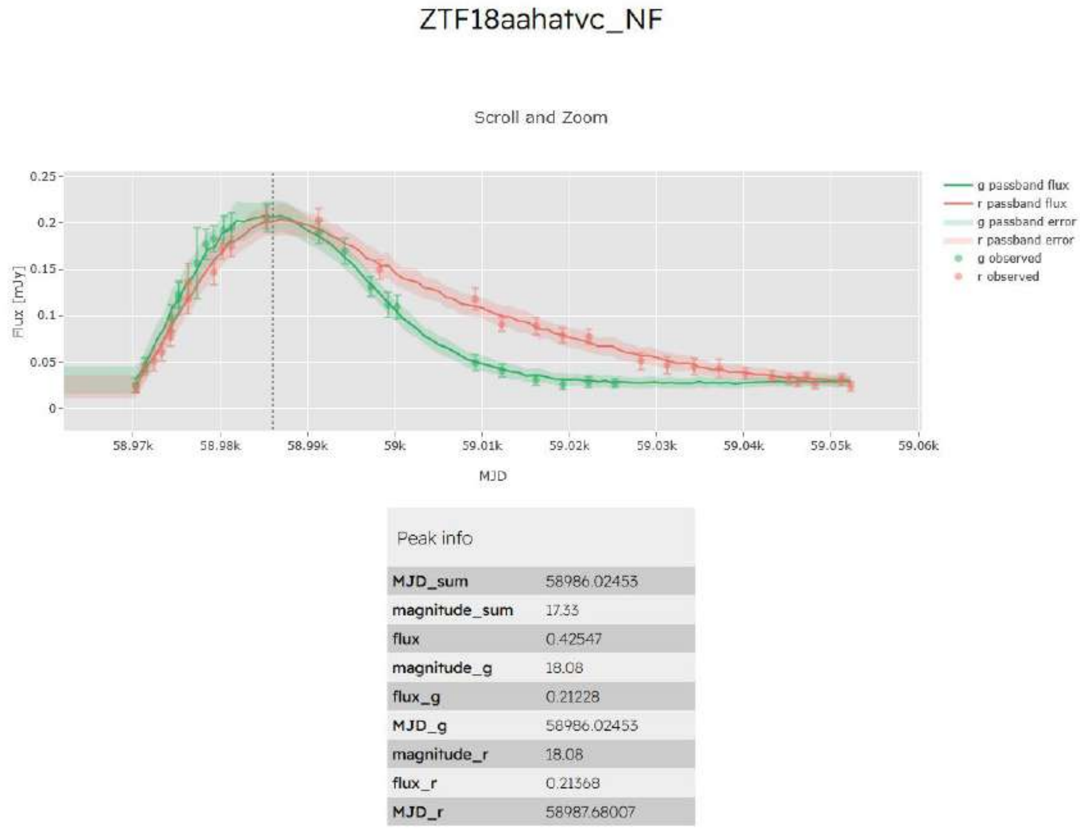

Figure 3. Interface example of the transient event light curve, approximated by normalizing flows at the Fulu page.

and developed as a branch of the RCSEDv2 project. The dedicated follow-up programs were designed using the advantages of visualization within the VALC sample (Chilingarian et al., 2022a,b). Particularly, monitoring programs resulted in the first photometric broad-line region (BLR) reverberation mapping campaign of a highly accreting intermediate-mass black hole (IMBH; Demianenko et al., 2025).

4. Prospects

We are preparing to release a web service that allows users to post-process ZTF and ATLAS light curves of AGNs. Optionally, the user could fit them using Brownian noise (non-stationary) or a damped random walk (DRW or Ornstein–Uhlenbeck process, requires stationarity), as implemented in the Fulu Python package (Demianenko et al., 2023b) by GP with a Matern1/2 kernel. Another option is to measure inter-band delays with linear interpolation of the cross-correlation function (CCF, Gaskell & Peterson (1987), Gaskell & Sparke (1986)), implemented in the pyCCF Python package (Sun et al., 2018). The plans also include publishing light curves in the German Astrophysical Virtual Observatory (GAVO) data centre (Demleitner et al., 2007).

Such a service will require a different system architecture, as the raw data processing will need to occur on the server side. It will be necessary to define a common and convenient format for raw data uploads, which users will use to submit their objects. Additionally, a new backend module will be introduced to handle the execution of our algorithms on user-provided data. To prevent system overload, a message queue will likely be required to control and limit the incoming flow of user requests.

Regarding the frontend, as previously mentioned, the current implementation has become difficult to maintain. At present, it is written in plain HTML and JavaScript, and the project suffers from poor code structure. As a result, adding new logic or reusing existing components is complicated. We plan to migrate the frontend to React (Meta Platforms, Inc. & contributors, 2025), which will allow modular component-based development and easier extension of functionality without affecting other parts of the system. Interaction with user input will also become more efficient, eliminating the need to manually attach event handlers to each element and process them elsewhere in the code. Overall, transitioning from legacy

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technologies to a modern framework will significantly improve maintainability and scalability.

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