

SCIENCE WITH THE VO: SPECTROSCOPIC STUDIES OF HERBIG Ae/Be STARS

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Abstract. The Virtual Observatory (VO) is opening up new ways of exploiting the huge amount of data provided by the ever growing number of ground-based and space facilities. Using VOSpec, a multi-wavelength spectral analysis tool developed by the ESA-VO Team at ESAC, and new developments on scripting with VOSpec (VOScript), we have started to undertake a comprehensive study of spectroscopic and photometric data in the VO on Herbig Ae/Be stars. By studying line strengths, variabilities and spectral energy distributions, from the X-ray to sub-millimeter ranges, we aim to gain insights into processes and disk properties of a large sample of these objects. This paper presents initial findings of the spectroscopic analysis and initial spectral energy distribution classifications.

Key words: stars: variables: Herbig Ae/Be – techniques: spectroscopic – virtual observatory tools

1. INTRODUCTION

Herbig Ae/Be stars are intermediate-mass ($2\text{--}10 M_{\odot}$) pre-main-sequence stars, first classified by Herbig (1960). These objects are young (1–10 Myr) stars at advanced stages of their pre-main-sequence evolution, they have large infrared excesses due to thermal re-emission of circumstellar dust and show emission lines in their spectra.

Herbig Ae/Be stars are interesting to study because they bridge the gap between low-mass T Tauri stars and the optically invisible, near-infrared-faint Massive Young Stellar Objects (MYSOs). It is here that the star formation mechanism switches from magnetically controlled accretion from disks with inner holes (as is widely accepted to be the case for T Tauri stars, Bertout 1989) to a yet unclear mechanism (possibly involving accretion disks reaching directly onto the MYSOs; see overview by Krumholz & Bonnell 2007). Herbig Ae/Be stars are also interesting to study because their ages (1–10 Myr) fall in the epoch where planet formation theories suggest planetary embryo formation is likely to occur. Exoplanets around A-type stars have recently been detected via direct imaging (Marois et al. 2008), implying that extrasolar planets could be forming in the circumstellar disks surrounding Herbig Ae stars.

The spectral energy distributions (SEDs) of Herbig Ae/Be stars were classified

into two groups by Meeus et al. (2001) based on Infrared Space Observatory (ISO) observations: group I sources have a relatively strong far-infrared flux, which is energetically comparable to the flux in the near-infrared range showing an almost flat SED. Group II sources show a similar near-infrared excess as group I sources but their flux falls off strongly towards the far infrared. The group II sources can be fitted with a power law at mid- to far-infrared wavelengths, whereas an additional blackbody component is required to fit the SEDs of group I sources at far-infrared wavelengths. Theoretical models of protoplanetary disks by Dullemond & Dominik (2004) show that disks with high optical depth turn out to be flaring and have a strong far-infrared emission (group I), while disks with an optical depth below a certain threshold drop into the shadow of their own puffed-up inner rim and are weak in the far infrared (group II). Dullemond & Dominik (2004) also proposed an evolutionary mechanism, where disks start out with a flaring shape (group I), and then go through the process of grain growth, causing the optical depth of the disk to drop and the disk to become self-shadowed, producing the steeper, bluer mid- to far-infrared SEDs of group II sources. Based on ISO observations, Acke and van den Ancker (2004) introduced a third group (group III) as objects with the amorphous $10\ \mu\text{m}$ feature in absorption. These objects are believed to possess disks whose luminosity is dominated by viscous dissipation of energy due to accretion, are deeply embedded systems and hence are fundamentally different from the other stars in the sample.

Most observational studies of Herbig Ae/Be stars tend to focus on one specific wavelength region, or even single spectral lines (e.g., Garcia-Lopez et al. 2006, on $\text{Br}\gamma$; van der Plas et al. 2008, on the $[\text{O I}]$ 6300 Å line), or are confined to in-depth studies of individual objects (e.g. Drew et al. 1997 on MWC 297). However, to begin to answer the open questions for Herbig Ae/Be stars and massive star formation, studies of substantial samples of objects, across wide wavelength ranges from the ultraviolet to sub-millimeter, need to be conducted.

The aim of this study is to do just this, by exploiting capabilities of the VO, and to perform a multi-wavelength campaign on a large number of objects, focusing on collecting and analyzing spectra and photometry available in the VO. Using VOSpec, VOScript, and other VO Tools, the project aims are to produce a database of line properties for a large sample of Herbig Ae/Be stars, to classify the SED types, and to analyze the results looking for any trends, e.g. between spectral lines, SED types, spectral types, etc.

As a first step of this study, we present our initial results of classifying the SED types and analyzing a number of spectral lines. Section 2 of this paper describes the sample selection and ESA-VO Tools used; Section 3 describes how the SEDs of Herbig Ae/Be stars can be classified using VO Tools. The initial results of the SED classification and spectroscopic line analysis are presented in Section 4, and a summary and final remarks are given in Section 5.

2. SAMPLE SELECTION AND ESA-VO TOOLS

An initial sample of Herbig Ae/Be stars was collated from the catalogues of Thé et al. (1994; their Tables 1 and 2) and Vieira et al. (2003).

VOSpec¹ is a multi-wavelength spectral analysis tool, developed by the Science Archives and VO Team at the European Space Astronomy Centre (ESAC), Euro-

¹<http://esavo.esac.esa.int/vospec/>

pean Space Agency (ESA), Madrid, Spain. It is designed to access and visualise spectra from worldwide facilities (such as XMM-Newton; the Hubble Space Telescope, HST; the European Southern Observatory, ESO; ISO; and many others), can overlay and fit spectra to theoretical models, and can perform line identification with direct access to atomic and molecular line databases, all registered in the VO. The SEDs of objects can be built up and visualized from spectra within the VO and by loading in local data. VOSpec accesses all spectra in the VO registry that follow the IVOA Simple Spectral Access Protocol (SSAP) format (Tody et al. 2008). VOSpec also has a suite of spectral analysis functions which include line and continuum fitting, redshift and reddening correction, spectral arithmetic, and convolution between spectra and equivalent width calculations, among others.

VOScript is the scripting tool of VOSpec, currently being developed to provide easy access from scripting interfaces to all the VOSpec functionalities. The tool is a jar library and can be called from the command line and from any language that runs on Java. The capabilities of VOScript include: searching the VO for spectra from a large list of objects; performing batch-oriented analysis with VOSpec functionalities (line flux, equivalent width, Gaussian calculations, etc.) on a large number of spectra; and sending data to other tools using SAMP interoperability (IVOA Recommendation: SAMP – Simple Application Messaging Protocol, Taylor et al. 2011).

This science case has been developed around using the ESA-VO Tool VOSpec and its scripting counterpart VOScript. Along with these tools, other VO Tools where also used, such as VOSED² (to search for photometry and include photometric points in the SEDs), and TOPCAT³ (Taylor 2005), and its scripting counterpart STILTS⁴ (Taylor 2006; to analyze tabular results from VOScript and create histograms and scatter plots).

3. SED CLASSIFICATIONS USING VO TOOLS

We used VOSpec to build up and display SEDs from spectra in the VO, which include, among others, spectra in the infrared from the ISO; in the optical and ultraviolet from the HST; in the ultraviolet from the International Ultraviolet Explorer (IUE) and the Far Ultraviolet Spectroscopic Explorer (FUSE). Figure 1 shows examples of a Group I SED and a Group II SED. Photometry was included in the SED, firstly by using VOSED, to search the catalogues of Tycho-2 (Høg et al. 2000), Strömgren photometry (Hauck & Mermilliod 1998), the Infrared Astronomical Satellite (IRAS) Point Source Catalogue (PSC) (Helou & Walker 1988), and the 2MASS PSC (Cutri et al. 2003), among others. VOSED saves the results in a format that can be displayed directly into VOSpec and be included in the SEDs.

To classify Group III objects, we used VOSpec to analyze the ISO spectra around the 10 μm feature. For SED classification of Group I and Group II objects, we used TOPCAT, to cross-correlate the objects with near infrared photometry, from 2MASS PSC, and mid-infrared photometry, from IRAS PSC. Based on the criterion of van Boekel et al. (2005), the quantities used to characterize the infrared SEDs of Herbig Ae/Be stars are the ratio of F_{NIR} (the integrated flux derived from

²<http://sdc.laef.inta.es/vosed/>

³<http://www.star.bris.ac.uk/~mbt/topcat/>

⁴<http://www.star.bris.ac.uk/~mbt/stilts/>

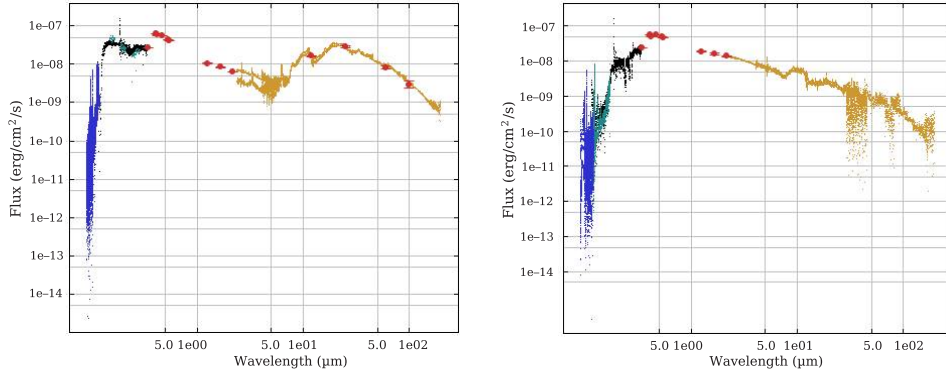


Fig. 1. Examples of Herbig Ae/Be star SEDs. A Group I source is shown on the left (HD 100546) and a Group II source, on the right (HD 104237). The SEDs have been built up, using VOSpec, from spectra within the VO: from FUSE (blue), IUE (black), HST (cyan) and ISO (orange), and from photometric data using VOSED: from Strömgren, Tycho-2, 2MASS PSC, and IRAS PSC catalogues (red). Neither SEDs are corrected for extinction.

the broad-band J , H and K photometry) and F_{IR} (the integrated flux derived from the IRAS 12, 25 and 60 μm photometry), and the non-colour-corrected IRAS [12]–[60] colour.

4. INITIAL RESULTS

4.1. Spectral energy distributions

Figure 2 displays the $F_{\text{NIR}}/F_{\text{IR}}$ flux ratio versus the IRAS [12]–[60] colour. The $F_{\text{NIR}}/F_{\text{IR}}$ flux ratio compares the strength of the near-infrared compared to the mid-infrared excess, which is lower for group I than for group II objects. The IRAS [12]–[60] colour compares the shape of the mid-infrared SED, which tends to be ‘double-peaked’, and redder for group I objects compared to group II objects. Therefore, the group II objects fall in the upper left region whilst the group I objects fall in the lower right. Also included in the diagram, for completeness, are the group III objects. These objects have strong mid-infrared excesses and fall in the same region as the group I objects (as was also found by Acke and van den Ancker 2004). A straight line can separate the group II and group I/III regions; in this case, $F_{\text{NIR}}/F_{\text{IR}} = 0.04([12] - [60]) + 0.02$. Figure 2 differs from the diagram of van Boekel et al. (2005), since we do not include broad-band L and M photometry in F_{NIR} . The majority of the classifications are from the literature (see Table 1, which presents our initial SED-type classifications, and also those from the literature).

4.2. Spectral lines

Figures 3 and 4 present initial results from the spectral-line analysis, respectively of the [OI] 63 μm and [CII] 158 μm infrared lines. Only group I and group III objects display [OI] 63 μm emission lines, from a sample of 32 Herbig Ae/Be stars with ISO Short Wave Spectrometer (SWS) spectra, with 4 sources having unclassified SEDs.

Table 1. Herbig Ae/Be SED classifications. The SED groups and references are in given in columns 4 and 5. References: (1) Acke & van den Ancker (2004); (2) Acke et al. (2005); (3) Meert et al. (2001); (4) Juhász et al. (2010); (5) this study.

Object Name	RA h m s	DEC ° ′ ″	SED Group	References	Object Name	RA h m s	DEC ° ′ ″	SED Group	References
Group I					Group II cont.				
V376 Cas	00 11 26.09	+58 50 03.5	I, I	1, 2	HD 36408	05 32 14.14	+17 03 29.25	II	5
V892 Tau	04 18 40.62	+28 19 15.5	I	1	T Ori	05 35 50.44	-05 28 34.94	II	5
AB Aur	04 55 45.85	+30 33 04.29	I, I, Ia, Ia	1, 2, 3, 4	V586 Ori	05 36 59.25	-06 09 16.36	II, IIa	2, 4
HD 34282	05 16 00.48	-09 48 35.42	I, I, Ib	1, 2, 4	BF Ori	05 37 13.26	-06 35 00.58	II, IIa	1, 2, 4
MWC 758	05 30 27.52	+25 19 57.08	I, Ia	2, 4	KMS 27	05 37 47.08	-06 42 30.25	IIa	4
HD 245185	05 35 09.61	+10 01 51.51	I	2	HD 37411	05 38 14.51	-05 25 13.30	IIb	4
PDS 16	05 43 11.89	-04 59 49.90	Ia	4	RR Tau	05 39 30.52	+26 22 26.97	II, IIb	1, 4
MWC 789	06 01 59.99	+16 30 56.73	Ia	4	MWC 120	05 41 02.29	-02 43 00.73	IIa	4
MWC 147	06 33 05.19	+10 19 19.99	Ia	4	NX Pup	07 19 28.26	-44 35 11.26	IIa	4
V590 Mon	06 40 44.64	+09 48 02.1	Ia	4	PDS 31	08 29 34.90	-38 36 21.13	IIa	4
HD 97048	11 08 03.32	-77 39 17.48	I, I, Ib	1, 2, 4	HD 85567	09 50 28.54	-60 58 02.95	II, IIa	2, 4
PDS 339	11 33 05.58	-54 19 28.54	I, I, Ib, Ib	1, 2, 3, 4	HD 95881	11 01 57.62	-71 30 48.35	II, IIa	1, 2, 4
HD 100546	11 33 25.44	-70 11 41.24	I, I, Ia, Ia	1, 2, 3, 4	HD 98922	11 22 31.67	-53 23 11.45	II, IIa	2, 4
T Cha	11 57 13.55	-79 21 31.54	I	5	HD 101412	11 39 44.46	-60 10 27.74	II, IIa	2, 4
SS73 44	15 03 23.81	-63 22 58.9	Ia	4	HD 104237	12 00 05.085	-78 11 34.57	II, IIa, IIa	1, 2, 3, 4
CD-36 10010B	15 15 48.44	-37 09 16.03	I, Ib	1, 3	HD 141569	15 49 57.745	-03 55 16.34	II, IIb	1, 2, 4
PDS 395	15 40 46.38	-42 29 53.55	I, I, Ib, Ia	1, 2, 3, 4	HD 142666	15 56 40.02	-22 01 40.01	II, IIa, IIa	1, 2, 3, 4
HD 142527	15 56 41.89	-42 19 23.27	I, I, Ia, Ia	1, 2, 3, 4	HD 144432	16 06 57.95	-27 43 09.79	II, IIa, IIa	1, 2, 3, 4
V921 Sco	16 59 06.79	-42 42 08.58	I, I	1, 2	HD 144668	16 08 34.29	-39 06 18.33	II, II, IIa	1, 2, 3, 4
HD 169142	18 24 29.78	-29 46 49.37	I, I, Ib, Ib	1, 2, 3, 4	HD 150193	16 40 17.92	-23 53 45.18	II, IIa, IIa	1, 2, 3, 4
TY CrA	19 01 40.83	-36 52 33.88	I	5	AK Sco	16 54 44.85	-36 53 18.57	II, IIa	1, 2, 4
R CrA	19 01 53.66	-36 57 07.87	I, II?	5, 1	KK Oph	17 10 08.07	-27 15 18.24	IIa	4
T CrA	19 01 58.78	-36 57 49.93	I, I, Ia	1, 2, 4	NSV 9037	17 31 24.95	-23 57 45.51	IIa, IIa	3, 4
MWC 614	19 11 11.25	+15 47 15.64	I, I, Ia, Ia	1, 2, 3, 4	MWC 275	17 56 21.29	-21 57 21.87	II, IIa, IIa	1, 2, 3, 4
V1685 Cyg	20 20 28.24	+41 21 51.56	I, I?	5, 1	VV Ser	18 28 47.87	+00 08 39.76	II, IIa	1, 2, 4
V1686 Cyg	20 20 29.26	+41 21 28.6	Ia, II?	4, 1	WW Vul	19 25 58.75	+21 12 31.28	II, IIa	1, 2, 4
MWC 361	21 01 36.92	+68 09 47.76	I, I	1, 2	V1295 Aql	20 03 02.51	+05 44 16.67	II, IIa	2, 4
HD 203024	21 16 03.02	+68 54 52.13	Ia	4	AS 477	21 52 34.10	+47 13 43.61	II	1
V361 Cep	21 42 50.18	+66 06 35.12	I	5	SV Cep	22 21 33.20	+73 40 27.07	II, II	1, 2
V373 Cep	21 43 06.82	+66 06 54.24	I	5	Group III				
MWC 1080	23 17 25.59	+60 50 43.62	I, I	1, 2	MWC 137	06 18 45.52	+15 16 52.25	III	5
Group II					Z CMa	07 03 43.16	-11 33 06.22	III, III	1, 2
VX Cas	00 31 30.68	+61 58 50.97	II, II	1, 2	DK Cha	12 53 17.23	-77 07 10.7	III	1
MWC 480	04 58 46.27	+29 50 36.98	II, II, IIa	1, 2, 4	MWC 297	18 27 39.5	-03 49 52	III, III	1, 2
UX Ori	05 04 29.99	-03 47 14.29	II	1	GSC 2150-0266	19 36 18.91	+29 32 50.0	III	5
HD 35929	05 27 42.79	-08 19 38.45	II, IIa	1, 4	PV Cep	20 45 53.9	+67 57 38	III, III	1, 2
HD 244604	05 31 57.25	+11 17 41.46	II, IIa	1, 4	V645 Cyg	21 39 58.24	+50 14 21.2	III, III	1, 2

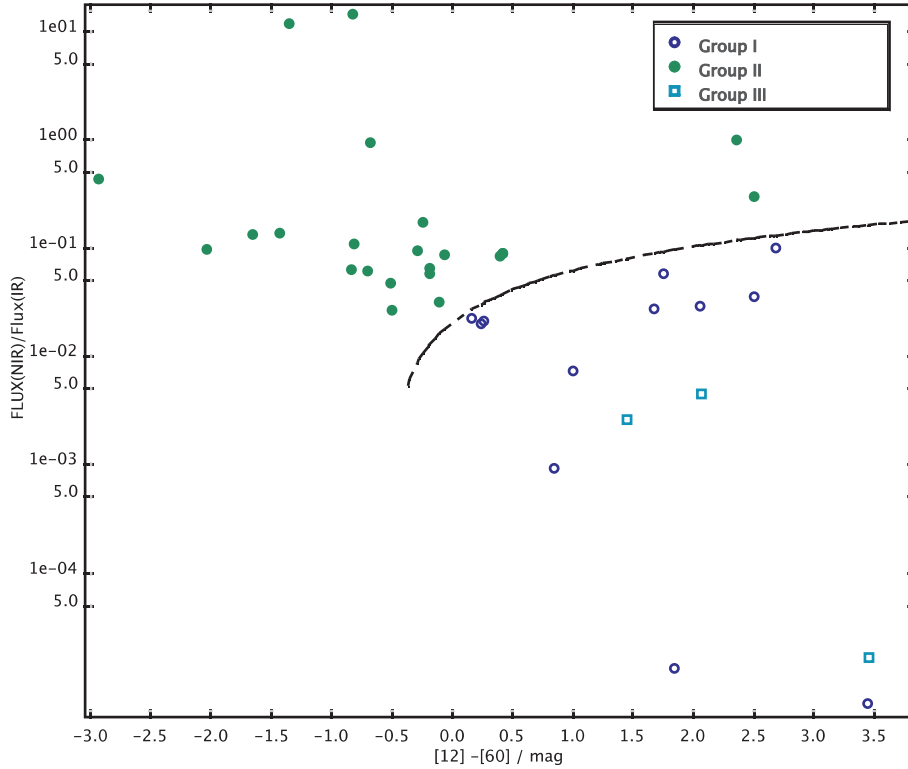


Fig. 2. The ratio of the near-infrared and infrared fluxes versus the IRAS [12]–[60] colour. Group I sources are plotted as open blue circles; group II, as filled green circles; and group III, as open cyan squares. The dashed curve indicates our division line between group II and groups I and III, $F_{\text{NIR}}/F_{\text{IR}} = 0.04([12] - [60]) + 0.02$.

In comparison, all three SED groups have [C II] 158 μm emission lines, from a sample of 54 Herbig Ae/Be stars with ISO Long Wave Spectrometer (LWS) spectra, with 8 sources having unclassified SEDs. The group II objects appear to have, on average, stronger [C II] 158 μm emission compared to the group I objects. Disk models by Pinte et al. (2010) show that the [C II] line originates from larger-radius and lower-density regions than the [O I] line and is very sensitive to the amount of ultraviolet radiation.

5. SUMMARY AND FINAL REMARKS

Using the ESA-VO tool VOSpec, a multi-wavelength spectral analysis tool, developed by the Science Archives and VO Team at the ESAC, new developments on scripting with VOSpec (VOScript), and other VO tools, we have started to undertake a comprehensive study of spectroscopic and photometric data in the VO on Herbig Ae/Be stars. The project is at an early stage and is linked with the development of VOScript, an exciting new development that will allow fast analysis of large numbers of spectra and targets.

Our initial SED classifications agree well with previous studies of Herbig Ae/Be

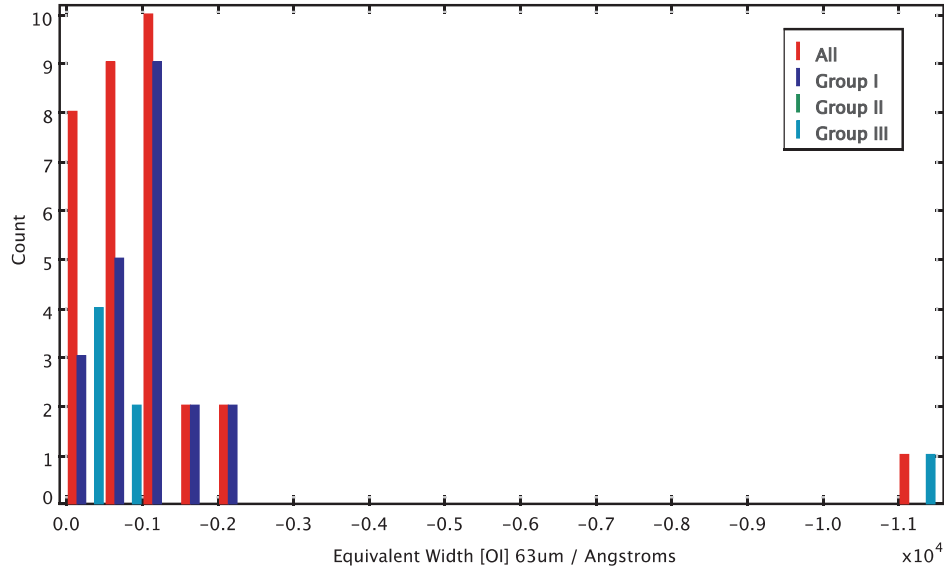


Fig. 3. Histogram of [O I] 63 μ m equivalent widths showing the SED groups: group I (blue), group II (green) and group III (cyan). The histogram for all sources is shown in red, four sources having unclassified SEDs (no IRAS or 2MASS photometry).

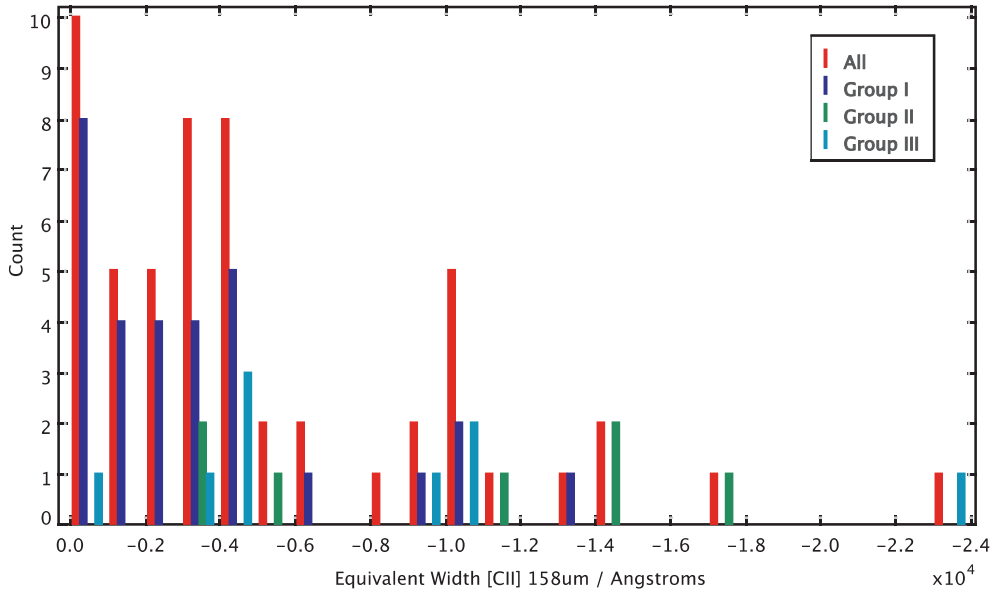


Fig. 4. Histogram of [C II] 158 μ m equivalent widths showing the SED groups: group I (blue), group II (green) and group III (cyan). The histogram for all sources is shown in red, eight sources having unclassified SEDs (no IRAS or 2MASS photometry).

stars (e.g. Meeus et al. 2001; Acke & van den Ancker 2004; Acke et al. 2005; Juhász et al. 2010), whilst the spectroscopic line analysis is showing promising results from the analysis of the [O I] 63 μm and [C II] 158 μm lines in the infrared. We continue to analyze all available spectra in the VO, from the ultraviolet to the infrared, and for as large a sample of Herbig Ae/Be stars as possible.

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