Astronomical and Astrophysical Transactions (*AApTr*), 2020, Vol. 32, Issue 1, pp. 71–80,
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Ultraviolet Luminous Objects in GALEX data: search and possible explanation of their nature

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Received 20 July, 2020

Multi-wavelength characterization of astrophysical objects by means of cross-matching of modern large sky surveys is a powerful tool intensively used for classification, parameterization and studies of various classes of sources. The objects detected in many or all surveys under study represent convenient material for the research, however, objects that are found in only one of the surveys, and absent in all others, should also attract close attention. Our goal is to identify and study objects apparent in only a single wave band, and invisible in the others. It is still a relatively poorly investigated field and may lead to the detection of a new unique (or transient) class of objects. Here we explore the possibility of detecting of objects with a significant UV excess in their spectra by cross-matching of the GALEX all-sky catalogue with several other surveys in different wavelength ranges and analyzing the ones visible in GALEX only (ultraviolet luminous objects). We describe the methodology for such investigation, explain the selection of surveys for this study, and show initial results based on the search in several small sky areas. The ultraviolet luminous objects should reside in the Milky Way Galaxy and must be either very hot massive stars in the main sequence stage of their evolution, or isolated old neutron stars, slowly accreting interstellar matter. Our results will be used as an input for a larger-scale investigation.

Keywords: Surveys – ultraviolet: stars

1 Introduction

The problem of parameterization of stars based on their photometry is a topical issue. A great variety of photometric systems and recently constructed large photometric

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surveys as well as VO-tools for cross-matching surveys' objects provide us with a possibility to get multicolour photometric data for millions of objects. This combined photometry can be used for a relatively accurate determination of the parameters of stars and the interstellar medium. In particular, it was shown (Malkov et al., 2018) that multicolour photometric data from large modern surveys can be used for parameterization of stars closer than around 4.5 kpc and brighter than $g_{\rm SDSS} = 19.^m6$, including estimation of parallax and interstellar extinction value.

The objects detected in **all** the surveys under study represent, naturally, the most favourable and convenient material for the research, since the photometric data for them are most abundantly presented and cover the electromagnetic spectrum from UV to IR. However, objects that are found in only **one** of the surveys under study, and absent in all others, should also attract close attention.

Here we report on the objects from the GALEX survey that are as yet unidentified with any optical/IR counterparts, based on an initial study of several areas. We make assumptions about the nature of these objects based on (relatively scarce) observational data.

2 Cross-matching of multi-wavelength surveys

In the process of studying interstellar extinction (Malkov et al., 2020), we have cross-matched objects from various sky surveys in several selected sky areas and noticed the presence of a significant amount of objects present in GALEX catalogue only, without any counterparts in optical and infrared surveys. Therefore we decided to make a dedicated study for these objects in order to assess their physical nature.

To do this, we made a grid of 408 sky fields, with 15 arcmin radius each, uniformly spaced in Galactic coordinates (see Fig. 1 for their positions), and acquired from VizieR (Ochsenbein et al., 2000) the lists of objects in these fields from the following catalogues:

- GALEX (Bianchi et al., 2017) – 318 fields have objects, with the median number of 587 objects per field (78–954 for 90%). It has nearly all-sky coverage except for the Galactic plane proper.

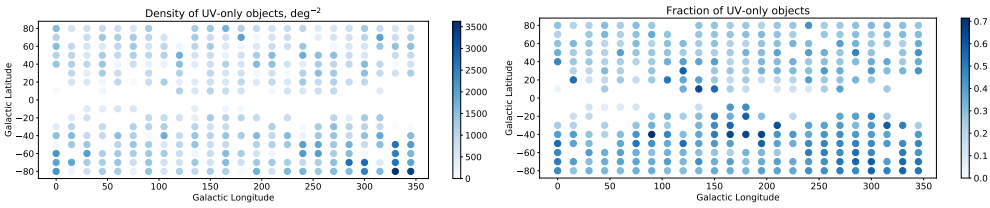


Figure 1 Density (number per square degree) of UV-only GALEX objects (left panel), and their fraction among all GALEX objects in the field (right panel) as a function of Galactic coordinates. Except for a gap along the Galactic plane due to lack of GALEX data there, no obvious structure is seen in both panels.

- Gaia DR2 (Gaia Collaboration et al., 2018) – all fields are populated, with the median number of 1053 objects per field (472–21512 for 90%).
- Pan-STARRS1 DR1 (Chambers et al., 2016) – 326 fields have objects, with the median number of 4317 objects per field (2921–27872 for 90%). It has a coverage of all sky to the North of declination –30 degrees.
- SkyMapper Southern Sky Survey DR1.1 (Wolf et al., 2018) – 210 fields have objects, with 1739 median number of objects per field (342–6377 for 90%). It has a coverage of Southern sky only.
- WISE (Cutri et al., 2014) – all fields are populated, with the median number of 3359 objects per field (2559–4665 for 90%).
- SDSS DR12 (Alam et al., 2015) – 190 fields have objects, with the median number of 6587 objects per field (3891–22380 for 90%). It has a coverage of significant part of Northern sky except for the Galactic plane.

Then, in every field, we cross-matched GALEX objects with all other catalogues using the pairwise distance threshold equal to the hypotenuse of positional accuracies of two surveys. For the latter, we used the value of $3''$ (roughly half of PSF) for GALEX, $2''$ for WISE, $0.1''$ for Gaia DR2, and $1''$ for all other surveys, the same way as in Malkov et al. (2018) and Malkov et al. (2020).

3 Properties of UV-only objects

Among the total of 179802 GALEX objects in all fields where GALEX data are available, 65087 (36%) have no counterparts in other wavebands. The spatial distribution of their density and fraction among all GALEX objects are shown in Fig. 1, with no obvious latitude dependence seen in both quantities. Hereafter we will call these objects "UV-only objects", or "ultraviolet luminous object (UVLO) candidates".

All of the UV-only objects in our sample are detectable in NUV band, while FUV detections are available for 3% (2105 objects) only. This is perhaps not surprising, given that only about 7% of all GALEX objects have FUV measurenets. The ones with detections in both bands share the locus of the majority of all GALEX objects in the colour–magnitude diagram (see right panel of Fig. 2). On the other hand, the distribution of UV-only objects (whole sample) in NUV band magnitude shows a prominent dominance of fainter ones with the lower signal to noise ratio (left panel of Fig. 2 and upper panels of Fig. 3). The distribution of NUV band FWHM shows no signs of changing fraction on UV-only objects, their ratio is also not correlated with the effective exposure of a sky position (lower panels of Fig. 3).

GALEX catalogue (Bianchi et al., 2017) lists various artefact flags for the objects. Their distribution for all sources and UV-only ones is shown in the upper panel of Fig. 4, again with no apparent dependency of UV-only ratio on their values.

The lower panel of Fig. 4 shows the distribution of sources without artefact flag set (i.e. with Nafl = 0) in NUV magnitude error (i.e. signal to noise ratio) vs NUV FWHM space. It is apparent there that all high signal to noise UV-only detections in our sample have large FWHM, significantly exceeding nominal $5''$ value for GALEX PSF. All UV-only objects with FWHM sizes comparable to point sources have NUV magnitude errors exceeding 0.2 (90% – exceeding 0.3), i.e. are detectable on the signal

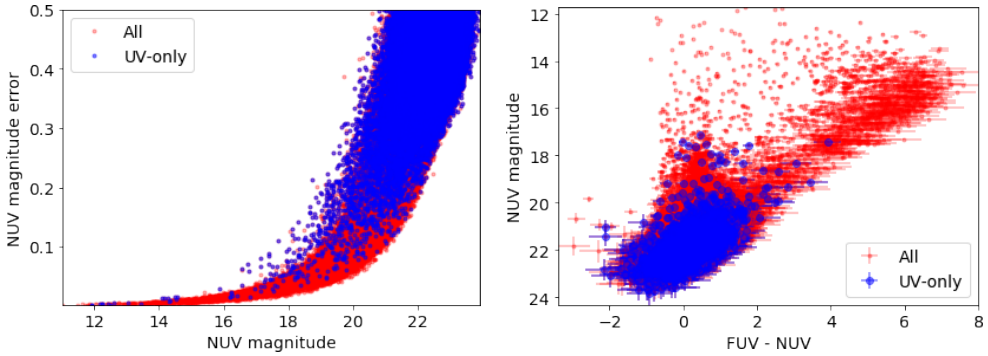


Figure 2 Left panel – GALEX NUV magnitude error versus magnitude. Right panel – GALEX colour–magnitude diagram. Red dots are all GALEX objects from the sky fields shown in Fig. 1, blue circles are UV-only objects.

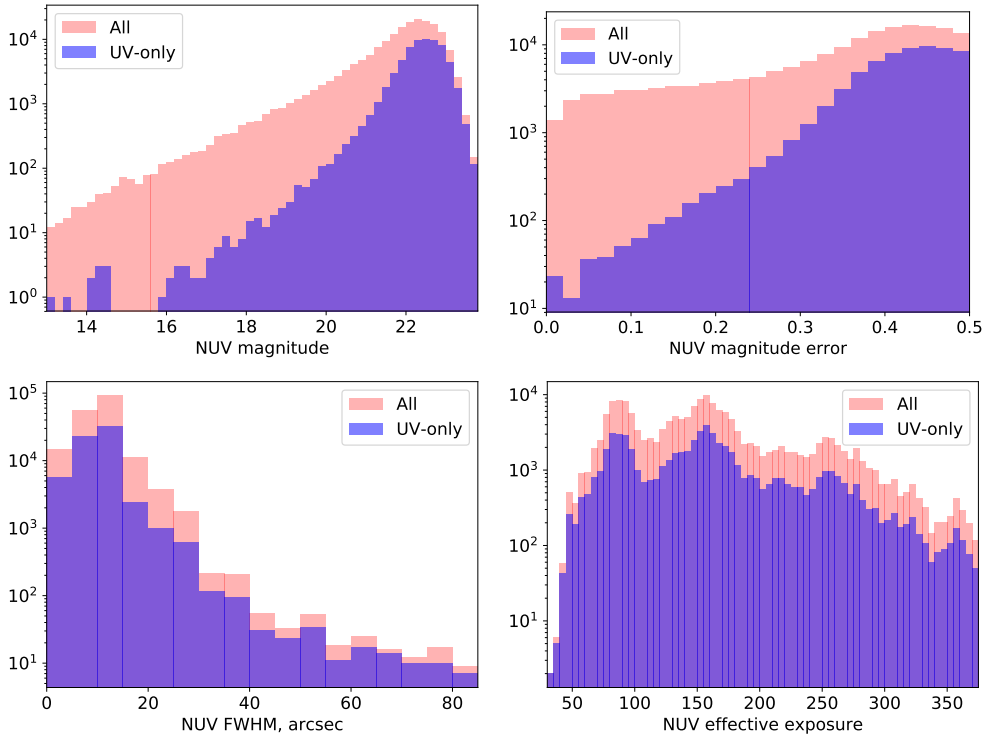


Figure 3 Distribution of objects by the NUV magnitude (upper left panel) by the NUV magnitude error (upper right panel), as well as by NUV FWHM (lower left panel) and NUV effective, i.e. corrected for the flat-field response, exposure (lower right panel). Red bars are all GALEX objects from the sky fields shown in Fig. 1, blue ones – UV-only objects.

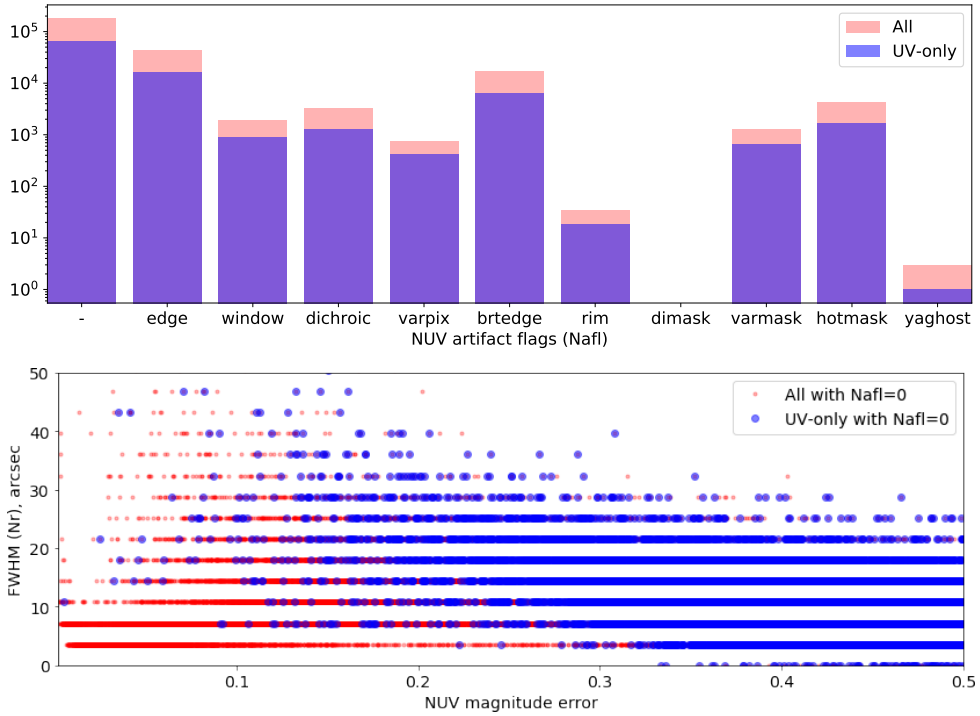


Figure 4 Upper panel – the distribution of objects by the NUV artefact flags. Lower panel – the distribution of source FWHM for objects without artefact flags. Red points are all GALEX objects from the sky fields shown in Fig. 1, blue ones – UV-only objects.

to noise ratio less than 3–5, and most probably represent various kinds of spurious detections. Some of them are shown in Fig. 5.

At first sight the non-detection in Gaia (no parallax, no proper motions) could be regarded as a very strong filter against any closely moving objects and in favour of, e.g., distant galaxies. However, distant galaxies are not observed at low galactic latitudes (the UV-only objects are observed, see Fig. 1), moreover, Gaia does not observe in the UV-range.

4 Discussion

Our initial search did not reveal any high significance (S/N $>$ 5) detection of UVLO, however, lower significance UV-only objects (UVLO candidates) are numerous (note that a lot of actual objects from other catalogues are detectable in GALEX at these low S/N levels). They are present in all sky fields we studied where GALEX data are available, and constitute a fraction of 0.19–0.56 (90%) to the total number of GALEX objects in these fields (see Fig. 1), with no apparent clustering towards the Galactic plane and no apparent correlation with ecliptic coordinates. They are

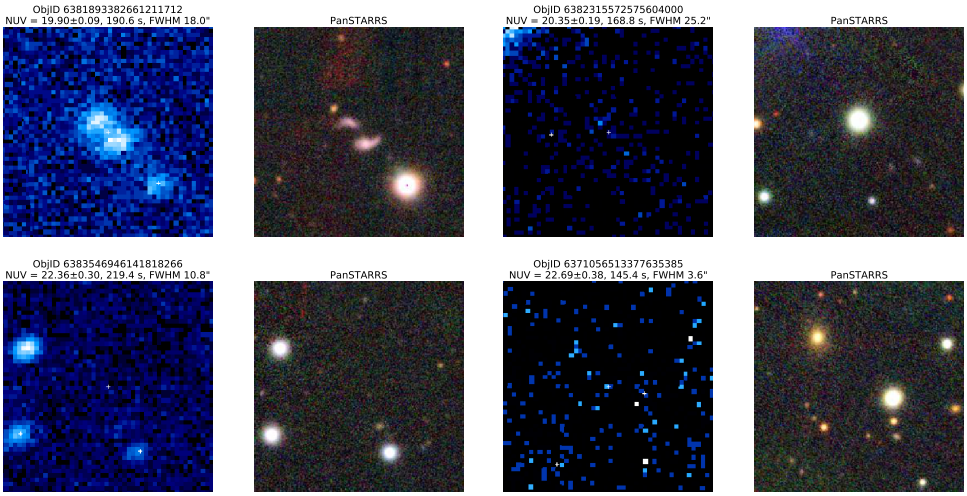


Figure 5 GALEX NUV and Pan-STARRS $72'' \times 72''$ cutouts for some of the UV-only objects, corresponding to various kinds of data problems – bright unresolved objects merged into single detection (upper left), object detection probably misplaced due to low S/N (upper right), and completely spurious low S/N detections of an extended (lower left) and compact (lower right) objects. All of these detections have no artefact flags set in GALEX catalogue.

predominantly weak, but it cannot be said that all the weakest GALEX objects belong to this category – indeed, many of objects with NUV$> 22^m$ are successfully cross-matched with one or more other surveys (see Fig. 3). The photometric error values for UVLO candidates are also on average higher than for other GALEX objects, which is expected due to their faintness.

One can roughly estimate the maximum luminosity of UVLO candidates in the optical/IR range from the following considerations. The faintest SDSS objects in the high-latitude fields covered by our analysis, where interstellar extinction can be neglected, have $g_{\rm SDSS} \approx 26^m$ and $i_{\rm SDSS} \approx 25^m$. Consequently, UVLO, depending on the distance (d, pc), cannot be brighter than $M_g = 31 - 5 \log d$ and $M_i = 30 - 5 \log d$. For the characteristic distance of ≈250 pc, where the concentration of stars to the Galactic equator starts to appear, it is about $M_g = 19^m$ and $M_i = 18^m$.

For lower galactic latitudes, estimation of the maximum luminosity of UVLO candidates in the optical/IR range should include interstellar extinction. We assume that the distribution of the reddening material quite closely obeys the Parenago (1940) law of the form

$$A(d, b) = \frac{a_0 \beta}{\sin |b|} \left(1 - e^{-\frac{d \sin |b|}{\beta}}\right), \qquad (1)$$

where a_0 is the value of absorption per kpc in the galactic plane and β is the scale-height. Here we use the average values $a_0 = 1.35 \pm 0.12$ mag per kpc and $\beta = 0.16 \pm 0.02$ kpc obtained for V-band by Pandey & Mahra (1987) in their comprehensive study of open clusters. The results of our estimation for galactic latitude $|b| = 5°$ are shown in Fig. 6. Interstellar extinction in V-band, A_V, calculated with Eq. (1), is transferred to A_λ, using $A_\lambda = R_\lambda * A_V / R_V$, where total-to-selective extinction ratios

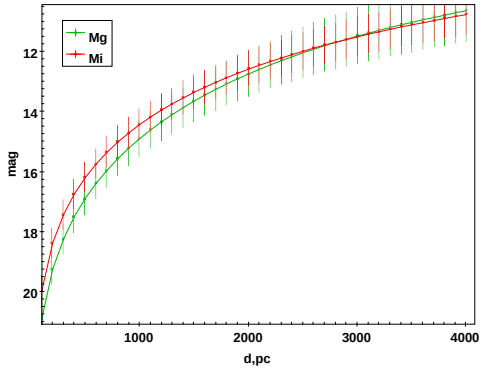


Figure 6 The maximum luminosity of UVLO candidates in g(SDSS) and i(SDSS) bands as functions of distance.

$R_g = 3.31 \pm 0.03$, $R_i = 1.72 \pm 0.02$ are taken from Yuan et al. (2013), and R_V is assumed to be 3.1.

One of the most obvious candidates for UVLO are young, massive stars of the Galaxy. However, early-type main sequence (MS) stars, visible in FUV/NUV, should also be bright enough in the optical range. Comparison of absolute magnitudes in GALEX and SDSS photometric bands (Findeisen et al. (2011), Covey et al. (2007)) shows that M_{NUV} of O5V stars should be about 3^m brighter than M_g (given the interstellar extinction the brightness difference will be even smaller). As can be seen in Fig. 3 (upper left panel) NUV magnitude of the UVLO candidates can significantly exceed the magnitude of the faintest SDSS objects ($g_{SDSS} \approx 25^m$). It means that at least part of the UVLO candidates do not belong to the early type MS stars (other bright UV objects, hot subdwarfs, are likely to be excluded for the same reason). To these reasons it must be added that galactic early type MS stars are not only very rare, but also extremely luminous. Assuming the UVLO candidates to be stars like that, their distances would place them in the outer halo, where no star formation happens right now.

Another possible candidate for the role of UVLO could be isolated (single or components of wide binaries) old neutron stars, slowly accreting interstellar matter. This type of object was proposed by Maoz et al. (1997) as candidates to the sources detected in the extreme ultraviolet by the ROSAT/WFC and EUVE all-sky surveys and unidentified with any optical counterparts. Such neutron stars are expected to be abundant in the Galaxy, to concentrate towards the Galactic plane, and have not been unambiguously detected yet.

Our initial analysis demonstrated the importance of such a study, and we hope to continue it using larger-scale cross-matching of the whole GALEX catalogue with other all-sky surveys in order to reliably detect individual UVLO and perform their detailed investigation.

5 Conclusions

For the first time, a cross-matching of sources from several large-scale sky surveys in a number of sky regions uniformly distributed in Galactic coordinates have been performed in order to characterize the properties of objects apparent in UV-only (GALEX) and without counterparts at longer wavelengths and to assess their nature as (possible) "ultraviolet luminous objects" (UVLO). While no significant (at better than S/N = 5) detection has been made in this pilot search, the amount of detected UV-only objects with lower significance, which we may consider UVLO candidates, is large, and undoubtedly require an additional study.

We conclude that UVLO reside in the Milky Way Galaxy, and must be either very hot massive stars on the MS stage of their evolution, or isolated old neutron stars, slowly accreting interstellar matter. It is also possible that the detected UVLO are a mixture of objects of different nature, including, probably, some artefacts. Based on their spatial distribution, we exclude the possibility that UVLO belong to the solar system or immediate solar vicinity, and we also rule out that UVLO are extragalactic objects.

We plan to continue this work by cross-matching the whole all-sky GALEX catalogue with corresponding surveys at longer wavelengths in order to better characterize the statistical properties of UVLO candidates, as well as to get a high-significance detection of UVLO proper.

Acknowledgements

We thank James Wicker for valuable comments. O.M. thanks the CAS President's International Fellowship Initiative (PIFI). Part of this work was supported by the National Natural Science Foundation of China under grant Nos. 11988101, 11890694 and the Chinese–Russian NSFC–RFBR project number 20-52-53009. S.K. was supported by European Structural and Investment Fund and the Czech Ministry of Education, Youth and Sports (Project CoGraDS – CZ.02.1.01/0.0/0.0/15 003/0000437). The work is partially performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. This research has made use of NASA's Astrophysics Data System, and use of the VizieR catalogue access tool, CDS, Strasbourg, France. This research made use of TOPCAT, an interactive graphical viewer and editor for tabular data (Taylor, 2005).

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