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Characterization of intermediate mass young stars from spectral energy distributions and Gaia EDR3.

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Abstract

Herbig Ae/Be objects (HAeBes) are young, intermediate-mass stars surrounded by protoplanetary disks. From the point of view of star and planet formation, these objects have crucial characteristics. First, their stellar parameters, such as mass or temperature, are between those belonging to the low-mass and high-mass regimes. Second, the presence of bright and large protoplanetary disks makes these stars excellent laboratories to learn how planets form. However, the relatively small amount of known HAeBes sharply contrasts with the large number of their low-mass counterparts. Furthermore, HAeBes have usually been studied on the basis of small samples scattered on the sky, and their stellar and circumstellar parameters have been derived using heterogeneous methodologies.
In this contribution I will show the work carried out by Guzmán-Díaz et al. (2021), who provided a homogeneous characterization of a sample of 209 HAeBes from their spectral energy distributions (SEDs) and Gaia EDR3 parallaxes. Using the online tool Virtual Observatory SED Analyzer (VOSA), multi-wavelength photometry of our objects was collected, and the stellar parameters were derived by fitting the optical SEDs with the best Kuruzc models. In addition, the infrared SEDs were classified according to two schemes, and the mass accretion rates, protoplanetary disks masses, and the sizes of dust inner cavities were uniformly estimated. Such a large amount of data allowed us to perform a statistical analysis searching for correlations between the stellar and circumstellar parameters. A major result is that the disk dissipation mechanism in B-type and A-type Herbig stars is most probably different. With the advent of new techniques and more powerful instrumentation, the number of known HAeBes is increasing. A homogeneous stellar and circumstellar characterization, such as the one presented here, will allow us to better understand the formation and evolution of Herbig Ae/Be stars.

1 Introduction

Herbig Ae/Be stars (HAeBes) are pre-main sequence, intermediate-mass objects that are surrounded by a circumstellar or protoplanetary disk. Their stellar masses range between 2 and 10 $M_{\odot}$. Such objects are the link between T Tauri stars, the low-mass counterparts of

HAeBes, and massive young stellar objects (MYSOs). Knowledge of the physical parameters (e.g., temperature or mass) of HAeBes will allow us to better understand the stellar evolution and to bridge the formation of low-mass objects with that of the more massive ones. HAeBes are also of interest in the field of planetary formation because they have bright and large protoplanetary disks. In contrast, this study is difficult for higher-mass stars because they evolve more rapidly from the embedded phase to the main sequence stage. However, only one candidate planet has been detected so far in the HAeBe star AB Aur (see [7, 30]), being PDS 70, a T Tauri star, the only pre-sequence object in which the presence of planets has been confirmed [15, 19]. Works such as those of [14] or [18], which have been carried out a study relating the stellar abundances observed in HAeBes to the possible presence of planets, in addition to others that have extended the known catalog of HAeBes [26, 27], may pave the way in the search for planets in this type of stars.

HAeBes have spectral types ranging from early B-types to late F-types. Nevertheless, these stars can be grouped into two groups: Herbig Ae stars (HAes), with stellar masses less than or equal to 4 $M_{\odot}$, and Herbig Be stars (HBes), with stellar masses larger than 4 $M_{\odot}$. One of the main differences between both groups is the accretion mechanism that takes place in them. In HAes, accretion is dominated by the magnetic field, as in T Tauri stars. The disk is truncated by the magnetic field and the ionized material from the disk flows along the magnetic field lines to the star, causing shocks on the stellar surface. This mechanism is called "magnetospheric accretion" (MA). In contrast, in HBes, these models are not able to explain the large accretion rates observed in this group of stars. Other mechanisms have been proposed in HBes, one of which is known as "boundary layer", where the star accretes material directly from the disk (see [22] or [28] for more information on accretion mechanisms in HAeBes).

In the next two sections I will discuss in a brief way the evolution of protoplanetary disks and their classification from the spectral energy distributions (SEDs), as well as the work carried out by [13], where a homogeneous characterization of a large sample of HAeBes has been performed from the SEDs and the Gaia EDR3 data [10].

2 Protoplanetary disks

The formation of protoplanetary disks is a common process that occurs as a consequence of the conservation of angular momentum at a stage almost immediately after the collapse of a molecular core. They can be observed directly from the (sub-)millimeter emission of the dust grains (see, e.g., [2]), or from the scattered light by such grains in the near-infrared (near-IR) range [11]. Telescopes as ALMA or VLT allow us to take high resolution images, being able to appreciate how the dust grains are distributed, and identifying structures such as rings, spirals or cavities. Protoplanetary disks are also possible to detect in an indirect way, either from the gas emission lines (one of the most used to trace the gas are those of the carbon monoxide molecule, see [16]), or from the excess in the IR observed in the SEDs [13]. Regarding the latter, the SED of HD 139614 can be seen in Fig. 1 as an example.

The disk lifetime is around 2-3 Myr for T Tauri stars, although this can range from 1 to 10

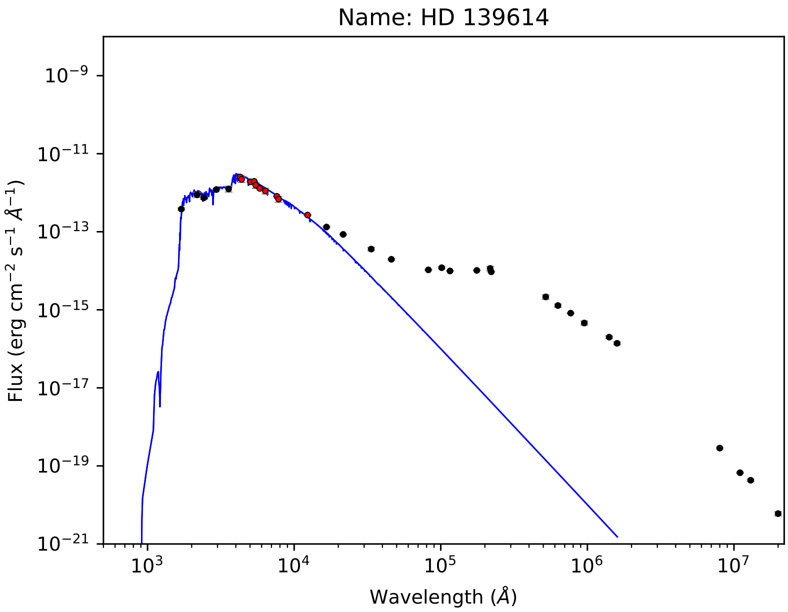

Figure 1: SED of HD 139614. The solid blue line corresponds to the best photospheric model that fits the optical photometry (red dots). On the other hand, black dots refer to the disk emission.

Myr (see [29]). In the case of more massive stars, the disks dissipate faster than in solar-type stars [29]. In their initial state, the disks are dominated by viscous evolution. Material from the inner part of the disk is accreted by the star whereas the outer part spreads as angular momentum is transported outward. At some point, the disk material starts to disperse from inside to outside by different mechanisms [9] that will dominate against the viscous evolution, and which are mentioned next: i) grain growth, which causes the decrease of small particles in the innermost regions; ii) ultraviolet and X-ray photoevaporative winds; iii) the presence of companions that sweep the material into their orbits. As a consequence of these processes, an inner cavity is formed. Protoplanetary disks with such cavities are known as transitional disks, which can be inferred from the SEDs. As an example, Fig. 2 shows the SED of HD 199603, where the presence of a cavity is deduced as there is no emission from the disk below 10 μm. Finally, the remnant of the transitional disks are called debris disks. These disks have low luminosities, with lack of gas and they contain large bodies.

The shapes of the SEDs can provide some hints on the evolution of protoplanetary disks. In particular, I will discuss two schemes used to classify the SEDs. The first one was proposed by [23], where the SEDs are classified into two groups: Group I and group II, which differ mainly in the mid-IR emission. The authors found that in group II SEDs the continuum from the IR to the submillimeter region could be only fit by a power-law component, whereas in group I SEDs an additional blackbody component had to be added. Such a classification has been related to the morphology of the protoplanetary disks, where group I and group

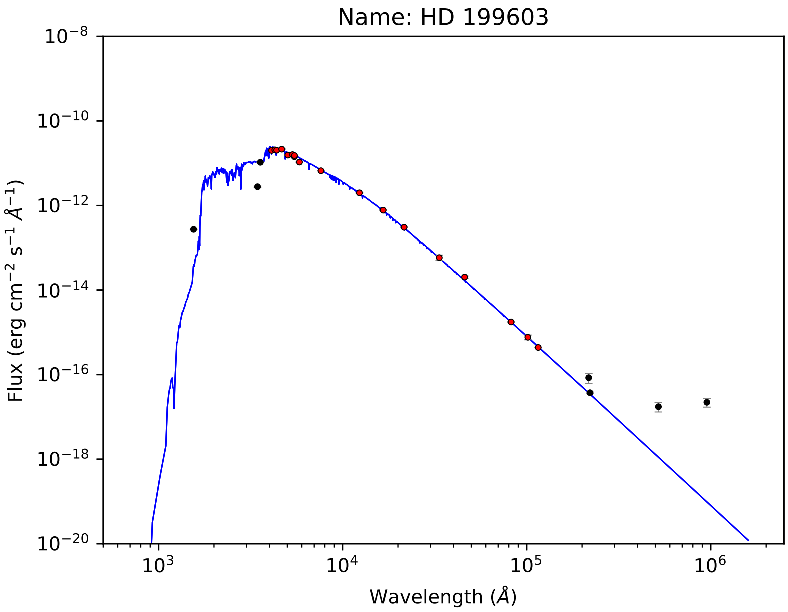

Figure 2: SED of HD 199603. The effect of a cavity can be observed as there is no emission in the near-IR range.

II sources are associated with "flared" and "flattened" disks, respectively. An evolutionary path from group I to group II disks has traditionally been proposed due to the grain growth and the settling of such grains in the midplane of the disk [1]. Nevertheless, a more complex scenario has arisen because recent high-resolution images have revealed that most of the disks belonging to group I show cavities (see, e.g., [11, 17]).

The second scheme is based on the wavelength at which the IR excess observed in SEDs begins (see [13, 21]). In this scheme the SEDs are also classified into two groups, one in which the excess starts at J or H bands (e.g., Fig. 1), and another in which such excess starts at K band or at longer wavelengths (e.g., Fig. 2). This type of classification is directly related to the size of the inner dust cavities.

3 Homogeneous characterization of HAeBes

This section is devoted to briefly describe the research carried out in our work [13]. One of the main reasons that motivated this study lay in the fact that, before the launch of Gaia, HAeBes were studied in small samples scattered on the sky, which contrasted with the hundreds of known T Tauri stars at that time. Furthermore, their stellar and circumstellar parameters were derived using different techniques. Therefore, departing from the sample presented in [25], we have homogeneously characterized a sample of 209 bonafide HAeBes from their SEDs and their Gaia EDR3 parallaxes [20]. The stellar parameters were estimated using the online tool VOSA (Virtual Observatory SED Analyzer) [3]. VOSA allows us to compare the optical observed SEDs, built from the catalogs available in such a tool, with the synthetic photometry from the photospheric theoretical models. The effective temperatures, visual extinctions, stellar luminosities and radii were obtained from the best-fitting Kurucz model [6], whereas stellar masses and ages were estimated from the PARSEC V2.1s evolutionary tracks and isochrones of [5].

The IR SED were classified according to the two schemes shown in Section 2. Firstly, the ratio between the near-IR and the mid-IR luminosity, and the non-color-corrected IRAS color were used in order to classify them into Meeus groups I and II (see the procedure following [1] and [24]). Secondly, the SEDs fits with VOSA were helpful with the classification into JHK groups, showing at which photometric point the IR excess starts or, equivalently, when the best Kurucz model obtained no longer fits the observed SED.

We also provide in our work circumstellar parameters such as mass accretion rates, disk masses and sizes of the inner dust cavities. The accretion rates were estimated from the correlations between the stellar luminosity and accretion luminosity quantified in [28], which depend on the stellar mass. The disk masses were calculated from the continuum (sub-)millimeter fluxes, assuming that the emission at this wavelength range is optically thin and the gas-to-dust ratio is equal to 100 [4]. However, several studies point out that the disk masses derived from this method could be underestimated. Thus, we used as well an alternative procedure to infer this parameter based on knowledge of the mass accretion rate and stellar age (see, e.g, [8, 21]). Finally, the sizes of the dust inner cavities have been known from the SEDs, depending on the wavelength at which the IR excess starts.

All stellar and circumstellar parameters of our 209 HAeBes are collected in an online archive called HArchiBe. This also includes the figures of the SEDs and a tool for visualizing the position of the objects on the sky. Recently, 109 new HAeBes have been added to this archive, which have been discovered and characterized by [26, 27].

Afterwards, we performed a statistical study relating the stellar and circumstellar parameters with both SED classifications, in order to find some hints on the evolution of protoplanetary disks. One of the major results we have obtained is described as follows. We found that the main mechanism driving the dissipation of the disks in HBes is probably photoevaporation, although other processes can not be ruled out, such as the presence of planets. Figure 3 shows two evidence that support this idea. In the top panel, the size of the inner dust cavities and the stellar mass are represent on the y- and x-axis, respectively. The blue dashed line indicates the critical radius. This parameter denotes the distance at which a cavity starts to open due to photoevaporation [12]. It can be observed that there are more HBes with sizes of the inner dust cavities above this line. On the other hand, the stellar age vs. the stellar mass is plotted in the bottom panel. The blue dashed line indicates in this case the disk lifetime if the photoevaporation is considered as the main mechanism involved in disk dissipation [12]. As you can see, most HBes have stellar ages below this line, whereas HAes are older, pointing out that there must be another mechanism governing the disk dissipation for the latter.

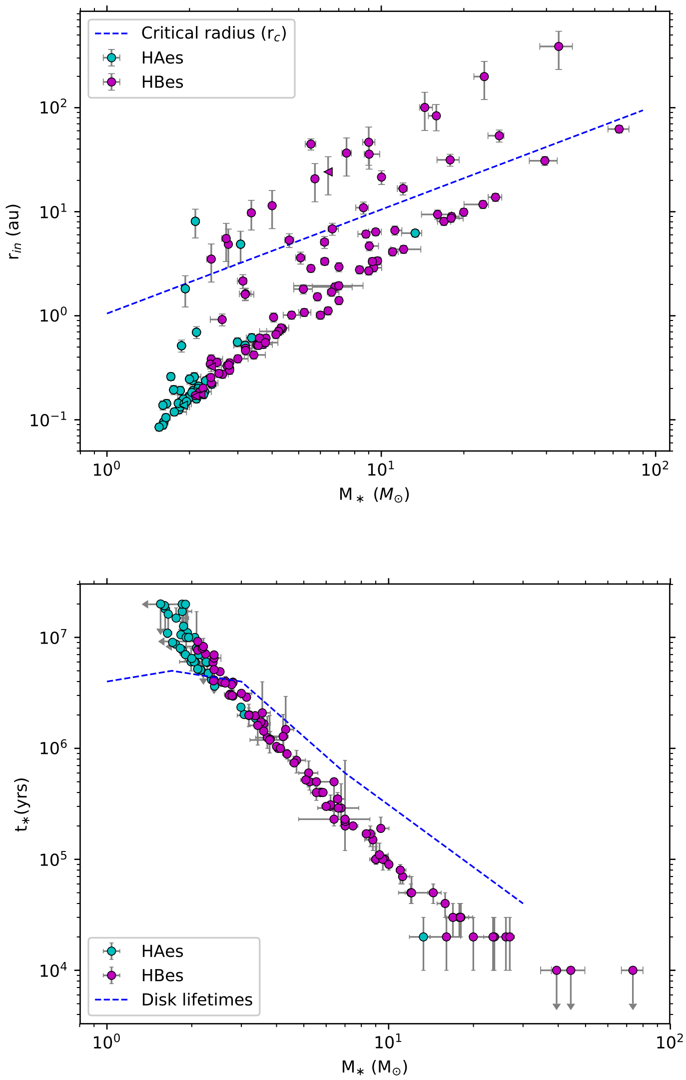

Figure 3: **Top panel:** Inner disk cavities as a function of the stellar mass for HAes and HBes. The dashed blue line represents the critical radius above which the stars are consistent with the photoevaporation scenario. Upper limits are indicated by arrows. **Bottom panel:** Stellar age vs. stellar mass for HAes and HBes. The dashed blue line represents the disk lifetime below which the stars are consistent with the photoevaporation scenario. Upper limits are indicated by arrows.

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References

[1] Acke, B., van den Ancker, M. E., Dullemond, C. P., van Boekel, R., & Waters, L. B. F. M. 2004, A&A, 422, 62

[2] Andrews, S. M., Huang, J., Pérez, L. M., et al. 2018, The Messenger, 174, 19

[3] Bayo, A., Rodrigo, C., Barrado Y Navascués, D., et al. 2008, A&A, 492, 2

[4] Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, AJ, 99, 924

[5] Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127

[6] Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 318, 841

[7] Currie, T., Lawson, K., Schneider, G., et al. 2022, Nature Astronomy, 6, 751

[8] Dong, R., Najita, J. R., & Brittain, S. 2018, ApJ, 862, 103

[9] Espaillat, C., Muzerolle, J., Najita, J., et al. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 497

[10] Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2022, arXiv e-prints, arXiv:2208.00211

[11] Garufi, A., Meeus, G., Benisty, M., et al. 2017, A&A, 603, A21

[12] Gorti, U., Dullemond, C. P., & Hollenbach, D. 2009, ApJ, 705, 1237

[13] Guzmán-Díaz, J., Mendigutía, I., Montesinos, B., et al. 2021, A&A, 650, A182

[14] Guzman-Diaz, J., Montesinos, B., Mendigutia, I., et al. 2022, arXiv e-prints arXiv:2212.14022

[15] Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, Nature Astronomy, 3, 749

[16] Hein Bertelsen, R. P., Kamp, I., Goto, M., et al. 2014, A&A, 561, A102

[17] Honda, M., Maaskant, K., Okamoto, Y. K., et al. 2015, ApJ, 804, 143

[18] Kama, M., Folsom, C. P., & Pinilla, P. 2015, A&A, 582, L10

[19] Keppler, M., Benisty, M., Müller, A., et al. 2018, A&A, 617, A44

[20] Lindegren L. et al., 2021, A&A, 649, A2

[21] Mendigutía, I., Mora, A., Montesinos, B., et al. 2012, A&A, 543, A59

[22] Mendigutía, I. 2020, Galaxies, 8, 39

[23] Meeus, G., Waters, L. B. F. M., Bouwman, J., et al. 2001, A&A, 365, 476

[24] van Boekel, R., Waters, L. B. F. M., Dominik, C., et al. 2003, A&A, 400, L21

[25] Vioque, M., Oudmaijer, R. D., Baines, D., Mendigutía, I., & Pérez-Martínez, R. 2018, A&A, 620, A128

[26] Vioque, M., Oudmaijer, R. D., Schreiner, M., et al. 2020, A&A, 638, A2

[27] Vioque, M., Oudmaijer, R. D., Wichittanakom, C., et al. 2022, ApJ, 930, 39

[28] Wichittanakom, C., Oudmaijer, R. D., Fairlamb, J. R., et al. 2020, MNRAS, 493, 234

[29] Williams J. P., Cieza L. A., 2011, ARA&A, 49, 67

[30] Zhou, Y., Sanghi, A., Bowler, B. P., et al. 2022, ApJ, 934, L13