Towards a Machine-Learning Census of Compact Stellar Objects in the Digitized First Byurakan Survey: Data, Gap and Project Plan

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Abstract

The Digitized First Byurakan Survey (DFBS) provides low-dispersion spectra in the range 3400-6900 Åfor about 20 million objects. Its stellar content has been explored by visual selection of individual classes and by three automated studies based on image patches or spectral templates; none of these released a catalogue of classified objects or used Gaia or high-energy data. We describe a two-stage project, supported by the ANSEF Yervant Terzian 2026 Award, that addresses this gap for compact stellar objects. We first audit the plate table used for the spectrum extraction: it lists 1643 unique plates with 23.2 million object entries, 17 emulsion labels and 277 fields observed more than once, and it has no plate centres between $\delta = +48.9^o and +62.7^o$. Stage 1 will build a catalogue of unique DFBS objects cross-identified with Gaia DR3 and classify them using three machine-learning branches combined by late fusion. Stage 2 will add X-ray, γ-ray, radio, and century-long photographic photometry to select white dwarfs, hot subdwarfs, cataclysmic variables, and neutron-star binaries. Each stage ends with a public catalogue.

Keywords: *Surveys, Catalogues, Objective Prism Low-Dispersion Spectra, Digitized First Byurakan Survey, Machine Learning, White Dwarfs, Cataclysmic Variables, Neutron Stars, X-ray Binaries.*

1. Introduction

The First Byurakan Survey (FBS), also known as the Markarian survey, was carried out in 1965-1980 by B. E. Markarian, V. A. Lipovetsky and J. A. Stepanian with the 1 m Schmidt telescope of the Byurakan Astrophysical Observatory and a 1.5^o objective prism (Markarian et al., 1989). The prism gives a reciprocal dispersion of 1800 $\AA\ mm^{-1}$ near Hγ, and the spectra cover 3400-6900 $\AA$ with a sensitivity gap near 5300 Å that divides them into a blue and a red part (Gigoyan et al., 2025, Topinka et al., 2017). The survey consists of 4° x 4° fields and covers about 17 000 deg^2 of the northern sky and part of the southern sky at $\delta > -15^o$ and $|b| > 15$ (Gigoyan et al., 2025, Mickaelian et al., 2007). Its original aim was the search for galaxies with ultraviolet excess, which produced the catalogue of 1515 Markarian galaxies (Markarian et al., 1989).

The same plates were later searched by eye for stellar objects. The second part of the FBS aimed at all bright (B < 16.5) starlike objects with ultraviolet excess (Mickaelian et al., 1999). It covered about 4000 deg^2 in the zones $33^o < \delta < 45^o$ and $\delta > 61^o$ and produced a catalogue of 1103 blue stellar objects (1101 distinct objects) that can be used to study white dwarfs, hot subdwarfs, horizontal-branch B stars, cataclysmic variables and bright active galactic nuclei (Mickaelian, 2008). Late-type stars were selected in the same way; the third catalogue of FBS late-type stars confirms 1091 objects with Gaia DR3 data

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(Gigoyan et al., 2025). The blue stellar objects show that hot and compact stars are recognisable in FBS spectra, but their selection was visual and covered about one quarter of the survey area.

In the Digitized FBS (DFBS) project about 1873 plates were scanned and processed (Demleitner et al., 2020), astrometric solutions with about 1" rms were computed, and spectra were extracted for about 20 million objects (Mickaelian et al., 2007); the database holds about 40 million spectra (Mickaelian et al., 2021). The plates and spectra are available through Virtual Observatory services of the German Astrophysical Virtual Observatory (GAVO) and the Armenian Virtual Observatory (Demleitner et al., 2020). In 2011 the Markarian Survey and its digitized version were included in the UNESCO Memory of the World International Register (Mickaelian et al., 2021).

The compact stellar objects bright enough for the DFBS are white dwarfs and cataclysmic variables, in which a white dwarf accretes from a companion. Hot subdwarfs are not compact remnants, but their blue continua resemble those of white dwarfs in low-dispersion spectra, so they form a separate class in our scheme. Isolated neutron stars are far fainter than the plate limit, which reaches about 17.5 mag in the photographic band on the best plates (Gigoyan et al., 2025). Neutron stars can therefore enter the DFBS only through the optical light of a binary companion or an accretion disc. Accretion in such binaries is also the channel that spins neutron stars up to millisecond pulsars (Rah et al., 2025). An example is the X-ray pulsar Her X-1, whose optical counterpart HZ Her is a thirteenth-magnitude blue variable (Davidsen et al., 1972); its position falls on three plates of the plate table described in Sect. 2.

This paper presents the project. Sect. 2 describes the audit of the plate table, Sect. 3 defines the gap, Sect. 4 lists the data, Sect. 5 describes the two stages of the work, and Sect. 6 gives a summary.

2. The DFBS plate table

The spectrum extraction uses a plate table provided by R. Nesci (version of 30 January 2016). For each plate it lists the FBS plate number, the field and plate centres (J2000), the emulsion, the limiting magnitudes B_{lim} and R_{lim}, the number of extracted objects, the observer and the rms of the astrometric solution. We audited this table before any further processing.

The table has 1667 rows, of which 24 are exact duplicates; 1643 unique plates remain. Plate numbers with the suffix M (126 plates) or a (6 plates) share their numerical part with other plates, so the suffix is kept as part of the identifier. The 1643 plates belong to 1305 distinct fields, and 277 fields were observed on 2-5 plates (615 plates in total), which gives a second DFBS epoch for the objects in these fields. The table lists 23 213 283 object entries, with a median of 10 389 per plate. These are entries, not unique objects: an object in a repeated field or in the overlap of neighbouring plates appears more than once.

Fig. 1 shows the plate centres in Galactic coordinates. They span $\delta = -20.8^o$ to $+88.7^o$, and 27 of them lie at $|b| < 15^o$. No plate centre lies between $\delta = +48.9^o$ and $+62.7^o$; Demleitner et al. (2020) attribute this gap to the use of the plates of that zone for the Second Byurakan Survey. In total, 544 plate centres (33%) fall in the half of the sky covered by eROSITA-DE DR1 ($179.944^o < l < 359.944^o$; Merloni et al. 2024).

The emulsion column contains 17 labels. The most frequent are IIF (543 plates), IIAF (533), IIaF (466) and 103aF (52); each of the remaining 13 labels has 1-13 plates. The spectra are not flux calibrated and their shape depends on the emulsion, so spectra from different emulsions should not be combined directly (Demleitner et al., 2020). We therefore keep every label separate until its spectral response has been compared with the others.

The listed B_{lim} has a median of 16.5 mag, with 90% of the plates between 15.7 and 16.7 mag; the median R_{lim} is 15.7 mag. The rms of the astrometric solution has a median of 0.96 (the table gives no unit; the DFBS plate database lists this quantity in arcsec, Mickaelian et al. 2005). Thirty-eight plates have rms $\geqslant$ 1.4, with a maximum of 2.9, and plates 0631M and 0632M have no emulsion, observer or rms entry. These plates are flagged, not removed.

3. The gap

Five points define what is missing for the study of compact stellar objects in the DFBS.

(1) No catalogue of unique objects. The DFBS spectra are distributed as extractions per plate. Objects in repeated fields and plate overlaps have several entries, the 17 emulsion labels give different spectral responses, and there is no flux calibration (Sect. 2). To our knowledge, no catalogue of unique

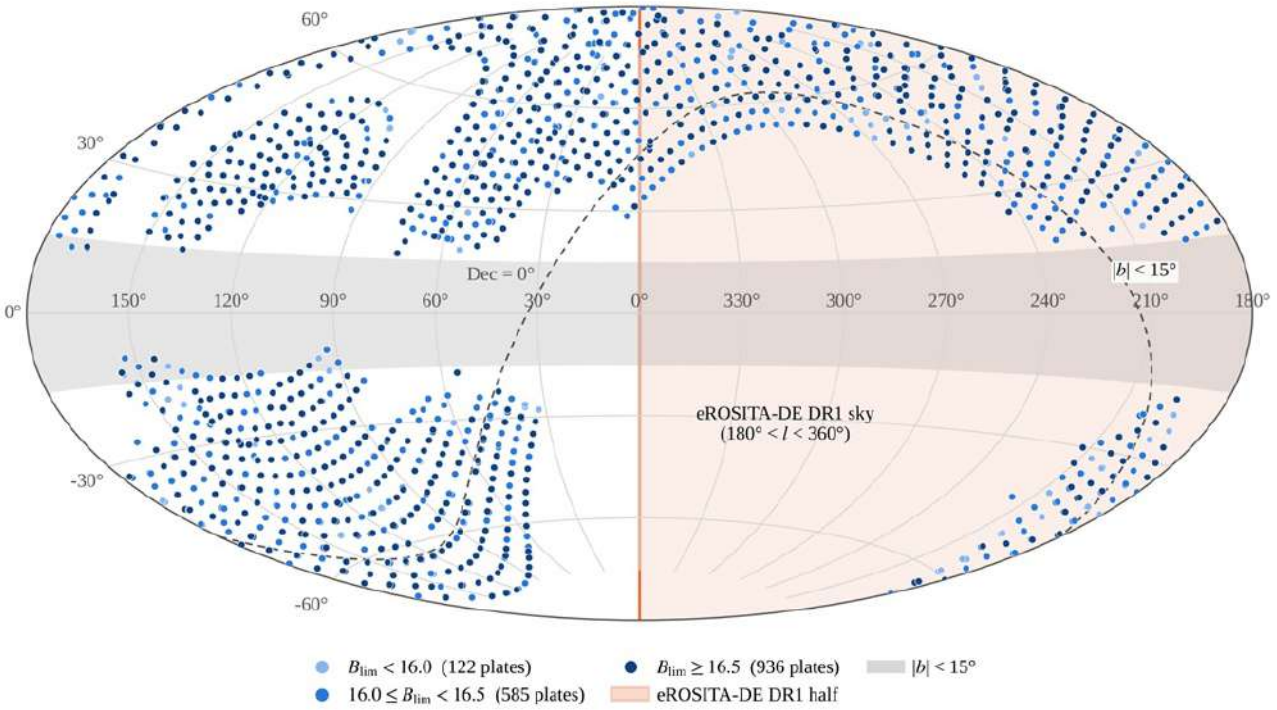

Figure 1. Centres of the 1643 unique plates of the DFBS plate table in Galactic coordinates (Aitoff projection, l increasing to the left), coloured by the listed limiting magnitude B_{lim}. The shaded right half is the sky of eROSITA-DE DR1 ($179.944^o < l < 359.944^o$), the grey band marks $|b| < 15^o$, and the dashed line is the celestial equator.

DFBS objects covering the whole survey, with quality flags and Gaia DR3 cross-identifications, has been published.

(2) Visual selection of single classes. The stellar results of the FBS were obtained by eye, one class at a time and in limited areas: the blue stellar objects in about 4000 deg^2 (Mickaelian, 2008) and the late-type stars (Gigoyan et al., 2025). Outside the zones of the blue-stellar-object programme, white dwarfs, hot subdwarfs and cataclysmic variables have not been selected from the DFBS.

(3) Automated classification without a catalogue. Three automated studies exist. Topinka et al. (2017) compared spectra with templates and applied principal component analysis and clustering to 404 270 sources on 24 plates, with groups that include white dwarfs and hot subdwarfs. Astsatryan et al. (2021) trained a convolutional neural network on 160 × 50 pixel image patches of the spectra for five classes (hot subdwarfs, carbon stars, ultraviolet-excess galaxies, M stars and planetary nebulae) and reached an overall accuracy of about 87%. Astsatryan et al. (2024) extended this to sub-classes, with accuracies of 96% for sub-classes and 93% for groups on their validation sets. None of these studies released a catalogue of classified objects or used Gaia or multi-wavelength data, and white dwarfs and cataclysmic variables were not among the trained classes of the two neural-network studies.

(4) No combination with other wavelengths and epochs. In low-dispersion spectra the blue continua of white dwarfs, hot subdwarfs and quasars are similar. Gaia parallaxes and proper motions separate them, and X-ray emission and variability identify accreting systems. Apart from the cross-correlation of the FBS blue stellar objects with ROSAT, infrared and radio catalogues (Mickaelian, 2008), the DFBS has not been combined with X-ray or γ-ray catalogues, with radio pulsars, with the century-long photometry of the digitized Chinese plates (Ma et al., 2025), or with its own repeated epochs in 277 fields.

(5) No search for neutron-star binaries. Neutron stars appear in the DFBS only through their binary companions or accretion discs (Sect. 1). To our knowledge, no systematic search for the optical counterparts of neutron-star binaries has been made in the DFBS.

4. Data for the project

All data used in the project are public (Table 1). The DFBS spectra and plate scans are read from the GAVO services (Demleitner et al., 2020). The external catalogues are read from CDS VizieR, NASA

doi: https://doi.org/10.52526/25792776-26.73.2-249

HEASARC, the eROSITA-DE DR1 archive, the Fermi Science Support Center, the ATNF pulsar catalogue and the China National Astronomical Data Center, where the photometric catalogues and light curves of the Chinese plates are published. The light curves of the Chinese plates are keyed by Gaia DR2 source identifiers (Ma et al., 2025).

Table 1. Data sets and their roles in the two stages of the project.

Data set	**Content**	**Role**	**Stage**
DFBS plates and spectra (Demleitner et al., 2020, Mickaelian et al., 2007)	≈1900 digitized plates; ≈20 million objects, ≈40 million spectra, 3400-6900 $\AA$	Primary data: spectra, plate cutouts, repeated epochs	1, 2
Gaia DR3 (Gaia Collaboration et al., 2023)	Astrometry, photometry, variability flags	Cross-identification, features, control class	1, 2
Culpan et al. (2022)	6616 known hot subdwarfs	Hot-subdwarf labels	1
Ritter & Kolb (2003)	Known cataclysmic variables and LMXBs	CV labels	1
Milliquas v8 (Flesch, 2023)	1 021 800 quasars and AGN	Quasar labels	1
FBS blue stellar objects (Mickaelian, 2008)	1103 entries (1101 objects), B $\lesssim$ 16.5	Independent test set	1
ROSAT 2RXS (Boller et al., 2016)	≈135 000 detections, 0.1–2.4 keV, all sky	X-ray features	2
eROSITA-DE DR1 (Merloni et al., 2024)	≈930 000 entries, 0.2–2.3 keV, $180^o < l < 360^o$	X-ray features	2
4XMM-DR14 (Webb et al., 2020)	Serendipitous sources in XMM-Newton fields	X-ray features where covered	2
Chinese digitized plates (Ma et al., 2025)	15 680 plates, 33.3 million sources, 1901-1999	Long-term variability; photometric comparison	2
ATNF pulsar catalogue (Manchester et al., 2005)	Radio pulsars	Neutron stars: pulsar channel	2
Fermi 4FGL-DR4 (Ballet et al., 2023)	7194 γ-ray sources, 50 MeV–1 TeV, 14 yr	Neutron stars: γ-ray channel	2
XRBcats (Avakyan et al., 2023, Neumann et al., 2023)	349 LMXBs, 169 HMXBs	Neutron stars: X-ray-binary labels	2

5. Planned work in two stages

The work is organised in two stages, each ending with a public catalogue (Fig. 2). Stage 2 uses the catalogue of Stage 1 as its input.

5.1. Stage 1: catalogue of unique objects and classification

Spectra are selected with the extraction quality class sp_class = $'OK'$ and a signal-to-noise ratio of at least 5, and spectra with negative or saturated flux runs are rejected. Entries within 3" of each other are grouped into unique objects, and every spectrum of an object is kept as an epoch. Gaia DR3 positions are propagated to the plate epoch with their proper motions and matched within three times the astrometric rms

doi: https://doi.org/10.52526/25792776-26.73.2-249

of the plate, and the DFBS B magnitude must agree with the B magnitude predicted from Gaia photometry. The false-match rate is measured by repeating the match after shifting the DFBS positions by 1′; the limit set in the proposal is 5%.

The labelled set has five classes: white dwarfs ($P_{WD} > 0.75$ in Gentile Fusillo et al. 2021), hot subdwarfs (known stars in Culpan et al. 2022), cataclysmic variables (Ritter & Kolb, 2003), quasars (Flesch, 2023) and a control class of Gaia DR3 stars with $\varpi/\sigma_{\varpi} > 10$ that are in none of these lists. The FBS blue stellar objects are not used in training; they serve as an independent test set. Objects that match ATNF pulsars or known X-ray binaries are excluded from training and kept for Stage 2.

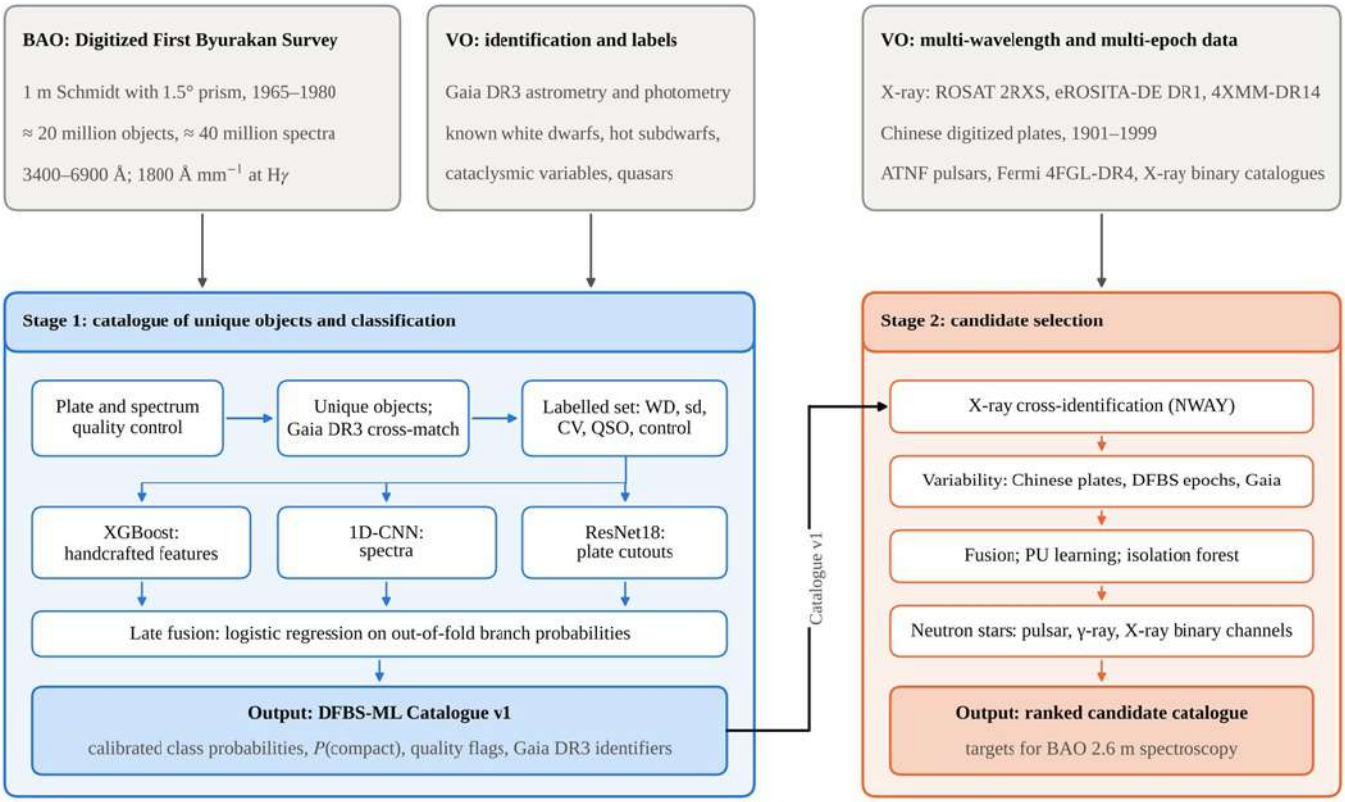

Figure 2. Data sources and the two stages of the project. Stage 1 builds and classifies the catalogue of unique DFBS objects; Stage 2 adds X-ray, γ-ray, radio and multi-epoch data and selects candidates.

Three branches are trained. Branch 1 is gradient boosting with XGBoost (Chen & Guestrin, 2016) on handcrafted features: B - R colour, spectral slope, Balmer-line indices ($H\beta, H\gamma, H\delta$), an emission-line index, Gaia G, GBP - GRP, absolute magnitude M_G, proper motion and RUWE, and the emulsion, rms and B_{lim} of the plate. Branch 2 is a one-dimensional convolutional network on the extracted spectrum with an emulsion embedding. Branch 3 is a ResNet18 network (He et al., 2016) on 128 × 128 pixel cutouts of the plate scans. A logistic regression combines the out-of-fold probabilities of the three branches (late fusion). Training uses the focal loss (Lin et al., 2017). The data are split into a held-out test set of 20% and five cross-validation folds grouped by plate field, so that no object appears in two folds. Probabilities are calibrated with Platt scaling, and the contribution of each branch is tested by ablation with McNemar tests.

The targets set in the proposal are a ROC-AUC of at least 0.88 for the separation of compact objects (white dwarfs and cataclysmic variables) from all other classes and a macro-averaged F1 score of at least 0.75 for the five classes. Both are reported whether or not they are reached, together with the results per class and per emulsion. The output is the DFBS-ML Catalogue v1: unique objects with Gaia DR3 identifiers, DFBS plates and epochs, calibrated class probabilities, P(compact) and quality flags. The catalogue and the labelled dataset will be deposited in Harvard Dataverse and submitted to CDS, and the code will be released on GitHub.

5.2. Stage 2: multi-wavelength and multi-epoch candidate selection

X-ray counterparts are assigned with NWAY (Salvato et al., 2018), which uses the positional errors of both catalogues and priors from Gaia magnitudes; the false-association rate is measured with sky-shifted catalogues. From 2RXS only detections with likelihood ≥ 9 are used, for which Boller et al. (2016) expect about 5% spurious sources, against about 30% for the full catalogue. The X-ray features are $\log(F_X/F_{opt})$, the hardness ratio and the X-ray luminosity derived with Gaia distances.

Long-term variability comes from three sources: the light curves of the Chinese plates (Ma et al., 2025), joined to the DFBS objects through their Gaia DR2 source identifiers; the repeated DFBS epochs in 277 fields; and the Gaia DR3 variability flag. The variability features are amplitude, χ^2 per degree of freedom, number of epochs and time baseline. The Chinese plates are used for every DFBS object they contain, and their coverage is reported as exact counts per class. For stars common to both data sets, the DFBS B magnitudes are compared with the Chinese-plate photometry, which tests the DFBS photometry independently.

A fourth branch, gradient boosting on the X-ray and variability features, is added to the Stage 1 branches. Besides the branch probabilities, the fusion step receives indicators of the data available for each object. X-ray binaries, which are rare, are modelled by positive-unlabelled learning (Elkan &*Noto*, 2008) with labels from XRBcats (Avakyan et al., 2023, Neumann et al., 2023) and Ritter & Kolb (2003). An isolation forest (Liu et al., 2008) flags objects that resemble none of the labelled classes. The target set in the proposal is a gain of more than 10% over the best single data set, measured on the objects that have that data set.

Neutron-star candidates are selected through three channels: positional matches to radio pulsars of the ATNF catalogue (Manchester et al., 2005), with proper-motion correction; DFBS objects inside the 95% error ellipses of unassociated 4FGL-DR4 sources (Ballet et al., 2023) that also have an X-ray counterpart or variability; and the X-ray-binary probability from the fused model, in which F_X/F_{opt} and L_X help to separate neutron-star from white-dwarf accretors. At $|b| > 15^o$ the pulsar channel mainly samples millisecond pulsars: these are old objects in a layer with a characteristic height of about 500 pc, whereas young γ-ray-emitting pulsars lie within about 160 pc of the plane (Andreasyan et al., 2016, 2025a,b). In the Galactic field 62% of the millisecond pulsars are binaries (Rah, 2026b), and spin-up by accretion in such binaries is one of the scenarios tested in a pulsar-evolution subroutine for NBODY6++GPU (Rah, 2026a). Objects with evidence in at least two channels form Tier 1, and objects with evidence in one channel and P(XRB) ≥ 0.5 form Tier 2. Her X-1 serves as a check of the selection. The result is a list of candidates or, if none is found, a 95% Poisson upper limit on the surface density of optical counterparts of neutron-star binaries brighter than the DFBS limit; in both cases the counts are exact.

The output is a ranked catalogue of compact-object candidates with their X-ray, γ-ray, radio and variability data. The 50 highest-ranked new candidates are inspected individually (spectrum, plate cutout, SIMBAD entry and finding chart), and 5–20 of them are selected for spectroscopy with the BAO 2.6 m telescope.

6. Summary

The DFBS holds low-dispersion spectra of about 20 million objects, and its blue stellar objects show that hot and compact stars are recognisable in these spectra. What is missing is a catalogue of unique objects with Gaia identifications, a classification over the whole survey that includes white dwarfs and cataclysmic variables, and the combination of the DFBS with X-ray, γ-ray, radio and long-term photometric data. The audit of the plate table fixes the starting point: 1643 unique plates, 23.2 million object entries, 17 emulsion labels, 277 repeated fields and no plate centres between $\delta = +48.9^o$ and $+62.7^o$. Stage 1 produces and classifies the catalogue of unique objects; Stage 2 adds the multi-wavelength and multi-epoch data and selects candidates, including neutron-star binaries. Each stage ends with a public catalogue and measured results: the performance is reported against the targets of the proposal, and the neutron-star search gives either candidates or an upper limit.

Author contributions

G. Paronyan and M. Rah contributed equally to this work and made the largest contributions to it. G. Paronyan is the principal investigator of the project and coordinates the work. M. Rah is the co-investigator and machine-learning lead of the project. S. Khachatryan prepared the background of the paper and the plots. V. Mnatsakanyan assisted G. Mikayelyan in the work on the observational data. G. Mikayelyan provided the observational data. A. Mickaelian is the advisor of the whole work.

Acknowledgements

This work is will be carried out with the support of the ANSEF grant (ANSEF Yervant Terzian 2026 Award) 26AN:PS-astroth-3529. We thank R. Nesci for the DFBS plate table.

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