# The Importance of UV Surveys for the Binary Fraction of Hot Evolved Stars in Regimes Elusive to Gaia

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**ABSTRACT**: A catalog of hot stellar sources (Teff hotter than approximately 18,000K, depending on gravity), mostly white dwarfs and subdwarfs, with GALEX FUV, NUV and SDSS u, g, r , i, z photometry was used to identify candidate single-star (22,848), and binaries with a cooler, less evolved and optically brighter companion (12,404). The identification of binary candidates is robust, when the optically-luminous companion is cooler than about 10,000K, albeit with a small contamination by QSOs with UV non-standard colors. The single-star counts instead are an upper limit because they may include "identical twins" and types of binaries whose composite SED -- in the wavelength range of this dataset-- is not distinguishable from a single-object SED. About 50% of the binaries and 20% of the single-star candidates are previously unclassified objects. Gaia DR3 gives a parallax value (error<=20%) for 34% of the binaries and 45% of the single-star candidates. For comparison, the extracted WD -binary sample is 4 times larger than the current Gaia sample of astrometric WD binaries (about 3,200, Sahaf et al. 2024) and comparable to the Gaia WD wide-binaries sample (16,000, El-Badry 2024), although our catalog covers only one-fourth of the sky. These comparisons highlight the specific leverage offered by UV surveys for detecting hot-compact stars, that are elusive at other wavelengths when a cooler, larger companion dominates optical-IR fluxes. The derived binary fraction for this specific sample, $B_f$>46%, compared with that of their progenitors (>80% to 50% for mass range 8 to 1Msun, Moe 2019) apparently implies a lower merging rate than found for the very massive stars (e.g., Sana et al. 2017); however, selection effects must be taken into account, such as types of binaries excluded by the sample definition (FUV-NUV<0.1mag). See Bianchi 2024 (ApJS, in press, DOI: 10.3847/1538-4365/ad6e7c)

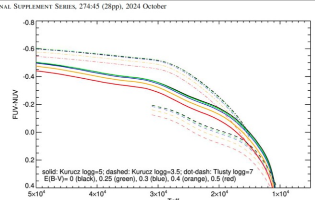


**Figure 1.** Broadband GALEX color FUV−NUV as a function of $T_{eff}$ from stellar models: Kurucz models with solar metallicity, with log $g$ = 5.0 and 3.5, and Tlusty pure-H models with log $g$ = 7.0. The effect of reddening is negligible for small $E_{B-V}$ values (for $E_{B-V}$ = 0 and = 0.25mag, shown in black and green, the lines are almost indistinguishable) and becomes appreciable at values higher than $E_{B-V}$ = 0.40 mag. Reddening is applied for a Milky Way–type extinction curve with $R_V$ = 3.1. The reddening effect is larger for UV-steep extinction curves such as those found in the Magellanic Clouds (see, e.g., Table 1 of L. Bianchi et al. 2017).

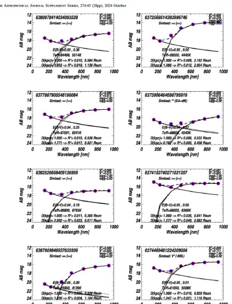


**Figure 9.** Examples of two-component SED-fitting with stellar model magnitudes (Kurucz for the cooler companion, Tlusty for the hot companion). The Simbad identification, and spectral type (in parentheses), are given when available. Resulting $T_{eff}$ values are printed for both components, and of $E_{B-V}$ (derived for the cool star, assumed = 0.05 mag for the hot star). Radii derived from scaling the best-fit model are given first for a reference distance of 1 kpc, then rescaled for the distance derived from the Gaia parallax. Dots are observed magnitudes, the black thick line connects the best-fit model magnitudes, and the thin black lines show the acceptable range of solutions. The dashed line is the composite model SED from both components.

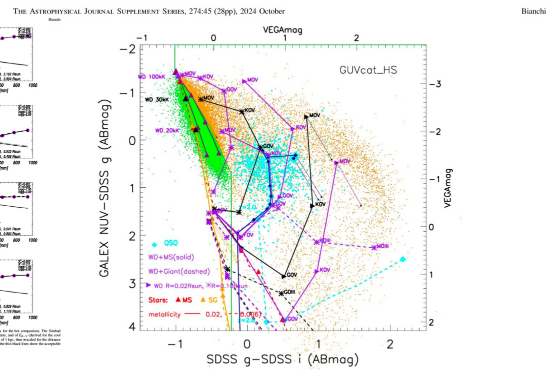


**Figure 5.** Same as in Figure 4; a green line shows the adopted separation between candidate single (green dots) and binary (orange dots) hot evolved stars. Sources with Simbad type = QSO or AGN or Seyfert are overplotted with cyan dots, of larger size than the other sources for visibility, but they are only 941 sources out of the 35,294 total analysis sample; they occupy exactly the locus of the QSO average-template colors for redshift ~0.5–1.5 (cyan for the standard QSO template, dark blue for the $Ly_\alpha$-enhanced template of L. Bianchi et al. 2009). Triangles on the purple single WD sequences (log $g$ = 7 and 9) mark $T_{eff}$ = 200 kK, 30 kK, 20 kK, and 15 kK.

## The Sample.

Matched GALEXxSDSS sources with FUV-NUV< 0.1mag were extracted from GUVmatch_AISxSDSSdr14 (Bianchi & Shiao 2020) and culled to retain 35,294 pointlike sources with reliable measurements. **Note** that SDSS overlap covers ≈ 11,100 sq.deg (Bianchi et al. 2019, AREAcat) and only GALEX AIS sources with both FUV and NUV measurements were used. Therefore, the resulting sample is a subset of the existing GALEX sources, and might be one-fourth of the binaries detectable with this method in the entire sky. Gaia DR3 was matched accounting for proper motions, given the differing epochs between Gaia and GALEX observations.

## Analysis. Results.

Figures from Bianchi (2024).

SEDs (GALEX FUV, NUV, SDSS *u, g, r, i, z*) were compared to model colors (progressively reddened) and to colors of known objects (less than half of the larger initial sample has a match in Simbad), to identify candidate single-star (22,848), and binaries with a cooler, less evolved and optically brighter companion (12,404). The single-star sample includes some binaries whose SED is indistinguishable from a single SED; the identification of binary candidates, instead, is robust but suffers a <15% contamination by AGNs. The binary census (over one-fourth of the sky) is 4x larger than the Gaia astrometric WD-binary sample and comparable to Gaia current WD-wide-binary census (El-Badry 2024). Work is needed to compare these different samples, to characterize which types of binaries are elusive to Gaia's methods applied so far and can be better identified with UV surveys, and which types of binaries are missed in our sample.

Gaia DR3 gives a good parallax value (error<=20%) for 34% of the binaries and 45% of the single-star candidates; Simbad provides identification with known objects for 49% of the binary candidates (but not all were known to have a hot companion) and for 80% of the single-star candidates. These simple numbers highlight the leverage offered by a UV survey to complement other large surveys.

The binary fraction in this specific sample of hot evolved objects is probably similar to the fraction derived by Moe (2019) for their progenitors, implying – at face value – a lower merging rate than for massive stars (e.g., Sana et a. 2017), but it must be kept in mind that the sample selection limits the detection to a given range of binary types, while it is very effective for binaries missed by other surveys.

**References:**

Bianchi, L. 2024, ApJS, in press, arxiv:2409.04626 ; Bianchi, L. & Shiao, B. 2020, ApJS, 250, 36 ; Bianchi, L. et al. 2019, ApJS, 241, 14 ; El-Badry, K. 2024, arXiv 2403.12146
Moe, M. 2019, Mem S.A.It 90, 347 ; Sana, H. et al. 2017, A&A, 599, L9 ; Shahaf et al., 2024, MNRAS, 529, 3729

## Questions for follow-up work using these catalogs, or similar recipes with different samples

1) Characterize the overlap between WD-binaries detected in this work and those detected by Gaia with different techniques, to assess limitations of each method and dataset. Why do we find (in only one-fourth of the sky) so many binaries wrt Gaia; how do they compare?
2) Which binary types are elusive in our SED range? Companions of A-type and later are generally excluded from the sample owing to the color cut. The sensitivity to differentiate singles vs binaries, and which binaries are missed, depend on the pair's stellar radii and Teffs.
3) How can the small contamination by QSO and AGN (pointlike in both SDSS and GALEX) be eliminated by using additional bands?
4) A similar selection of binaries vs singles could be attempted using GALEXxGaia matched catalogs (Bianchi & Shiao 2020), over the whole sky; detection limits must be accounted for
5) How does the sample compare with Milky Way population models predictions?

## Where to find the catalogs:

**Reference**: Bianchi 2024 ApJS, in press,
paper DOI: 10.3847/1538-4365/ad6e7c ; arxiv:2409.04626

**ALL CATALOGS AVAILABLE FROM MY WEBSITE:**
**http://dolomiti.pha.jhu.edu/uvsky/GUVcatHS/**
**A snapshot of the website is shown below.**

**MAST HLSP** (High Level Science Products) same files as in the UVsky website , to be available soon at
https://archive.stsci.edu/hlsp/guvcat-hotstars/
(data doi:10.17909/w9k5-tm92),

**Vizier:** not yet, files will be provided

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**http://dolomiti.pha.jhu.edu/uvsky/GUVcatHS/** **shown below**

**GUVcat_AISxSDSS_HS. Hot Stars in the GALEX Ultraviolet Sky Surveys**
**and the Binary Fraction of Hot Evolved Stars**

GALEX sources with FUV-NUV < 0.1mag and SDSS photometry classified as point-like at SDSS resolution. Catalogs include GALEX and SDSS photometry, Gaia DR3 information from Gaia's *source* table and *vari_summary* table (variability information) when available, Simbad match if available, GALEX individual observations (visits), flags to mark sources in the footprint of extended galaxies or clusters, flags to track multiple matches, source classification as binary- or single-star candidates

**Reference:** Bianchi, Luciana, 2024, ApJS, in press, DOI: 10.3847/1538-4365/ad6e7c ; arxiv:2409.04626
(pdf of accepted paper here )
**Title:** Hot Stars in the GALEX Ultraviolet Sky Surveys (GUVcat_AISxSDSS_HS) and the Binary Fraction of Hot Evolved Stars
**DOI:** 10.3847/1538-4365/ad6e7c

Resulting catalogs (below) are also available at MAST as High-Level Science Products (HLSP) at: guvcat-hotstars ; Database DOI: https://doi.org/10.17909/w9k5-tm92

**Abstract from paper :**
We present a catalog of 71,364 UV sources with GALEX FUV-NUV≤0.1mag with SDSS photometry. The limit corresponds to stellar Teff>15,000−20,000K, slightly depending on gravity but nearly reddening-independent for Milky-Way-type dust. Most sources are hot white-dwarfs (WDs) and sub-dwarfs (SDs). Comparing the SED (GALEX FUV, NUV, SDSS u,g,r,i,z) of 35,294 sources having good photometry with colors of stellar models and known objects, we identify 12,404±1871-1267 binary hot-compact stars with a cooler, less-evolved companion (with a possible 8%−15% contamination by low-redshift QSOs), and 22,848±1267-3853 single-star candidates. Single-star counts are an upper limit because pairs of similar stars have single-star-like SED, and hot-WDs with main-sequence companions of certain types (depending on WD's radius) are missed or counted as single in the available wavelength range and selection. The catalog offers unique leverage for identifying hot WDs, elusive at longer wavelengths especially when a cooler, larger companion dominates optical-IR fluxes: 51% of the binary- and 20% of the single-star candidates are previously un-known objects. Gaia DR3 provides a parallax with error≤20% for 34% of the binaries- and 45% of the single-star candidates, allowing Teff, E(B−V), radius and Lbol to be derived from SED analysis. The binary-candidate sample usefully expands the overall current binary-WD census to subpopulations elusive to Gaia and to other searches. The binary fraction among this specific sample of hot-compact objects, albeit with the mentioned biases, b_f>46%, compared with that of their progenitors (>80%−50% for mass range 8−1Msun, Moe 2019), implies a lower merging rate than found for massive stars by Sana et al (2017).

Master Catalog - columns description (Table 1 of the paper)

**GUVcat_AISxSDSS_HSpoint (point sources catalog, before culling)**

Master Catalog of point sources: csv file
Master Catalog of point sources: fits file
Catalog of 71,364 point-like sources, selected from SDSS tag TYPE='STAR' from 278,375 sources in GUVmatch_AISxSDSS (Bianchi and Shiao 2020) with FUV-NUV less or equal 0.1mag; no other culling. This is the ``master catalog'' used as a starting point; it contains, in addition to the tags from the initial GUVmatch_AISxSDSS, additional information to facilitate the science analysis. Specifically, columns 223-231 contain distilled information from the Simbad match (Section 2.3 in the paper), columns 233-257 contain some parameters from the GALEX best visit (individual observation, see Appendix A in the paper) among the visits from which the source was extracted, and columns 258-314 contain information distilled from the Gaia DR3 match (Section 2.2) including serendipitous detection of variability in the Gaia DR3 database. The columns are described in Table 1 of the paper, that can be downloaded here. See Section 2.1 of the paper for other useful tags, such as ``INLARGEOBJ''; sources in the footprint of stellar clusters are excluded from the analysis in this work, but retained in the master catalog, and may be of interest of a variety of purposes but require careful checks of photometric quality.

**GUVcat_AISxSDSS_HSpointXGaiaDR3**

GUVcat_AISxSDSS_HSpointXGaia3arcsecREWINDED_noNULLS.csv
GUVcat_AISxSDSS_HSpointXGaia3arcsecREWINDED_noNULLS.fits
The complete results of the Gaia DR3 cross-match to the **71,364 point-like sources** of the master catalog. See Section 2.2 in the paper. Columns 1-222 are from the GUVcat_AISxSDSS_HSpoint catalog. Subsequent columns contain all the tags from the Gaia DR3 *source* table, followed by the tags from the Gaia DR3 *vari_summary* table. These files contain the full match output, where all Gaia multiple matches within the match radius are retained, as defined in Section 2.2; in the master catalog only the Gaia tags of the ``primary'' match are distilled, i.e. the only match if MMRANK_GAIA = 0, or the closest among multiple matches (MMRANK_GAIA =1), in order to keep a list of unique sources. Therefore, if multiple matches are found and needs to be examined, they can be found in this catalog.

**GUVcat_AISxSDSS_HSpointXvisits**

GUVcat_AISxSDSS_HSpointXvisits_3arcsec.fits
GUVcat_AISxSDSS_HSpointXvisits_3arcsec.csv
Match of the master catalog with GALEX database table *visitphotoobj* , to link each source to all its existing GALEX observations, as described in Appendix A. The full results are given in this catalog. Relevant parameters, such as the number of visits found in FUV and NUV, and the GALEX "best-visit" parameters, are distilled in the master catalog. The file is the full output of all visits returned with sources within 3arcsec of the input list: **352,641** rows. Description for all tags from the *visitphotoobj* table are found in the MAST Casjobs Context ``GALEX GR6plus7''. Values returned as ``null'' are set to -888.

**GUVcat_AISxSDSS_HSpointXsimbad_[5 and 10]arcsec**

catHSpointXsimbad_5arcsec_1681832401503A.csv
catHSpointXsimbad_10arcsec_1681832559998A.csv
Full results of the match of GUVcat_AISxSDSS_HSpoint with the Simbad database (Section 2.3), with match radius of 5 and 10arcsec. All the Simbad columns of the resulting matched sources are appended after columns 1-222 from Table 1. The files are the original outputs from the Vizier match. The relevant parameters of the nearest Simbad match, and the number of Simbad matches within 5arcsec and 10arcsec, are also included in the master catalog of point-like sources, see Table 1 - columns 265-271. Values are set to ``=='' if there is no match, and to ``-888.'' if no value of a given tag is given for the match.

**GUVcat_AISxSDSS_HSculled**

GUVcat_AISxSDSS_HSculled.fits
GUVcat_AISxSDSS_HSculled.csv
The analysis sample of 35,294 sources after removing sources with SDSS saturation, sources with possible inconsistencies between the source measurements in the GALEX FUV and NUV images, and trimming to SDSS photometric errors to less or equal 0.2mag in *u, g, r, i* as described in Section 3.1. This culled subsample is used for analysis in Section 3.2 and in the discussion. Bulk classification of the sources as "single" or "binary" (according to colors) are given in the last column ("color_locus") (Appendix B in the source paper).

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