ASTROPHYSICS SENIOR PROJECT

Identification of Unknown "Green" Subdwarf Candidates In Tycho-2 & 2MASS catalogs using Virtual Observatory tools

Drew Reilly
dreilly2@suffolk.edu
Suffolk University
8 Ashburton Place, Boston MA 02108

Supervisor: F. Jiménez-Esteban

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1. Abstract

Aims: With available Virtual Observatory tools, we looked for new objects below the main sequence in the entire sky.

Methods: We preformed an all-sky cross-match between the *Hipparcos* catalog and a Tycho-2-2MASS cross-match with TOPCAT. We also collected photometry, constructed spectral energy distributions, and estimated effective temperature from fits to atmospheric models with VOSA for a sample of targets.

Results: We got a sample of 17 bright high proper-motion objects that had not been studied before. We classify them into "Sun-like" stars, possible halo candidates and possible subdwarfs.

2. Introduction

The Virtual Observatory (VO) is one of the most useful tools in astrophysics today. The VO allows astronomers access to a multitude of astronomical archives for sky surveys which enable astronomers to compare their observational data with such power that before was impossible. The power of these tools can be seen in papers such as Kim et al. (2005), Bayo et al. (2008), Caballero et al. (2009), and Jimenez-Esteban et al. (2011).

Subdwarfs are dwarf stars that fall below the main sequence on the HR diagram. They are 1.5 to 2 magnitudes dimmer than main sequence stars with the same spectral type and their spectra's are mostly featureless. First discovered by Adams and Joy (1922), subdwarfs were first thought to be stars transitioning to the whitedwarf phase of their lives. Since then, purposeful discoveries of subdwarfs have been linked with high proper-motion studies, like Eggen et al. (1962) and Sandage and Fouts (1987). All subdwarfs have higher effective temperatures, higher surface gravities, and lower metallicities compared to stars with the same spectral type. Hot subdwarfs, discussed in papers like Geier et al. (2013), Nemeth et al. (2013), and Kupfer et al. (2013), have effective temperature greater than 20,000K and have metallicities close to that of the sun. Cool subdwarfs in Rajpurohit et al. (2013), Jao et al.

(2009) and Burgasser et al. (2009) have G, K, or M type spectra. These stars are thought to be "Population II" stars, which means they are the second generation of stars in our universe. Because metals in a star are a mechanism for transferring energy generated in the core, the low metallicity explains why these object are fainter than they should be for their spectral class. The reason hot subdwarfs are not "Population II" stars is that they are far too hot to have been born in the previous population of stellar generation. In this paper we will focus on the the "Green" objects (stars at the tip of the "Cool" subdwarf spectrum).

3. The Sample

The initial sample was obtained from Jiménez-Esteban et al. (2011). The sample takes the Tycho-2 (Hog et al. 2000) & 2MASS (Skrutskie et al. 2006) catalogs. Tycho-2 has the position and proper-motion of the brightest 2.5 million stars in the sky with typical uncertainties in position and proper-motion being 60 mas and 2.5 mas yr¯1, respectively. Photometric data given catalog are in the *Bt* and *Vt* filters at 442 and 540, respectively, has an error in magnitude of of 0.1 mag. 2MASS has photometric data for 471 million sources. The data is in the *J*, *H*, & *Ks* near-infrared bands at 1.235, 1.662, 2.159 micrometers, respectively. The typical errors in position and magnitude are less than 100 mas and 0.03 mag.

The sample obtained by Jimenez-Esteban et al. (2011) was obtained using the following workflow.

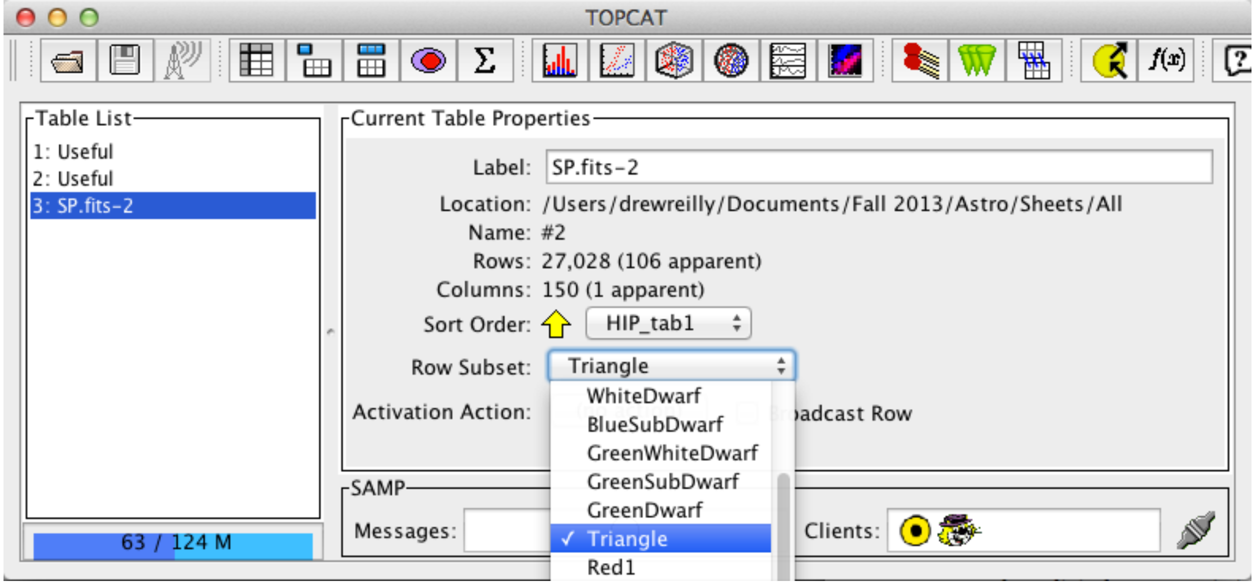
1. Select all Tycho-2 with proper-motion mu > 50 mas yr-1
2. Select all 2MASS sources within a radius of 40 arcsec around each selected high proper motion Tycho-2 source.
3. Convert 2MASS coordinates into J2000.0 epoch using the proper motion of the related Tycho-2 source.
4. Select for the each Tycho-2 source the nearest proper-motion-corrected 2MASS source.

The final sample size sources fulfilling each of these requirements was 157,184. The sample was reduced by further crossing-matching it with the van Leeuwen (2007) reduction of the *Hipparcos* catalog, which holds the information of position, proper motion and parallax for all stars brighter than 9 mag, leading to the new sample size being 26,902.

4. VO Tools

The three VO tools used to collect and analyze the data were TOPCAT, Aladin (Bonnarel et al. 2000) and VOSA (Bayo et al. 2008).

TOPCAT (Figure 1) is a graph and table application with many functions designed specifically for astronomical analysis. It allows the user to download, analyze, and cross-match astronomical databases from a number of online catalogs with either the astronomers own observations or other catalogs.



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Columns: 150 (1 apparent)
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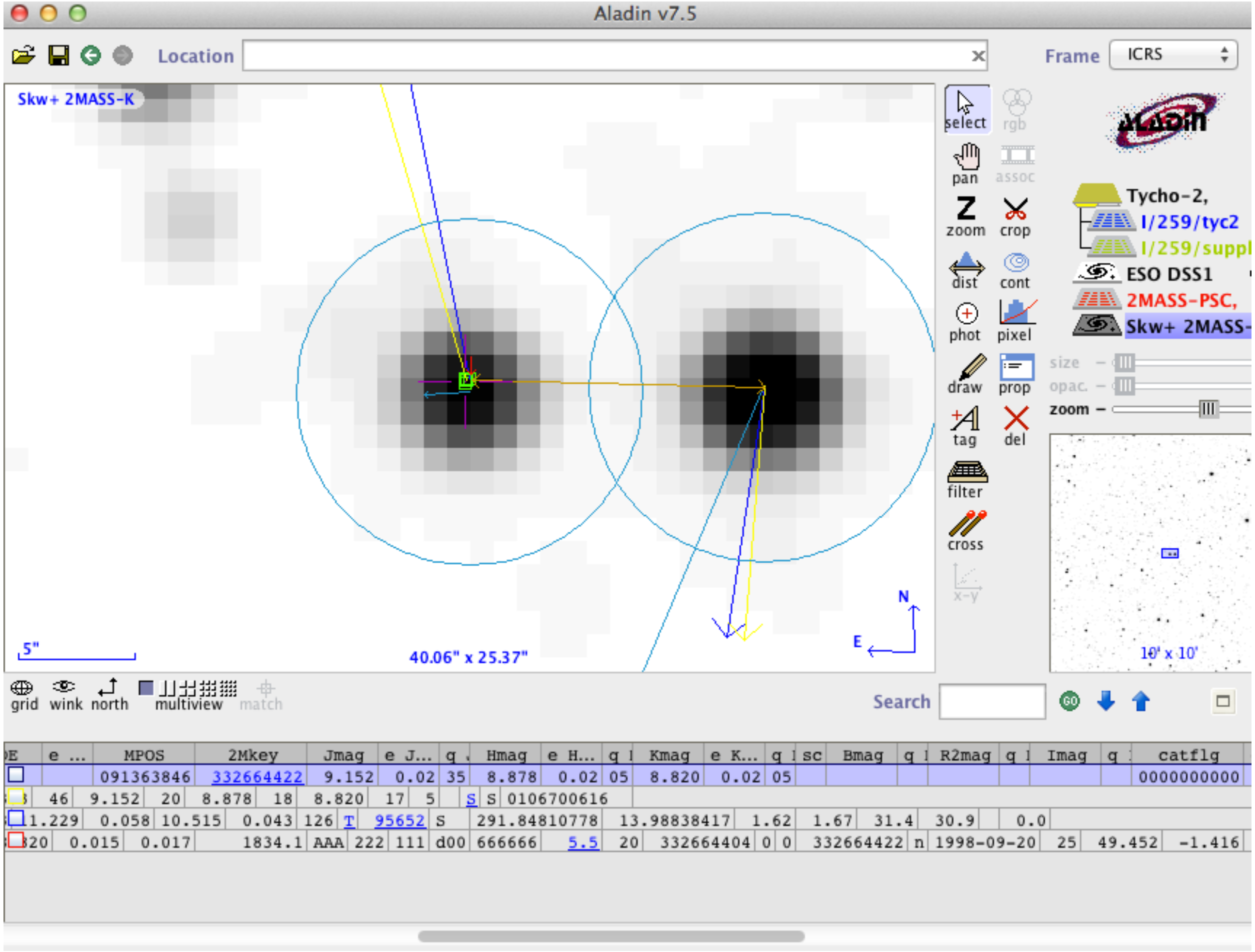
Row Subset: Triangle

Figure 1. Screenshot of TOPCAT "Control Panel", where data is selected to be used.

Aladin (Figure 2.) is an interactive visual tool that lets the user locate, view and analyze digital astronomic images from catalogs and the users own data. The user can make measurements of the images such as distance between objects and the flux of the stars as distance from the center of the star increases.



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)E   | e ... |   MPOS    |   2Mkey   |  Jmag | e J... | q | Hmag  | e H... | q | Kmag  | e K... | q | sc | Bmag | q | R2mag | q | Imag | q |   catflg
☐    |       | 091363846 | 332664422 | 9.152 |  0.02  | 35| 8.878 |  0.02  | 05| 8.820 |  0.02  | 05|    |      |   |       |   |      |   | 0000000000
☐3 | 46 | 9.152 | 20 | 8.878 | 18 | 8.820 | 17 | 5 |  | S | S | 0106700616
☐1.229 | 0.058 | 10.515 | 0.043 | 126 | T | 95652 | S | 291.84810778 | 13.98838417 | 1.62 | 1.67 | 31.4 | 30.9 |  | 0.0
☐320 | 0.015 | 0.017 | 1834.1 | AAA | 222 | 111 | d00 | 666666 | 5.5 | 20 | 332664404 | 0 | 0 | 332664422 | n | 1998-09-20 | 25 | 49.452 | -1.416
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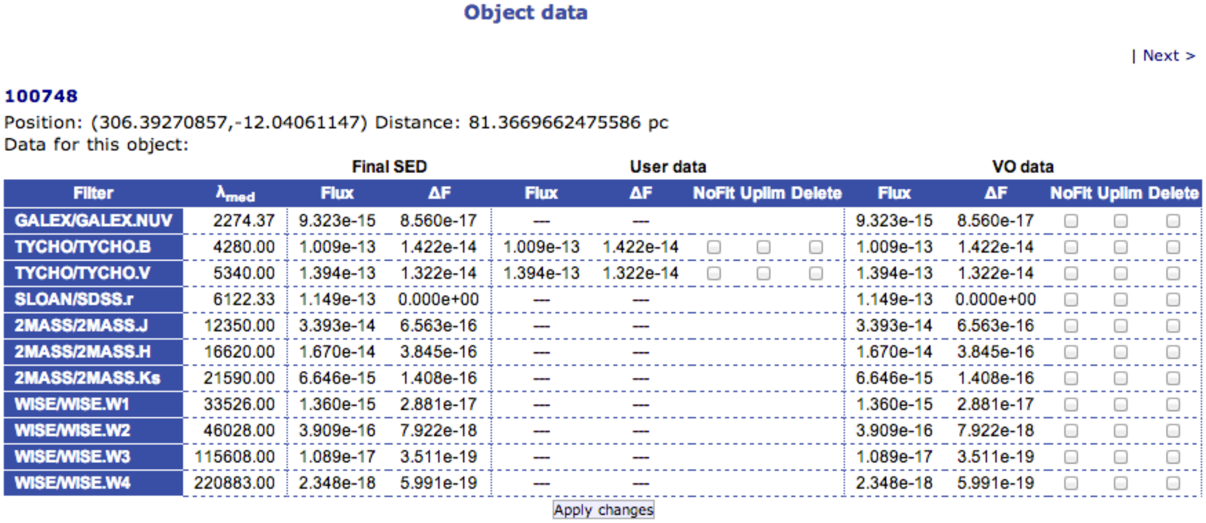
Figure 2. Screenshot of Aladin being used to check if objects have been polluted by surrounding ones.

VOSA (Figure 3), an initialism for Virtual Observatory Spectral Energy Distribution Analyzer, is a tool from the Spanish Virtual Observatory team that lets the user upload physical parameters (RA, Dec, Distance) of a star and photometric data about the star in magnitudes or fluxes (magnitudes in our case) and returns all available photometric data from infrared, optical and ultraviolet online catalogs available through the VO. Once the catalog data has been downloaded, VOSA constructs a Spectral Energy Distribution (SED) and models a fit to the SED to get the star's effective temperature, surface gravity and metallicity for a number of models depending on the type of star. When fitting the theoretical spectrum of the SED, VOSA allows the user to set upper and lower limits on the three variables to be determined to prevent erroneous data points from influencing the fits.



Object data

100748

Position: (306.39270857,-12.04061147) Distance: 81.3669662475586 pc
Data for this object:

		Final SED		User data					VO data				
Filter	λ_{med}	Flux	ΔF	Flux	ΔF	NoFit	Uplim	Delete	Flux	ΔF	NoFit	Uplim	Delete
GALEX/GALEX.NUV	2274.37	9.323e-15	8.560e-17	—	—				9.323e-15	8.560e-17	☐	☐	☐
TYCHO/TYCHO.B	4280.00	1.009e-13	1.422e-14	1.009e-13	1.422e-14	☐	☐	☐	1.009e-13	1.422e-14	☐	☐	☐
TYCHO/TYCHO.V	5340.00	1.394e-13	1.322e-14	1.394e-13	1.322e-14	☐	☐	☐	1.394e-13	1.322e-14	☐	☐	☐
SLOAN/SDSS.r	6122.33	1.149e-13	0.000e+00	—	—				1.149e-13	0.000e+00	☐	☐	☐
2MASS/2MASS.J	12350.00	3.393e-14	6.563e-16	—	—				3.393e-14	6.563e-16	☐	☐	☐
2MASS/2MASS.H	16620.00	1.670e-14	3.845e-16	—	—				1.670e-14	3.845e-16	☐	☐	☐
2MASS/2MASS.Ks	21590.00	6.646e-15	1.408e-16	—	—				6.646e-15	1.408e-16	☐	☐	☐
WISE/WISE.W1	33526.00	1.360e-15	2.881e-17	—	—				1.360e-15	2.881e-17	☐	☐	☐
WISE/WISE.W2	46028.00	3.909e-16	7.922e-18	—	—				3.909e-16	7.922e-18	☐	☐	☐
WISE/WISE.W3	115608.00	1.089e-17	3.511e-19	—	—				1.089e-17	3.511e-19	☐	☐	☐
WISE/WISE.W4	220883.00	2.348e-18	5.991e-19	—	—				2.348e-18	5.991e-19	☐	☐	☐

Figure 3. Screen shot from VOSA after the user has queried online photometric databases

5. Analysis

Taking the original same from Jiménez-Esteban et al. (2011) with a size of 155,384 stars, we cross-referenced the table with the *Hipparcos* catalog using the “Mulitple Cone Search” tool in TOPCAT. This gave us a new sample size of 26,902. The next was to construct a Hertzsprung–Russell diagram. This was done by using the parallax from the *Hipparcos* catalog to find the distance, and the apparent magnitude to find the absolute magnitude of each object. We had preselected possible green subdwarfs using a diagram of *Vt-Ks* color and the stars’ proper-motions. There were 126 objects eliminated for the sample at this point because we noticed the unrealistic brightness. This was because of an error in the *Hipparcos* catalog which returned negative parallaxes, which tainted the absolute magnitude calculations. Once we had the HR diagram, we identified all the stars in the sample that had been studied in Jiménez-Esteban et al. (2011) and Jiménez-Esteban et al. (2012) so that well-studied stars were studied as part of our new study. We then identified our green subdwarf candidates.

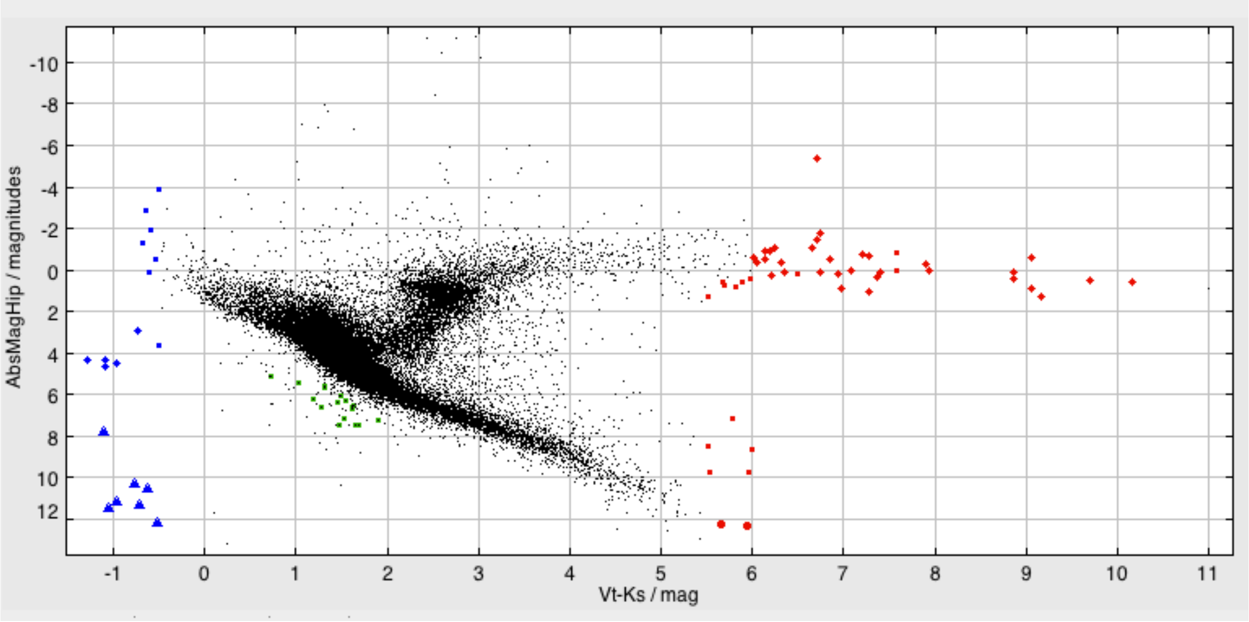
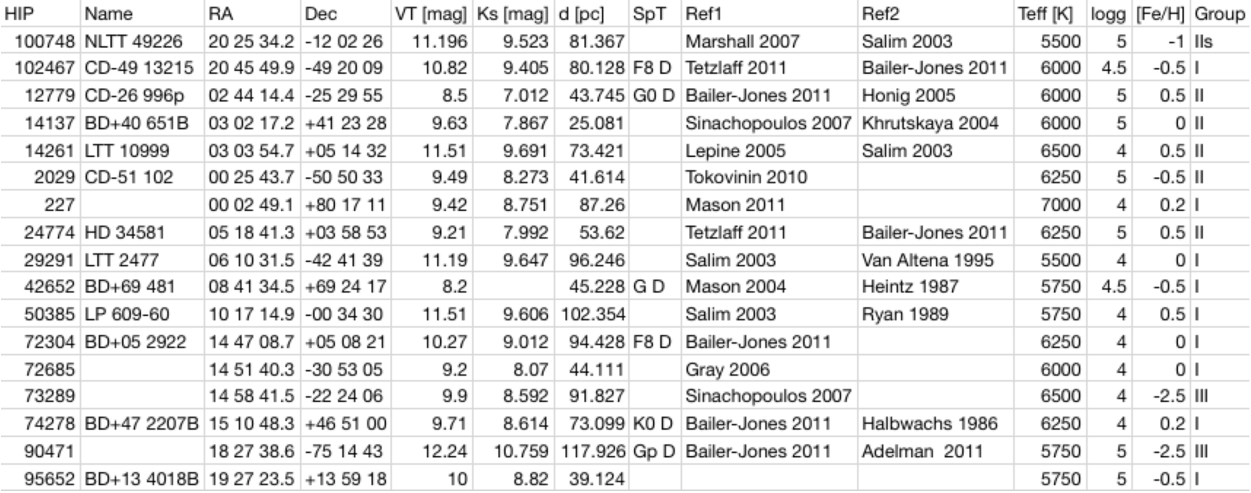


Figure 4. HR Diagram after cross-referencing the original sample with Hipparcos Catalog. Green Objects are the sample of 17 studied in depth in this paper. Blue and Red objects were studied in Jimenez-Esteban et al. (2011) and Jimenez-Esteban et al. (2012). Blue triangles are white dwarfs, blue diamonds are subdwarfs, and blue circles are young main sequence. red diamonds are red giants and red circles are red dwarfs.

We selected a triangular area just below the main sequence between 0 and 3 magnitudes on the Vt-Ks scale and 3 and 9 on the absolute magnitude scale. The size of this sample was 59. We then cross-referenced these sources with SIMBAD to see how many of them had not been previously studied using the number of references ("BIBLIST") to each star. No stars with 2 references or fewer were part of papers that were not catalogs, ensuring that it would be the first time that any object in this paper would be studied in depth, which left us with a sample of 25 objects. The sample was then reduced to 23 because of the separation between two of the sources and their SIMBAD cross-match identifications was too large to be the stars in the table. To make sure that each star correctly identified in the cross-match, we loaded the Tycho-2 and 2MASS catalogs into Aladin with their proper motions to make sure they were the right star and not an error in the catalogs. 4 objects were eliminated because they were too close to other stars and the fluxes of the other stars were measured instead of the stars we were interested in. While double checking the number of references manually, we noticed that 2 sources had 5 references and not the number reported in the cross-match. This was unexpected because the point of cross-matching our table with SIMABD was to get rid of sources with more than 2 references. Our final sample sized to be fitted for spectra contained 17 objects.

Finally, we uploaded the table of new objects to VOSA to get the spectra and temperature of the stars using the "Kurucz" model fit. The Kurucz models were chosen because they provide a wide range of possible metallicities needed to identify subdwarfs. In our sample, VOSA used on average, more than 10 data points to fit the models to the SEDs. Our first result (no limits set manually) results in unrealistic surface gravities for stars in this section of the HR diagram (9 stars with the log of gravity to the order of 2, with 5 stars with orders of 0). Because subdwarfs are known to have relatively high surface gravities, we decided to set a lower limit of 4 orders of magnitude on the surface gravities of the stars for the models.

6.Results



HIP	Name	RA	Dec	VT [mag]	Ks [mag]	d [pc]	SpT	Ref1	Ref2	Teff [K]	logg	[Fe/H]	Group
100748	NLTT 49226	20 25 34.2	-12 02 26	11.196	9.523	81.367		Marshall 2007	Salim 2003	5500	5	-1	IIs
102467	CD-49 13215	20 45 49.9	-49 20 09	10.82	9.405	80.128	F8 D	Tetzlaff 2011	Bailer-Jones 2011	6000	4.5	-0.5	I
12779	CD-26 996p	02 44 14.4	-25 29 55	8.5	7.012	43.745	G0 D	Bailer-Jones 2011	Honig 2005	6000	5	0.5	II
14137	BD+40 651B	03 02 17.2	+41 23 28	9.63	7.867	25.081		Sinachopoulos 2007	Khrutskaya 2004	6000	5	0	II
14261	LTT 10999	03 03 54.7	+05 14 32	11.51	9.691	73.421		Lepine 2005	Salim 2003	6500	4	0.5	II
2029	CD-51 102	00 25 43.7	-50 50 33	9.49	8.273	41.614		Tokovinin 2010		6250	5	-0.5	II
227		00 02 49.1	+80 17 11	9.42	8.751	87.26		Mason 2011		7000	4	0.2	I
24774	HD 34581	05 18 41.3	+03 58 53	9.21	7.992	53.62		Tetzlaff 2011	Bailer-Jones 2011	6250	5	0.5	II
29291	LTT 2477	06 10 31.5	-42 41 39	11.19	9.647	96.246		Salim 2003	Van Altena 1995	5500	4	0	I
42652	BD+69 481	08 41 34.5	+69 24 17	8.2		45.228	G D	Mason 2004	Heintz 1987	5750	4.5	-0.5	I
50385	LP 609-60	10 17 14.9	-00 34 30	11.51	9.606	102.354		Salim 2003	Ryan 1989	5750	4	0.5	I
72304	BD+05 2922	14 47 08.7	+05 08 21	10.27	9.012	94.428	F8 D	Bailer-Jones 2011		6250	4	0	I
72685		14 51 40.3	-30 53 05	9.2	8.07	44.111		Gray 2006		6000	4	0	I
73289		14 58 41.5	-22 24 06	9.9	8.592	91.827		Sinachopoulos 2007		6500	4	-2.5	III
74278	BD+47 2207B	15 10 48.3	+46 51 00	9.71	8.614	73.099	K0 D	Bailer-Jones 2011	Halbwachs 1986	6250	4	0.2	I
90471		18 27 38.6	-75 14 43	12.24	10.759	117.926	Gp D	Bailer-Jones 2011	Adelman 2011	5750	5	-2.5	III
95652	BD+13 4018B	19 27 23.5	+13 59 18	10	8.82	39.124				5750	5	-0.5	I

Table 1. Table with stars names, references, and VOSA results

The 17 stars in the final sample were grouped according to effective temperature, surface gravity and metallicity. This formula produced the results seen in Table 1.

Group I consists of "Sun-like" stars with effective temperatures between 5500K and 6250K, the log of the surface gravity between 4 and 4.5 and metallicities between -.5 and .5. Group II were put together because their surface gravities make them candidates to be subdwarfs, especially the HIP 100748 because it has low metallicity. Group III are stars with extremely low metallicity. These stars are very good candidates to be subdwarfs, and are possibly in the halo of the Galaxy.

All graphs of the Models fitted to the SEDs can be found in Appendix 1. For objects 14137, 47839, 50385, and 95652 had saturation in some passbands, so those points were excluded from the models. Several objects had excess in the WISE passbands which observed stars in the infared can be explained but dust surrounding the star.

7. Acknowledgements

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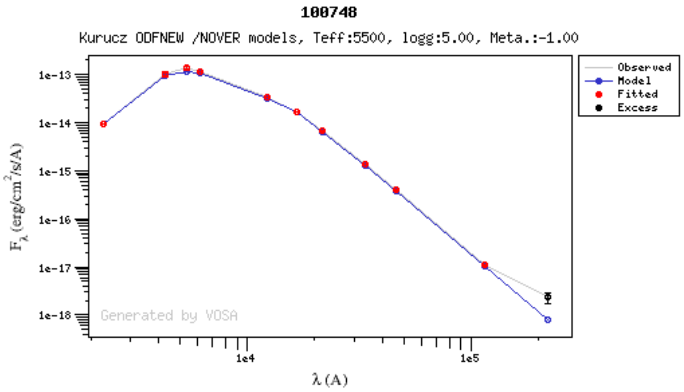
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1e-15
1e-16
1e-17
1e-18
1e4
1e5
λ (A)
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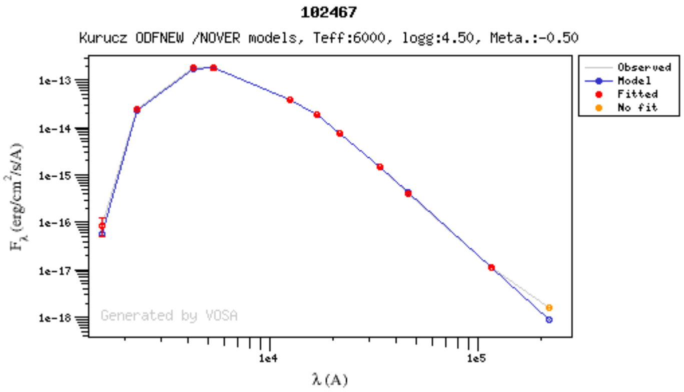
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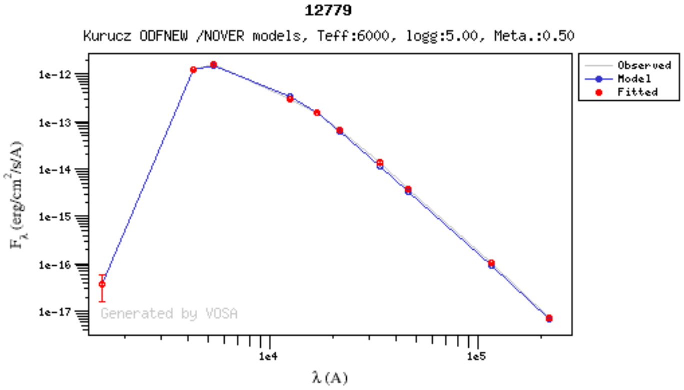
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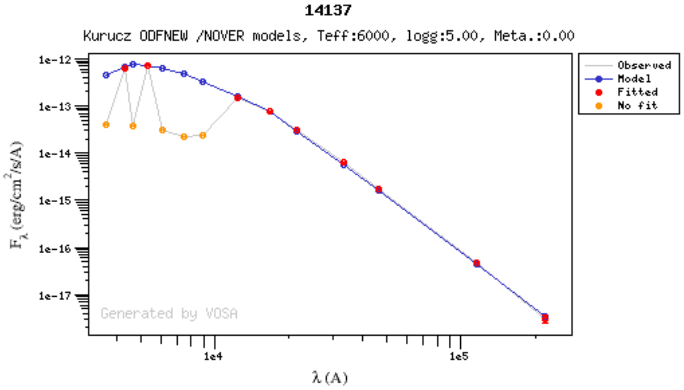
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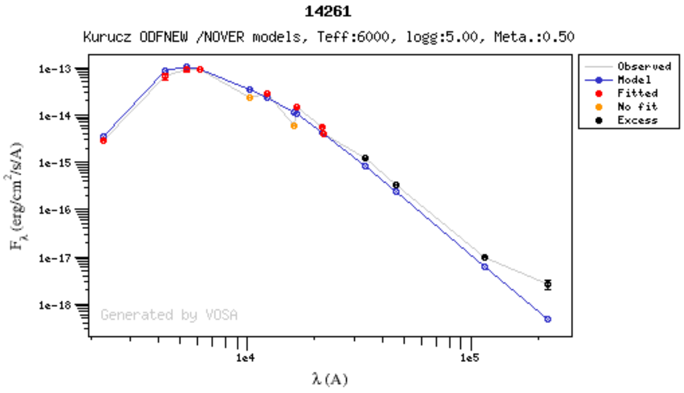
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No fit
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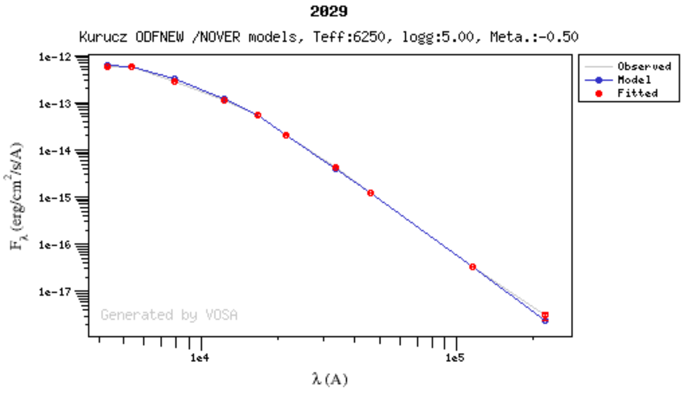
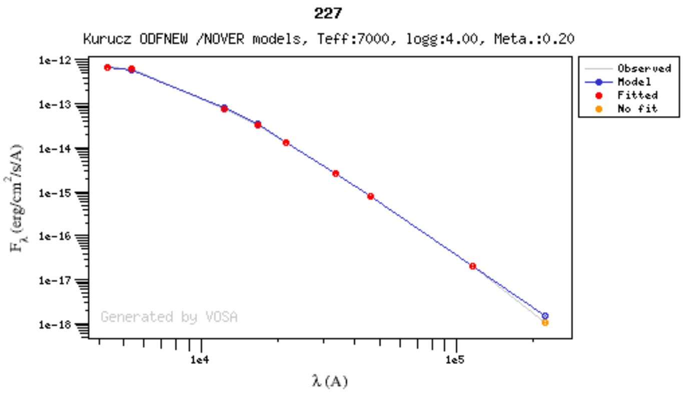
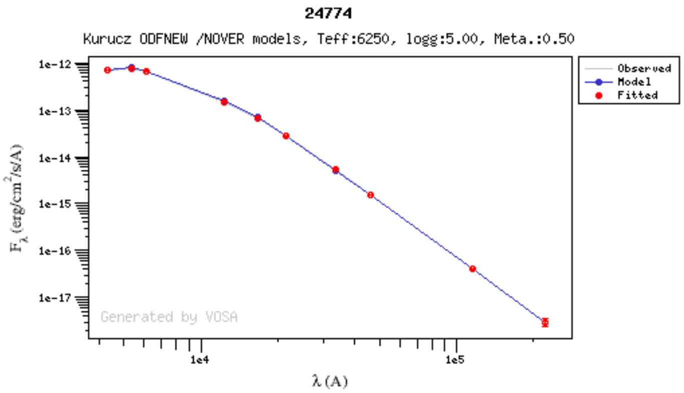
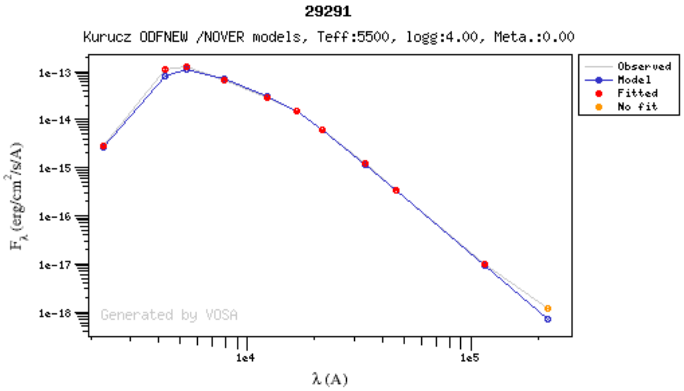
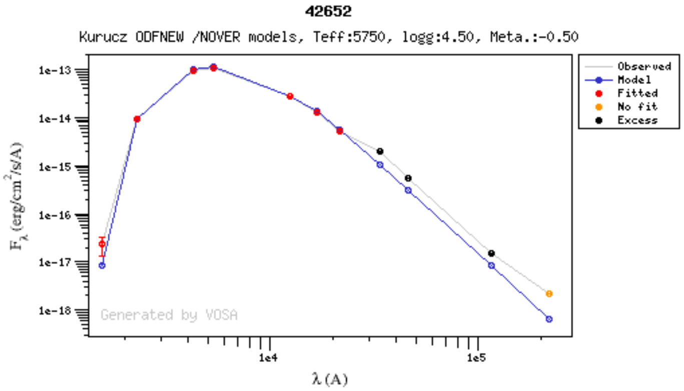

2029
Kurucz ODFNEW /NOVER models, Teff:6250, logg:5.00, Meta.:-0.50
Observed
Model
Fitted
F_λ (erg/cm^2/s/A)
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e4
1e5
λ (A)
Generated by VOSA

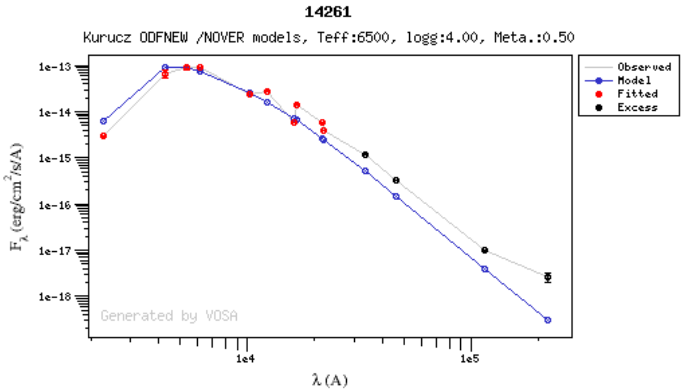

227
Kurucz ODFNEW /NOVER models, Teff:7000, logg:4.00, Meta.:0.20
Observed
Model
Fitted
No fit
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)

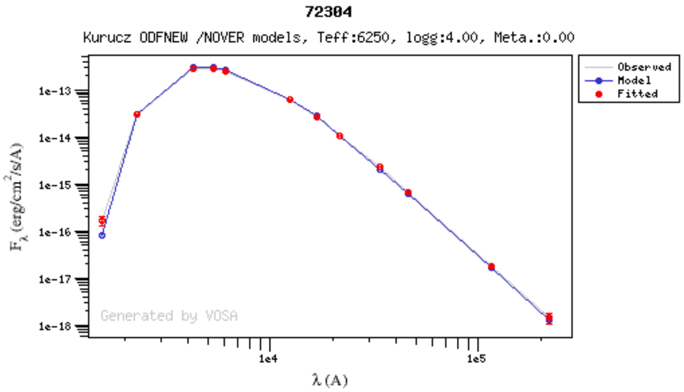

24774
Kurucz ODFNEW /NOVER models, Teff:6250, logg:5.00, Meta.:0.50
Observed
Model
Fitted
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)

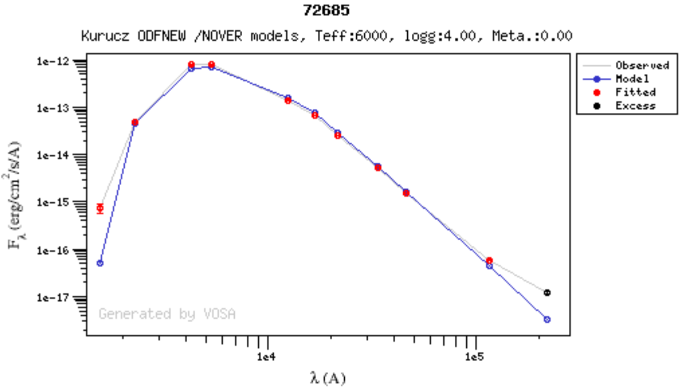
9. Appendix 1

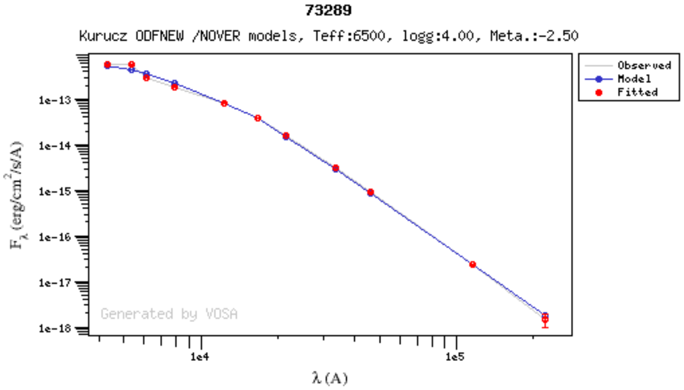

29291
Kurucz ODFNEW /NOVER models, Teff:5500, logg:4.00, Meta.:0.00
Observed
Model
Fitted
No fit
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)

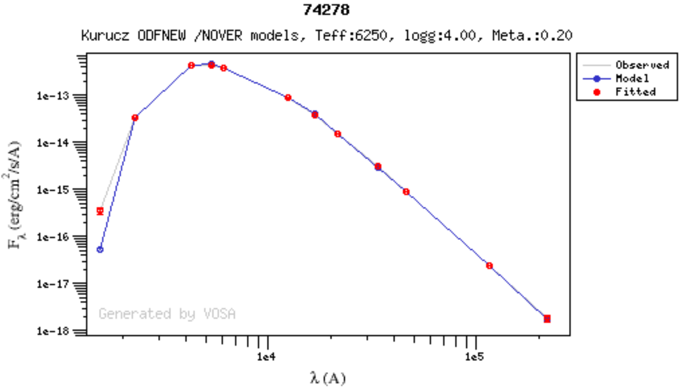

42652
Kurucz ODFNEW /NOVER models, Teff:5750, logg:4.50, Meta.:-0.50
Observed
Model
Fitted
No fit
Excess
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)

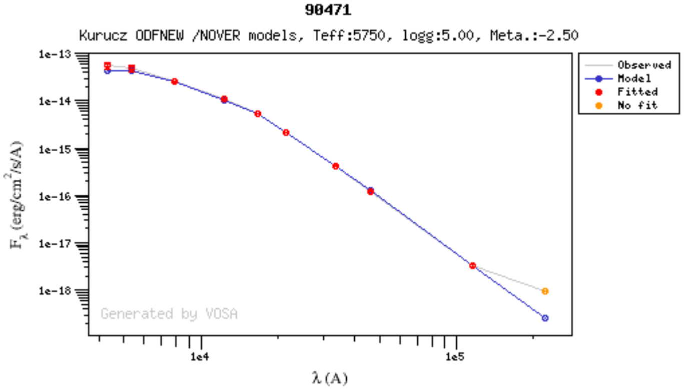

14261
Kurucz ODFNEW /NOVER models, Teff:6500, logg:4.00, Meta.:0.50
Observed
Model
Fitted
Excess
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)

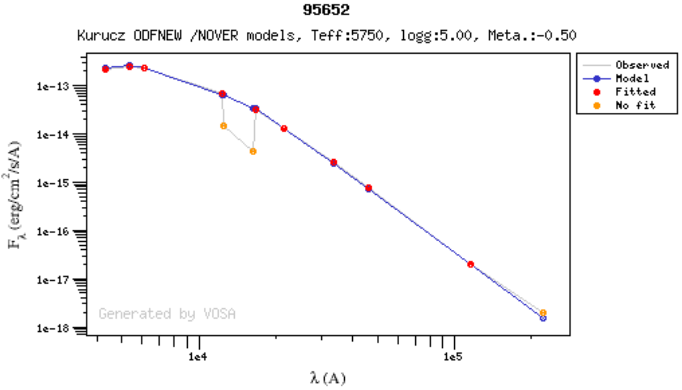

72304
Kurucz ODFNEW /NOVER models, Teff:6250, logg:4.00, Meta.:0.00
Observed
Model
Fitted
Generated by VOSA
F_λ (erg/cm^2/s/A)
λ (A)


72685
Kurucz ODFNEW /NOVER models, Teff:6000, logg:4.00, Meta.:0.00
Observed
Model
Fitted
Excess
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
F_λ (erg/cm^2/s/A)
1e4
1e5
λ (A)
Generated by VOSA


73289
Kurucz ODFNEW /NOVER models, Teff:6500, logg:4.00, Meta.:-2.50
Observed
Model
Fitted
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
F_λ (erg/cm^2/s/A)
1e4
1e5
λ (A)
Generated by VOSA


74278
Kurucz ODFNEW /NOVER models, Teff:6250, logg:4.00, Meta.:0.20
Observed
Model
Fitted
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
F_λ (erg/cm^2/s/A)
1e4
1e5
λ (A)
Generated by VOSA


90471
Kurucz ODFNEW /NOVER models, Teff:5750, logg:5.00, Meta.:-2.50
Observed
Model
Fitted
No fit
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
F_λ (erg/cm^2/s/A)
1e4
1e5
λ (A)
Generated by VOSA


95652
Kurucz ODFNEW /NOVER models, Teff:5750, logg:5.00, Meta.:-0.50
Observed
Model
Fitted
No fit
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
F_λ (erg/cm^2/s/A)
1e4
1e5
λ (A)
Generated by VOSA