The population of hot subdwarf stars studied with Gaia

III. Catalogue of known hot subdwarf stars: Data Release 2

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ABSTRACT

In light of substantial new discoveries of hot subdwarfs by ongoing spectroscopic surveys and the availability of new all-sky data from ground-based photometric surveys and the Gaia mission Data Release 2, we compiled an updated catalogue of the known hot subdwarf stars. The catalogue contains 5874 unique sources including 528 previously unknown hot subdwarfs and provides multi-band photometry, astrometry from Gaia, and classifications based on spectroscopy and colours. This new catalogue provides atmospheric parameters of 2187 stars and radial velocities of 2790 stars from the literature. Using colour, absolute magnitude, and reduced proper motion criteria, we identified 268 previously misclassified objects, most of which are less luminous white dwarfs or more luminous blue horizontal branch and main-sequence stars.

Key words. subdwarfs – stars; horizontal-branch – catalog

1. Introduction

Hot subdwarf stars (sdO/Bs) are situated at the extreme blue end of the horizontal branch (HB), the extreme horizontal branch (EHB; Heber 1986). To evolve to the EHB, red giants must lose almost their entire hydrogen envelopes. This is best explained by various scenarios of binary mass transfer (Han et al. 2002, 2003; see Heber 2016, for a review). Although not initially recognised as such, sdOB stars were discovered via photometric surveys of faint blue stars (Humason & Zwicky 1947; Iriarte & Chavira 1957; Chavira 1958, 1959; Haro & Luyten 1962; Green et al. 1986; Downes 1986). Subsequently, Kilkenny et al. (1988) published the first catalogue of 1225 spectroscopically identified hot subdwarf stars. Objective prism surveys obtaining low-resolution spectra detected many more hot subdwarfs (Hagen et al. 1995; Wisotzki et al. 1996; Stobie et al. 1997; Mickaelian et al. 2007; Mickaelian 2008). Østensen (2006) compiled a database containing more than 2300 stars.

Subsequently, the Sloan Digital Sky Survey (SDSS) provided spectra of almost 2000 sdO/Bs (Geier et al. 2015a; Kepler et al. 2015, 2016) and new samples of bright hot subdwarf stars were selected (e.g. Vennes et al. 2011). Furthermore, data from new large-area photometric and astrometric surveys have been conducted in multiple bands from the UV to the far-infrared.

This motivated us to compile a new catalogue of hot subdwarf stars (Geier et al. 2017a). We started with the catalogue of Østensen (2006) and added hot subdwarf candidates from several recent spectroscopic surveys (Mickaelian 2008; Østensen et al. 2010a; Geier et al. 2015a; Kepler et al. 2016; Gentile Fusillo et al. 2015; O’Donoghue et al. 2013; Kilkenny et al. 2015, 2016; Vennes et al. 2011; Ghezzi et al. 2011; Perez-Fernandez et al. 2016; Luo et al. 2016) and unpublished sources. We cross-matched all those objects with large-area photometric and light curve survey catalogues. Proper motions were obtained from diverse ground-based surveys (see Geier et al. 2017a for details).

The spectroscopic catalogue of Geier et al. (2017b) has been used as an input catalogue for photometric (TESS; Stassun et al. 2018) and spectroscopic surveys (LAMOST; Lei et al. 2020); it has also been used to select stars for more detailed studies (Boureaux et al. 2017; Carrillo et al. 2020). Furthermore, this previous catalogue has been used to determine selection criteria for an all-sky catalogue of hot subluminous star candidates selected from Gaia Data Release 2 (DR2; Gaia Collaboration 2018) by means of colour, absolute magnitude, and reduced proper motion cuts (Geier et al. 2019). In this work, I present Data Release 2 of the catalogue of known hot subdwarf stars.

2. Constructing the catalogue Data Release 2

2.1. Input data

In addition to the spectroscopically classified hot subdwarf stars from Data Release 1 (DR1) of this catalogue (Geier et al. 2017a), several new samples of hot subdwarfs have recently been published, most of which have atmospheric parameters and radial velocity determinations. Kepler et al. (2019) identified sdO/Bs in SDSS DR14 and Geier et al. (2017b) provided atmospheric parameters for a large sample of hot subdwarfs from SDSS DR7. However, the most important new source of yet undiscovered sdO/Bs is the LAMOST survey (Lei et al. 2018, 2019, 2020; Luo et al. 2019). It has to be pointed out that a lot of the recently published stars had already been classified and that there are large overlaps between the samples. By carefully cross-matching the new samples with the catalogue and each other, I found that 528 new sdO/Bs have been discovered since the publication of DR1.

New hot subdwarfs have also been identified in globular clusters (Latour et al. 2018), but owing to the different types of photometric and astrometric data available for those objects, they are not included in this catalogue. This means that the catalogue...
The data collected were used to identify and remove objects misclassified as hot subdwarf stars (Geier et al. 2017a). To separate all kinds of cooler objects, colour indices were used. Objects with SDSS colours \( u - g > 0.6 \) and \( g - r > 0.1 \), NUV\_GALEX - \( g_{PS1} > 1.7 \), SkyMapper \( u - g > 0.9 \) and NUV\_GALEX - \( g_{APASS} > 2.0 \) have been excluded if different indices were consistent. If only one of those indices was available, \( Gaia G_{BP} - G_{RP} > 0.4 \) was used as additional constraint.

\( Gaia \) DR2 provides us with accurate parallax distances with uncertainties smaller than 20% for distances up to about 1–2 kpc (Lindgren et al. 2018). Calculating the absolute magnitudes of all stars with accurate parallaxes, it was possible to identify misclassified white dwarfs (WDs) and also brighter objects such as blue horizontal branch (BHB) or main-sequence B (MS-B) stars (see Fig. 1).

To distinguish WDs from the more luminous and distant sdOBs, I also used the reduced proper motion method as outlined in Gentile Fusillo et al. (2015). The reduced proper motion \( H = G + 5 \log \mu + 5 \) was calculated using the \( Gaia \) G magnitudes and proper motions because accurate \( Gaia \) proper motions are available for all stars in the catalogue. Stars with \( H > 15 \) are WD candidates and therefore excluded (Geier et al. 2017a). Most of the WD candidates identified in this work are also listed in the \( Gaia \) WD catalogue (Gentile Fusillo et al. 2019). Some bright BHB and MS-B stars have been identified from new follow-up spectra (Schneider et al., in prep.). The catalogue was also cross-matched with SIMBAD and misclassified objects known from the literature were also excluded.

The 268 misclassified objects are provided with their correct classifications as a separate catalogue. Based on their previous classifications as sdBs or sdOs and their colours, a tentative classification of the WD candidates as either DAB (hydrogen and possibly neutral helium lines) or DAO (hydrogen and/or ionised helium lines) candidates is provided. If there was no detailed classification before, they are classified as WD.

The final DR2 catalogue contains 3874 unique objects (see Fig. 2). Thanks to \( Gaia \), which allows us to separate the WDs and bright MS-B stars very efficiently, BHB stars should now be the most important class of contaminant objects remaining in the catalogue.

### 2.5. Classification of hot subdwarfs

For spectroscopic and photometric classifications, we follow the scheme outlined in Geier et al. (2017a). The empirical scheme for the photometric classification by inspecting the locations of the subclasses in two-colour diagrams could be extended using new colour criteria based on multi-band photometry from Pan-STARRS (Chambers et al. 2016) and SkyMapper (Wolf et al. 2018).

The SDSS- and SkyMapper-based colour classes should be regarded as the most trustworthy because the \( u - g \) colour allows us to distinguish between sdB and the hotter sdO types better than a combination of NUV and g band (see Fig. 3). The updated colour criteria are provided in Table 1.

### 2.6. Spectroscopic parameters and radial velocities

The catalogue contains spectroscopic parameters such as effective temperatures, surface gravities, and helium abundances for 2187 stars from the literature; this is more than twice as many as in DR1. This fraction is still not complete because only papers
Fig. 2. Sky distribution of the objects in the catalogue in equatorial coordinates. The colour scale represents the densities of the stars starting from green to red, and yellow indicates the most crowded regions.

Fig. 3. Two-colour diagrams for spectroscopically classified objects from the hot subdwarf catalogue. The sdB and sdOB stars are indicated in green, sdO stars in blue, and composite binaries in red. Upper panel: SkyMapper. Lower panel: GALEX/PS1.

Table 1. Colour-classification schemes.

|         | SDSS              | GALEX/APASS | GALEX/PS1 | SkyMapper |
|---------|-------------------|-------------|-----------|-----------|
| sdO     | $-0.55 < u_{SDSS} - g_{SDSS} < -0.35$ | NUV$_{GALEX} - g_{APASS} < 2.0$ | NUV$_{GALEX} - g_{PS1} < 1.7$ | $0.9 < u_{SKYM} - g_{SKYM} < 1.4$ |
|         | $-0.65 < g_{SDSS} - r_{SDSS} < -0.45$ | $g_{APASS} - r_{APASS} < -0.15$ | $g_{PS1} - r_{PS1} < -0.2$ | $0.1 < g_{SKYM} - r_{SKYM} < 0.55$ |
| sdB     | $g_{SDSS} - r_{SDSS} > 0.208(u_{SDSS} - g_{SDSS}) - 0.516$ | NUV$_{GALEX} - g_{APASS} < 2.0$ | NUV$_{GALEX} - g_{PS1} < 1.7$ | $-0.8 < u_{SKYM} - g_{SKYM} < -0.4$ |
|         | $g_{SDSS} - r_{SDSS} < 0.208(u_{SDSS} - g_{SDSS}) - 0.376$ | $g_{APASS} - r_{APASS} < -0.15$ | $g_{PS1} - r_{PS1} < -0.2$ | $-0.5 < u_{SKYM} - g_{SKYM} < -0.5$ |
| sd+MS   | $-0.5 < u_{SDSS} - g_{SDSS} < 0.7$ | NUV$_{GALEX} - g_{APASS} < 2.0$ | NUV$_{GALEX} - g_{PS1} < 1.7$ | $-0.4 < u_{SKYM} - g_{SKYM} < -0.17$ |
|         | $g_{SDSS} - r_{SDSS} > 0.208(u_{SDSS} - g_{SDSS}) - 0.376$ | $g_{APASS} - r_{APASS} < -0.15$ | $g_{PS1} - r_{PS1} < -0.2$ | $-0.5 < u_{SKYM} - g_{SKYM} < -0.17$ |
|         | $g_{SDSS} - r_{SDSS} < 0.208(u_{SDSS} - g_{SDSS}) - 0.376$ | NUV$_{GALEX} - g_{APASS} < 2.0$ | NUV$_{GALEX} - g_{PS1} < 1.7$ | $-0.8 < u_{SKYM} - g_{SKYM} < -0.9$ |
|         | $g_{SDSS} - r_{SDSS} > 0.208(u_{SDSS} - g_{SDSS}) - 0.376$ | $g_{APASS} - r_{APASS} < -0.15$ | $g_{PS1} - r_{PS1} < -0.2$ | $-0.17 < g_{SKYM} - r_{SKYM} < 0.3$ |

containing larger samples of sdO/B stars have been taken into account (Heber et al. 1984; Bixler et al. 1991; Saffer et al. 1994, 1997; Maxted et al. 2001; Edelmann et al. 2003; Lisker et al. 2005; Ströer et al. 2007; Hirsch 2009; Østensen et al. 2010b; Nemeth et al. 2012; Geier et al. 2013, 2015a, 2017b; Kupfer et al. 2015; Luo et al. 2016, 2019; Kepler et al. 2016, 2019; Lei et al. 2018, 2019, 2020). Since the main purpose of this catalogue is the identification and classification of hot subdwarf stars, only
3. Summary

The catalogue of known hot subdwarf stars DR2 and the catalogue of objects previously misclassified as hot subdwarfs are both available via the VizieR service. A detailed description of the catalogue columns for both catalogues is provided in Table A.1. The catalogue is by no means complete and heterogeneously selected, which has to be taken into account when using it for statistical analyses. The large samples from LAMOST for example only include single-lined sdOBs and the composite sdB+MS binaries are supposed to be published in the future. DR2 contains 528 newly discovered sdOB/B stars and is significantly cleaner than DR1. With the growing number of large area spectroscopic surveys it is important to keep track of the known objects to allow for a most efficient follow-up of the yet unclassified candidates. The multitude of new designations that comes with each survey does not make this effort easier.

The previously misclassified objects are a mixed bag of interesting and often peculiar stars. The MS-B stars for example are all quite faint and found mostly at high Galactic latitudes. This indicates large distances and a likely runaway origin. Most WDs are likely quite young, young, and short-lived, and therefore rare.

The Gaia catalogue of hot subluminous star candidates will be maintained and updated in parallel (Geier et al. 2019) to provide a comprehensive list of new hot subdwarf candidates. Together with the WD catalogue (Gentile Fusillo et al. 2019) and the catalogue of extremely low-mass WD candidates (Pelisoli & Vos 2019) the whole parameter space of hot subluminous stars is now covered. In addition, we are currently compiling catalogues of variable hot subdwarfs based on the diverse light-curve surveys now available. The first such catalogue including eclipsing HW Vir-type binaries has recently been published by Schaffenroth et al. (2019).

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The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating
## Appendix A: Additional table

Table A.1. Catalogue columns.

| Column         | Format | Description                  | Unit       |
|----------------|--------|------------------------------|------------|
| NAME           | A30    | Target name                  |            |
| GAIA_DESIG     | A30    | Gaia designation             |            |
| RA             | F10.6  | Right ascension (J2000)      | deg        |
| Dec            | F10.6  | Declination (J2000)          | deg        |
| GLON           | F10.6  | Galactic longitude           | deg        |
| GLAT           | F10.6  | Galactic latitude            | deg        |
| SPEC_CLASS     | A15    | Spectroscopic classification |            |
| SPEC_SIMBAD    | A15    | Spectroscopic classification from SIMBAD | |
| COLOUR_SDSS    | A10    | Colour classification SDSS   |            |
| COLOUR_APASS   | A10    | Colour classification GALEX/APASS | |
| COLOUR_PS1     | A10    | Colour classification GALEX/PS1 | |
| COLOUR_SKYM    | A10    | Colour classification SkyMapper | |
| PLX            | F8.4   | Gaia parallax                | mas        |
| e_PLX          | F8.4   | Error on PLX                 | mas        |
| M_G            | F8.4   | Absolute magnitude in G-band | mag        |
| G_GAIA         | F6.3   | Gaia G-band magnitude        | mag        |
| e_G_GAIA       | F6.3   | Error on G_GAIA              | mag        |
| BP_GAIA        | F6.3   | Gaia BP-band magnitude       | mag        |
| e_BP_GAIA      | F6.3   | Error on BP_GAIA             | mag        |
| RP_GAIA        | F6.3   | Gaia RP-band magnitude       | mag        |
| e_RP_GAIA      | F6.3   | Error on RP_GAIA             | mag        |
| PMRA_GAIA      | F7.3   | Gaia proper motion $\mu_\alpha \cos \delta$ | mas yr$^{-1}$ |
| e_PMRA_GAIA    | F7.3   | Error on PMRA_GAIA           | mas yr$^{-1}$ |
| PMDEC_GAIA     | F7.3   | Gaia proper motion $\mu_\delta$ | mas yr$^{-1}$ |
| e_PMDEC_GAIA   | F7.3   | Error on PMDEC_GAIA          | mas yr$^{-1}$ |
| RV_SDSS        | F5.1   | Radial velocity SDSS         | km s$^{-1}$ |
| e_RV_SDSS      | F5.1   | Error on RV_SDSS             | km s$^{-1}$ |
| RV_LAMOST      | F5.1   | Radial velocity LAMOST       | km s$^{-1}$ |
| e_RV_LAMOST    | F5.1   | Error on RV_LAMOST           | km s$^{-1}$ |
| TTEFF          | F8.1   | Effective temperature        | K          |
| e_TTEFF        | F8.1   | Error on T_EFF               | K          |
| LOG_G          | F4.2   | Log surface gravity (gravity in cm s$^{-2}$) | dex |
| e_LOG_G        | F4.2   | Error on LOG_G               | dex        |
| LOG_Y          | F5.2   | Log helium abundance n(He)/n(H) | dex |
| e_LOG_Y        | F5.2   | Error on LOG_Y               | dex        |
| PARAMS_REF     | A20    | Reference for atmospheric parameters (Bibcode) | |
| EB-V           | F6.4   | Instellar reddening E(B − V) | mag |
| e_EB-V         | F6.4   | Error on E(B − V)            | mag        |
| AV             | F6.4   | Interstellar extinction A_V  | mag        |
| FUV_GALEX      | F6.3   | GALEX FUV-band magnitude     | mag        |
| e_FUV_GALEX    | F6.3   | Error on FUV_GALEX           | mag        |
| NUV_GALEX      | F6.3   | GALEX NUV-band magnitude     | mag        |
| e_NUV_GALEX    | F6.3   | Error on NUV_GALEX           | mag        |
| V_APASS        | F6.3   | APASS V-band magnitude       | mag        |
| e_V_APASS      | F6.3   | Error on V_APASS             | mag        |
| B_APASS        | F6.3   | APASS B-band magnitude       | mag        |
| e_B_APASS      | F6.3   | Error on B_APASS             | mag        |
| g_APASS        | F6.3   | APASS g-band magnitude       | mag        |
| e_g_APASS      | F6.3   | Error on g_APASS             | mag        |
| r_APASS        | F6.3   | APASS r-band magnitude       | mag        |
| e_r_APASS      | F6.3   | Error on r_APASS             | mag        |
| i_APASS        | F6.3   | APASS i-band magnitude       | mag        |
| e_i_APASS      | F6.3   | Error on i_APASS             | mag        |
| u_SDSS         | F6.3   | SDSS u-band magnitude        | mag        |
| e_u_SDSS       | F6.3   | Error on u_SDSS              | mag        |
| g_SDSS         | F6.3   | SDSS g-band magnitude        | mag        |
| e_g_SDSS       | F6.3   | Error on g_SDSS              | mag        |
| r_SDSS         | F6.3   | SDSS r-band magnitude        | mag        |
| e_r_SDSS       | F6.3   | Error on r_SDSS              | mag        |
| i_SDSS         | F6.3   | SDSS i-band magnitude        | mag        |
| e_i_SDSS       | F6.3   | Error on i_SDSS              | mag        |
| z_SDSS         | F6.3   | SDSS z-band magnitude        | mag        |
| e_z_SDSS       | F6.3   | Error on z_SDSS              | mag        |
Table A.1. continued.

| Column     | Format | Description                        | Unit |
|------------|--------|------------------------------------|------|
| u_VST      | F6.3   | VST surveys (ATLAS, KiDS) u-band magnitude | mag  |
| e_u_VST    | F6.3   | Error on u_VST                     |      |
| g_VST      | F6.3   | VST surveys (ATLAS, KiDS) g-band magnitude | mag  |
| e_g_VST    | F6.3   | Error on g_VST                     |      |
| r_VST      | F6.3   | VST surveys (ATLAS, KiDS) r-band magnitude | mag  |
| e_r_VST    | F6.3   | Error on r_VST                     |      |
| i_VST      | F6.3   | VST surveys (ATLAS, KiDS) i-band magnitude | mag  |
| e_i_VST    | F6.3   | Error on i_VST                     |      |
| z_VST      | F6.3   | VST surveys (ATLAS, KiDS) z-band magnitude | mag  |
| e_z_VST    | F6.3   | Error on z_VST                     |      |
| u_SKYM     | F6.3   | SkyMapper u-band magnitude          | mag  |
| e_u_SKYM   | F6.3   | Error on u_SKYM                     |      |
| v_SKYM     | F6.3   | SkyMapper v-band magnitude          | mag  |
| e_v_SKYM   | F6.3   | Error on v_SKYM                     |      |
| g_SKYM     | F6.3   | SkyMapper g-band magnitude          | mag  |
| e_g_SKYM   | F6.3   | Error on g_SKYM                     |      |
| r_SKYM     | F6.3   | SkyMapper r-band magnitude          | mag  |
| e_r_SKYM   | F6.3   | Error on r_SKYM                     |      |
| i_SKYM     | F6.3   | SkyMapper i-band magnitude          |      |
| e_i_SKYM   | F6.3   | Error on i_SKYM                     |      |
| z_SKYM     | F6.3   | SkyMapper z-band magnitude          | mag  |
| e_z_SKYM   | F6.3   | Error on z_SKYM                     |      |
| g_PS1      | F7.4   | PS1 g-band magnitude                | mag  |
| e_g_PS1    | F7.4   | Error on g_PS1                      |      |
| r_PS1      | F7.4   | PS1 r-band magnitude                | mag  |
| e_r_PS1    | F7.4   | Error on r_PS1                      |      |
| i_PS1      | F7.4   | PS1 i-band magnitude                |      |
| e_i_PS1    | F7.4   | Error on i_PS1                      |      |
| z_PS1      | F7.4   | PS1 z-band magnitude                |      |
| e_z_PS1    | F7.4   | Error on z_PS1                      |      |
| y_PS1      | F7.4   | PS1 y-band magnitude                |      |
| e_y_PS1    | F7.4   | Error on y_PS1                      |      |
| J_2MASS    | F6.3   | 2MASS J-band magnitude              | mag  |
| e_J_2MASS  | F6.3   | Error on J_2MASS                    |      |
| H_2MASS    | F6.3   | 2MASS H-band magnitude              | mag  |
| e_H_2MASS  | F6.3   | Error on H_2MASS                    |      |
| K_2MASS    | F6.3   | 2MASS K-band magnitude              | mag  |
| e_K_2MASS  | F6.3   | Error on K_2MASS                    |      |
| Y_UKIDSS   | F6.3   | UKIDSS Y-band magnitude             | mag  |
| e_Y_UKIDSS | F6.3   | Error on Y_UKIDSS                   |      |
| J_UKIDSS   | F6.3   | UKIDSS J-band magnitude             | mag  |
| e_J_UKIDSS | F6.3   | Error on J_UKIDSS                   |      |
| H_UKIDSS   | F6.3   | UKIDSS H-band magnitude             | mag  |
| e_H_UKIDSS | F6.3   | Error on H_UKIDSS                   |      |
| K_UKIDSS   | F6.3   | UKIDSS K-band magnitude             | mag  |
| e_K_UKIDSS | F6.3   | Error on K_UKIDSS                   |      |
| Z_VISTA    | F6.3   | VISTA surveys (VHS, VIKING) Z-band magnitude | mag  |
| e_Z_VISTA  | F6.3   | Error on Z_VISTA                    |      |
| Y_VISTA    | F6.3   | VISTA surveys (VHS, VIKING) Y-band magnitude | mag  |
| e_Y_VISTA  | F6.3   | Error on Y_VISTA                    |      |
| J_VISTA    | F6.3   | VISTA surveys (VHS, VIKING) J-band magnitude | mag  |
| e_J_VISTA  | F6.3   | Error on J_VISTA                    |      |
| H_VISTA    | F6.3   | VISTA surveys (VHS, VIKING) H-band magnitude | mag  |
| e_H_VISTA  | F6.3   | Error on H_VISTA                    |      |
| Ks_VISTA   | F6.3   | VISTA surveys (VHS, VIKING) K_s-band magnitude | mag  |
| e_Ks_VISTA | F6.3   | Error on Ks_VISTA                   |      |
| W1         | F6.3   | WISe W1-band magnitude              |      |
| e_W1       | F6.3   | Error on W1                         |      |
| W2         | F6.3   | WISe W2-band magnitude              |      |
| e_W2       | F6.3   | Error on W2                         |      |
| W3         | F6.3   | WISe W3-band magnitude              |      |
| e_W3       | F6.3   | Error on W3                         |      |
| W4         | F6.3   | WISe W4-band magnitude              |      |
| e_W4       | F6.3   | Error on W4                         |      |