Characterizing brown dwarf companions with IRDIS long-slit spectroscopy: HD 1160 B and HD 19467 B

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ABSTRACT
The determination of the fundamental properties (mass, separation, age, gravity, and atmospheric properties) of brown dwarf companions allows us to infer crucial informations on their formation and evolution mechanisms. Spectroscopy of substellar companions is available to date only for a limited number of objects (and mostly at very low resolution, \( R < 50 \)) because of technical limitations, i.e. contrast and angular resolution. We present medium resolution \( (R = 350) \), coronagraphic long-slit spectroscopic observations with SPHERE of two substellar companions, HD 1160 B and HD 19467 B. We found that HD 1160 B has a peculiar spectrum that cannot be fitted by spectra in current spectral libraries. A good fit is possible only considering separately the \( Y+J \) and the \( H \) spectral band. The spectral type is between M5 and M7. We also estimated a \( T_{\text{eff}} \) of 2800–2900 K and a log \( g \) of 3.5–4.0 dex. The low surface gravity seems to favour young age (10–20 Myr) and low mass (\( \sim 20 \) MJup) for this object. HD 19467 B is instead a fully evolved object with a \( T_{\text{eff}} \) of \( \sim 1000 \) K and log \( g \) of \( \sim 5.0 \) dex. Its spectral type is T6 ± 1.

Key words: instrumentation: spectrographs – methods: data analysis – techniques: imaging spectroscopy – infrared: planetary systems.

1 INTRODUCTION
Brown dwarfs (BDs) are low-mass objects populating the mass range between stars and planets. First theorized by Kumar (1963) and Hayashi & Nakano (1963), it was not until 1995 that the first unquestionable evidence of their existence was provided (Nakajima et al. 1995; Rebolo, Zapatero Osorio & Martín 1995). Because of their low mass, these objects are not capable to sustain hydrogen burning in their cores and they continuously cool down during their lifetime (Baraffe et al. 2003). The distinction between BDs and planets is conventionally set at the minimum mass for which deuterium (D) can fuse into \(^3\text{He} \) nuclei. This value has been defined as the mass of objects able to burn the 90 per cent of their initial D in 10 Gyr and it was found to range from 13.1 to 12.4 MJup, for cloudless and cloudy models, respectively (Saumon & Marley 2008). Furthermore, Spiegel, Burrows & Milsom (2011) found that this value is valid for objects at solar metallicity, while it varies from 11.0 MJup for a metallicity three times the solar value to 16.3 MJup for zero metallicity.

An alternative approach to distinguish between planets and BDs is through their formation mechanism. The detection of substellar objects in young stellar clusters (e.g. De Marchi, Paresce & Portegies Zwart 2010) and the fact that collapse formation scenarios foresee that the minimum fragment masses are well extended in the substellar regime (e.g. Vázquez-Semadeni et al. 2019) are clear hints that the formation through the fragmentation of molecular clouds is possible also for this type of objects. Alternatively, they could form following planet-like mechanisms like the gravitational instability (Cameron 1978) into protoplanetary discs. It is nowadays

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recognized that these two formation mechanisms overlap on mass ranges of few Jupiter masses (Kiefer et al. 2019).

To clarify the nature of these objects, studies both in the visible (Cruz, Kirkpatrick & Burgasser 2009) and in the near-infrared (NIR; e.g. Allers et al. 2010; Seeliger, Neuhauser & Eisenbeiss 2011; Allers & Liu 2013; Martin et al. 2017) were performed on field BDs. Observing these objects in the NIR is very important because a large fraction of the flux emitted by L and T dwarfs is at wavelengths ranging between 1 and 2.5 μm. In addition, the NIR spectrum of these objects contains a wealth of spectral features ranging from narrow atomic lines to broad molecular bands that have different dependencies on their temperature, gravity, and metallicity (Kirkpatrick 2005).

In recent years, new high-contrast imaging instruments like NACO (Lenzen et al. 2003), GPI (Macintosh et al. 2014), NICI (Chun et al. 2008), NIRI (Hodapp et al. 2003), NIRC2 (e.g. Mawet et al. 2017), and SPHERE (Beuzit et al. 2019) allowed to detect several BDs companions of main-sequence or pre-main-sequence stars (see e.g. Mawet et al. 2015; Konopacky et al. 2016; Milli et al. 2017; Cheetham et al. 2018). The possibility to study the spectral characteristics of these BD companions can provide additional, complementary information to observations of isolated, field BDs. Currently, only a handful of BD companions has been spectroscopically investigated exploiting the limited resolution (R ~ 30–50) of integral-field spectrograph such as SPHERE and GPI. Some examples include HR 2562 B (Konopacky et al. 2016; Mesa et al. 2018), HD 984 B (Johnson-Groh et al. 2017), HD 1160 B (Maire et al. 2016; Garcia et al. 2017), HD 206893 B (Delorme et al. 2017), HD 4747 B (Crepp et al. 2018; Peretti et al. 2019), and HD 13724 B (Rickman et al. 2020). In only five more cases, it was possible to obtain a spectrum with a larger resolution (R = 350), using the SPHERE long-slit spectroscopy (LSS; Vigan et al. 2008) observing mode. This has been done for 2MASS J01225093−2439505 B (Hinkley et al. 2015), PZ Tel B (Maire et al. 2016), HR 3549 B (Mesa et al. 2016), HD 284149 B (Bonavita et al. 2017), and HIP 64892 B (Cheetham et al. 2018). Moreover, spectra in the NIR for companions at large separation from the host star were obtained at medium resolution (1500–2000) with SINFONI (e.g. Bonnefoy et al. 2014).

In this paper, we expand upon the current sample and we focus on two substellar objects orbiting the nearby stars HD 1160 and HD 19467. These systems are described in detail in Section 2. Furthermore, we present in Section 3 our data and the data reduction procedure adopted. In Section 4, we then present and discuss our main results. Finally, in Section 5 we give our conclusions.

2 TARGET PROPERTIES

HD 1160 is an A0V (Houk & Smith-Moore 1988) star at a distance of 125.9 ± 1.2 pc (Gaia Collaboration 2018). Around this star, Nielsen et al. (2012) detected two companions, HD 1160 B and HD 1160 C at separations of ~80 and 530 au, respectively, using NICI at the Gemini telescope. They found a spectral type of L0 for HD 1160 B and a spectral type of M3.5 for HD 1160 C. They were also able to determine a mass in the range between 24 and 45 M_jup in the BDs regime, for the former and in the range between 0.18 and 0.25 M_Jup in the stellar regime, for the latter assuming an age between 10 and 100 Myr.

HD 1160 was also observed with SPHERE in IRDIS_EXT mode obtaining a low-resolution (R = 30) spectrum of HD 1160 B in the NIR between 0.95 and 1.65 μm (Maire et al. 2016). This allowed to re-classify its spectral type as M6 and to derive a T_eff of 3000 ± 100 K and a subsolar metallicity. However, they could not provide constraints on the surface gravity. They assumed a wider range for the age (30–300 Myr) resulting in masses between 39 and 165 M_Jup.

More recently, this system was studied through SCExAO and GPI by Garcia et al. (2017). They found for HD 1160 B T_eff = 3000–3100 K and log g = 4–4.5 dex, in agreement with the relatively young age of the system. Differently from Maire et al. (2016), they did not find evidence of subsolar metallicity, as expected according to standard Galactic chemical evolution models and observations (see e.g. Bensby, Feltzing & Oey 2014; Spina et al. 2017, and references therein). The authors also clearly stressed that the main uncertainty on the mass determination for this object is due to the estimation of the age of the system (for ages between 80 and 125 Myr, the mass of this object can vary from the BD regime to hydrogen-burning limit).

Recently, Curtis et al. (2019) assigned HD 1160 as a member of the recently discovered Pisces–Eridanus (Psc–Eri) stellar stream (Meingast, Alves & Fürrkenr 2019) exploiting kinematics. They also defined for the stream an age of 120 Myr, in fair agreement with the estimate of 135 Myr later found by Röser & Schilbach (2020). Should the membership of HD 1160 to the Psc-Eri stream be confirmed, the mass of HD 1160 B would be of the order of 0.12 M_Jup, well into the stellar mass range (Curtis et al. 2019).

HD 19467 is a G3 (Houk & Smith-Moore 1988) star at a distance of 32.02 ± 0.04 pc (Gaia Collaboration 2018). Using NIRC2 high-contrast imaging and HIRES radial velocity (RV) data, Crepp et al. (2014) detected a companion at a separation larger than 1.6 arcsec. Combining Doppler observations and imaging, they estimated a minimum mass just above 50 M_Jup for the companion. Moreover, they estimated an age of 4.3 Gyr through gyrochronology while isochrones provided an older age of 9 ± 1 Gyr. By adopting these ages and using K_s photometry, Crepp et al. (2014) obtained companion masses of 56.7 and 67.4 M_Jup, respectively. Finally, from the measured colours they inferred a T5–T7 spectral type.

HD 19467 was also observed using the Project 1640 instrument at the Palomar Observatory by Crepp et al. (2015). They extracted a low-resolution (R ~ 30) spectrum of HD 19467 B that allowed to define a spectral type of T5.5 ± 1 and a T_eff of 980 K. Recently, Wood et al. (2019) estimated, through isochronal models, an age of 10.06 +1.16 −0.62 Gyr for HD 19467, and found a mass of 67–69 M_Jup for HD 19467 B. Very recently, Maire et al. (2020) presented a thorough investigation of the host star properties and found for the system an age of 8.0 +0.9 −0.8 Gyr. We will then assume in our work this age estimation for consistency with that paper.

3 OBSERVATIONS AND DATA REDUCTION

We observed HD 1160 and HD 19467 with the SPHERE IRDIS (Dohlen et al. 2008) scientific subsystem operating in the LSS medium resolution (MRS) observing mode. This mode allows to obtain spectra with a resolution of R ~ 350 covering the Y, J, and H spectral bands simultaneously for companions with contrasts of the order of 10^−5 to 10^−6 at separations larger than 0.5 arcsec.

We observed HD 1160 in the night of 2018 August 20 and HD 19467 in the night of 2019 January 26. Both these observations were obtained in service mode. In Table 1, we report the main informations regarding the two observing nights. In both nights, seeing and coherence time were stable along all the observations resulting in a stable Strehl ratio with values above 80 per cent. In the same table, we also listed the number of datacubes obtained for each observation together with the number of frames obtained.
for each datacube and the exposure time for each frame. The total observing time on the target was of 24 min for HD 1160 and around 30 min for HD 19467. In both cases, we alternated observations with the slit on the position of the companion and observations with the slit rotated outside the position of the companion. This observing technique was first proposed for the case of the SPHERE LSS observing mode in Vigan et al. (2016b) and its aim is to use the data with the slit outside the companion to create a reliable model of the speckle pattern to be subtracted from the data with the slit on the companion. All the data (i.e. with/without the companion into the slit) were taken with the host star behind the coronagraph.

Table 1. Characteristics of the SPHERE observations presented in this work. In column 1 we list the observing night, in column 2 we list the target name, and in column 3 we report the coronagraph used. In columns 4 and 5, we list the number of datacubes, the number of frames for each datacube, and the exposure time expressed in s for each frame for observation with the slit on (labelled Obs. comp.) and outside the companion position (labelled Obs. no comp.). In columns 6, 7, and 8, we report the median values of seeing, coherence time, and wind speed during the observations.

| Date      | Target | Coronagraph | Obs. comp. | Obs. no comp. | $S$ (arcsec) | $\tau_0$ (ms) | Wind (m s$^{-1}$) |
|-----------|--------|-------------|------------|---------------|-------------|---------------|-----------------|
| 2018-08-20| HD 1160| N_S_MR_WL   | 5 x 9:32   | 5 x 8:32      | 0.49        | 4.6           | 11.10           |
| 2019-01-26| HD 19467| N_S_MR_WL | 5 x 11:32  | 5 x 10:32     | 0.47        | 17.4          | 2.13            |

We prepared a custom Python-based pipeline to reduce these data (detailed information will be provided in a forthcoming publication; Mesa et al., in preparation). As first step, master dark, bad pixels map, and master detector flat are produced. We then create the wavelength calibration file. The scientific data with the companion in the slit and those with the companion outside the slit are then reduced separately applying the appropriate calibrations and finely registering each frame. We also corrected a known problem of the PSF at different wavelengths. The reduced wavelength calibration file. The scientific data with the companion in the slit and those with the companion outside the slit are then reduced separately applying the appropriate calibrations and finely registering each frame. We also corrected a known problem of the PSF at different wavelengths. The reduced data without the companion were then used to create a model of the speckle pattern using a procedure based on the principal components analysis (PCA; Soummer, Pueyo & Larkin 2012). This model was then subtracted from each frame of the data set with the companion into the slit to effectively subtract the speckle pattern from them and to improve the signal to noise ratio (SNR) of the extracted spectrum that is composed by 780 wavelengths ranging between 0.94 and 1.82 μm. For the spectral extraction, we used a fixed extraction window following the method devised in Bonavita et al. (2017). The uncertainties on the extracted spectrum were obtained calculating the standard deviation on a window defined in the same way of that used for the spectrum extraction. Moreover, this window was at the same separation of the companion but on the opposite side with respect to the host star. We extracted also the spectra of the host star and of the standard star following the same method used for the companion. We then finely recalibrated the wavelengths of the companion and of the host star spectra using as reference the positions of the telluric lines found in the standard star. Finally, we obtained the spectrum of the companion in contrast dividing it by the spectrum of the host star.

With the aim to check the reliability of our results, we also reduce our data using the SILSS pipeline (Vigan 2016) that is purposely designed to reduce SPHERE LSS data sets. Both for HD 1160 and for HD 19467, the extracted spectra with the two pipelines were in good agreement confirming the reliability of our results. To quantify the agreement between the two methods, we calculated the differences between the two spectra and we verified that, for each wavelength, this is smaller than the uncertainties.

4 RESULTS AND DISCUSSION

4.1 HD 1160 B

The contrast spectrum of the companion extracted following the method described in Section 3 is transformed in flux multiplying it for an appropriate BT-NEXTGEN (Allard, Homeier & Freytag 2012) theoretical spectrum, following a standard procedure previously used in other works of our group (e.g. Maire et al. 2016; Vigan et al. 2016a; Zurlo et al. 2016; Bonavita et al. 2017; Mesa et al. 2018). To identify the appropriate model spectrum, we used the VOSA SED analyser$^1$ (Bayo et al. 2008) to find the model with the best fit with the stellar spectral energy distribution (SED). At the end of this procedure, we selected a model with $T_{\text{eff}} = 9200$ K, surface gravity $\log g = 4.5$ dex, and solar metallicity.

The spectrum resulting from this procedure was very noisy for the lower and for the higher wavelengths and for this reason we excluded all the wavelengths below 0.97 μm and above 1.80 μm. Furthermore, we excluded also all the wavelengths in the spectral region around 1.4 μm that are affected by the presence of water telluric absorption. At the end of this procedure, we remained with a spectrum composed of 658 data points that is shown in Fig. 1. From the extracted spectrum, we obtained the photometric values for $Y$ (wavelengths below 1.15 μm), $J$ (wavelengths between 1.15 and 1.4 μm), and $H$ (wavelengths above 1.4 μm) spectral bands that are listed in the second column of Table 2. Thanks to these values and exploiting the BT-Settl models (Allard 2014), we estimated the mass of the companion. To this aim, we adopted both a young system age of 50+50−40 Myr as proposed by Nielsen et al. (2012) and the older age of ∼120 Myr proposed by Curtis et al. (2019). In this second case, as an error on the age was not given by Curtis et al. (2019), we considered an uncertainty of 15 Myr using also the age determination from Röser & Schilbach (2020) for the Psc-Eri stellar stream. The results of this procedure are listed in the second and the third column of Table 3. In the first case (i.e. young age), the uncertainties on the mass are very large mainly due to the large uncertainties on the system age, so that masses encompass the low-mass brown dwarfs/stellar regime. As for the old age, the

$^1$http://svo2.cab.inta-csic.es/theory/osa/

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of the fitting template spectra both for the $Y+J$ bands and the $H$ band. As highlighted by the two vertical lines, it is apparent that the two distributions have two different minimum at $\sim$M7 and $\sim$M5, respectively. While this difference is not large, it is however an indication that HD 1160 B has a peculiar spectrum.

An alternative way to classify the spectral type of this substellar object is to use spectral indices. To this aim, we have used the indices described in Allers & Liu (2013) that are fitted to the wavelength band of our observations. It is important to stress that these indices were thought for spectra at resolution slightly higher ($\sim$700) than that used in our analysis. While these results should be then taken with care, they can however give a good indication of the spectral type of HD 1160 B. In particular, we used the $\text{H}_2\text{O}$ index (Allers et al. 2007) that is effective for spectral types between M5 and L4 with an rms of 0.390 in spectral type and the $\text{H}_2\text{O} - 1$ index (Slesnick, Hillenbrand & Carpenter 2004) that is effective for spectral types between M4 and L5 but with a larger rms of 1.097. The $\text{H}_2\text{O}$ index, that is based on $H$-band wavelengths gives a spectral index of M4.8 while the $\text{H}_2\text{O}$ index, that based on $J$-band wavelengths gives a later spectral type of M6.

These results confirm what we found with the fit with spectral templates and are a further indication of the peculiarity of the spectrum of HD 1160 B. The reasons of this peculiarity are not completely clear but we can do the hypothesis that it could be due to the presence of dust in its photosphere or to its young age (few tens of Myr). The second possibility would imply a still not fully evolved object explaining its peculiar spectrum. The presence of dust is in conflict with the high $T_{\text{eff}}$ found for this object while the young age is in disagreement with the age of $\sim$120 Myr for the HD 1160 system proposed by Curtis et al. (2019).

With the aim to better define the physical characteristics of HD 1160 B, we also fitted the extracted spectrum to a grid of BT-Settl atmospheric models (Allard 2014) with a $T_{\text{eff}}$ ranging between 900 and 4000 K with a step of 100 K, with $\log g$ ranging between 0.0 and 6.0 dex and a solar metallicity following what previously found for this object by Garcia et al. (2017). The results of this procedure are displayed in Fig. 4 where the extracted spectrum of HD 1160 B is compared with the three best-fitting models. The best fit is obtained for a model with a $T_{\text{eff}}$ of 2800 K and a surface gravity of $\log g = 3.5$ dex but comparably good fits are obtained for $T_{\text{eff}}$ of 2900 K and a surface gravity of 3.5–4.0 dex. From this analysis we conclude that HD 1160 B has $T_{\text{eff}} = 2800$–2900 K and $\log g = 3.5$–4.0 dex. This $T_{\text{eff}}$ is in good agreement with the spectral classification of M7 found through the comparison with the $Y+J$-band spectral templates (Pecaut & Mamajek 2016).

Like for the case of the fit with the template spectra, we note that it is not possible to obtain a completely satisfactory fit between the extracted spectrum and the atmospheric models. This is a further indication that the spectrum of HD 1160 B is peculiar and that its classification is difficult. Also in this case, possible explanations are the presence of dust and/or the youth of the system.

To further constrain the gravity of HD 1160 B, we considered the alkali lines ($\text{Na I}$ at 1.14 $\mu$m and $\text{K I}$ doublets at $\sim$1.17 and $\sim$1.25 $\mu$m) that, for a given $T_{\text{eff}}$, tend to become weaker at lower gravity (e.g. Gorlova et al. 2003; Cushing, Rayner & Vacca 2005). To this aim we have fitted the $J$-band (between 1.10 and 1.30 $\mu$m) spectrum of HD 1160 B with the atmospheric models with a fixed $T_{\text{eff}}$ of 2800 K. In Fig. 5, we show how the value of $\chi^2$ varies with $\log g$. The best fit is obtained for $\log g$ of 3.5–4.0 dex confirming what we found with the fit on the whole spectrum and with different $T_{\text{eff}}$.

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**Table 2.** Absolute magnitude in $Y$, $J$, and $H$ bands for HD 1160 (second column) and HD 19467 (third column).

| Sp. band | Abs. mag. (HD 1160) | Abs. mag. (HD 19467) |
|----------|---------------------|----------------------|
| $Y$      | 9.92 ± 0.01         | 16.39 ± 0.07         |
| $J$      | 9.37 ± 0.01         | 15.13 ± 0.07         |
| $H$      | 9.01 ± 0.01         | 15.84 ± 0.08         |

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https://jgagneastro.com/the-montreal-spectral-library/
Table 3. Mass estimates in $Y$, $J$, and $H$ bands for HD 1160 B considering the younger ages proposed by Nielsen et al. (2012) (second column – labelled as YA in the Table), for HD 1160 B considering the older age proposed by Curtis et al. (2019) (third column – labelled as OA in the table) and HD 19467 (fourth column).

| Sp. band | Mass (HD 1160 B – YA) $(M_{\text{Jup}})$ | Mass (HD 1160 B – OA) $(M_{\text{Jup}})$ | Mass (HD 19467 B) $(M_{\text{Jup}})$ |
|----------|---------------------------------|---------------------------------|---------------------------------|
| $Y$      | $70.3^{+27.5}_{-47.2}$          | $106.0^{+6.1}_{-6.4}$          | $64.1^{+2.0}_{-2.4}$           |
| $J$      | $70.4^{+28.0}_{-49.4}$          | $107.5^{+5.7}_{-7.1}$          | $66.4^{+3.1}_{-1.9}$           |
| $H$      | $62.8^{+25.2}_{-42.6}$          | $96.2^{+4.8}_{-6.3}$           | $62.2^{+2.5}_{-3.5}$           |

Furthermore, we tested the gravity sensitive spectral index linked to the Na I line at 1.14 $\mu$m defined in Allers et al. (2007) for spectra with a resolution of the order of 300 similar to that of our data. We obtained for this index a value of 1.08 that indicates low gravity. This index is however reliable only for spectral types later than M6 so that our target is at the edge of the validity range of this index. We also calculated the KIJ index defined in Allers & Liu (2013) obtaining a value of 1.032 that is coherent with an intermediate value for the surface gravity. From all these results, we can then conclude that HD 1160 B is an intermediate gravity object with a log $g$ of 3.5–4.0 dex.

Also, in this case, our results are not in agreement with an age of the system of the order of 120 Myr and a mass of 0.1 $M_{\odot}$ as proposed by Curtis et al. (2019). Indeed, according to the BT-Settl models, an object with such mass and age would require a log $g$ of the order of 5.0 dex. To match the values of log $g$ deduced from our analysis, we would instead need an object at the younger end (10–20 Myr) of the age range proposed by Nielsen et al. (2012) and as a consequence, the lower mass in the range calculated in Table 3 (around 20 $M_{\text{Jup}}$). Using the wide-band photometry listed in Table 2 we produced, following the procedure described in Bonnefoy et al. (2018), the
Figure 6. Absolute $J$ magnitude versus $J-H$ colour–magnitude diagram with the position of HD 1160 B that is indicated by a green asterisk. The positions of field M, L, and T dwarfs are also represented in different colours according to the spectral type. Black asterisk represents the positions of other substellar companions.

Figure 7. Extracted spectrum for HD 19467 B using the method described in Section 4.2.

4.2 HD 19467 B

Following the same procedure used for HD 1160 B, we transformed the contrast spectrum of HD 19467 B into the flux spectrum displayed in Fig. 7. In this case, the BT-Nextgen synthetic model with the best fit to the stellar SED and used for this procedure was that with $T_{\text{eff}} = 5600$ K, a surface gravity with $\log g = 4.5$ dex and solar metallicity. As for HD 1160 B, we also used the extracted spectrum to calculate the absolute magnitude and to estimate the mass of the companion. To this aim we adopted the system age of $8.0^{+2.0}_{-1.0}$ Gyr as mentioned in Section 2. Because the magnitude of HD 19467 B is outside the range covered by the BT-Settl models, we employed the AMES-Cond grid of atmospheric models (Allard et al. 2003). The values resulting from this procedure are listed in the third column of Table 2 and in the fourth column of Table 3. In this case, the uncertainties are small and the mass ranges between 60 and 68 M$_{\text{Jup}}$, compatible to what found by Wood et al. (2019).

We followed for HD 19467 B the same procedure used for HD 1160 B comparing its spectrum with those of template spectra. In this case, however, we were not able to find a large library of high-resolution spectra in the T spectral type regime. For this reason we used the lower resolution spectra in the Spex Prisms spectral libraries (Burgasser 2014). This will not allow to exploit the full potential of the spectral lines in the spectral classification but will however allow to perform a reliable definition of the spectral type. The results of this procedure are displayed in Fig. 8 where the LSS extracted spectrum is compared to the three best-fitting spectra. In this case, the best fit is obtained with the T7 spectrum of SDSSp J134646.45−003150.4 (Burgasser, Burrows & Kirkpatrick 2006) but a comparable good fit is obtained for spectra with spectral type between T5 and T7. For this reason, we can conclude that the spectral type for this object is T6 ± 1.

As done for HD 1160 B, we have tried to confirm this spectral classification calculating appropriate spectral indices. To this aim we have used the H$_2$O index at 1.15 $\mu$m, the H$_2$O index at 1.5 $\mu$m and the CH$_4$ index at 1.6 $\mu$m defined by Geballe et al. (2002). The first index is accurate only for subtyping in the T sequence, the second one is reliable both on the L and T sequences while the third one is again effective for the T sequence. We found for these three indices values of 6.35, 5.56, and 3.13, respectively, for the case of HD 19467 B. According to the values for the L–T dwarfs subtyping listed in table 5 of Geballe et al. (2002), these values are coherent with a T6 spectral type. This is in good agreement with the spectral type defined through the comparison with template spectra.

Similarly to the case of HD 1160 B, we have fitted also the extracted spectrum of HD 19467 B with a grid of BT-Settl atmospheric models.

Figure 8. Comparison of the extracted spectrum for HD 19467 B (green squares) with the three best-fitting spectra from the Spex Prism library (red, orange, and blue solid lines).

http://ponto.ucsd.edu/~adam/browndwarfs/spexprism/
models. In this case, their $T_{\text{eff}}$ ranges between 500 and 2500 K with a step of 100 K, the surface gravity ranges between 2.5 and 5.5 dex while we used solar metallicity models. The results of this procedure are displayed in Fig. 9 where we compare the extracted spectrum with the three best-fitting models. The best-fitting model is obtained for a $T_{\text{eff}}$ of 1000 K and a log $g$ of 5.5 dex. Good fits were however obtained also for $T_{\text{eff}}$ between 900 and 1100 K while the surface gravity is generally higher than 4.5 dex. From these results, we can conclude that HD 19467 B has $T_{\text{eff}} = 1000 \pm 100$ K and log $g = 5.0 \pm 0.5$ dex. In this case, the $T_{\text{eff}}$ obtained is in good agreement with what foreseen by Pecaut & Mamajek (2016) for the spectral type that we derived previously for this object.

Following the procedure used for HD 1160 B, we have created also for HD 19467 B an absolute $J$ magnitude versus $J-H$ colour–magnitude diagram (see Fig. 10). In this diagram, the position of this object is in good agreement with the expected positions of medium T spectral type objects.

### 4.2.1 Atmospheric retrieval of HD 19467 B

In this section, we use the extracted spectrum of HD 19467 B to perform a retrieval analysis in order to obtain a more in-depth insight into the physical and chemical properties of HD 19467 B. For the retrieval, we use the Bayesian, nested-sampling retrieval model Helios-r2 (Kitzmann 2020). The model and its application to emission spectra of brown dwarfs is extensively discussed in Kitzmann et al. (2020).

Besides the surface gravity log $g$, the calibration factor $f$, and the distance $d$, we retrieve the abundances of $\text{H}_2\text{O}$, $\text{CH}_4$, $\text{K}$, and $\text{Na}$. We also tried to include the mixing ratios of $\text{NH}_3$, $\text{CO}$, and $\text{CO}_2$, which led to unconstrained, prior-dominated posterior distributions. We, therefore, omit these molecules in the final analysis. For a step of 100 K, the surface gravity ranges between 2.5 and 5.5 dex and the distance $d$ was used as a Gaussian prior with a mean value of 32.02 pc and a standard deviation of 0.04 pc, based on GAIA parallax measurements. The temperature profile is described by six first-order elements (see Kitzmann et al. 2020, for details on the parametrization of the temperature profile). We also add a grey cloud layer to the retrieval, determined by three parameters.

Note that for this retrieval we cut the spectrum below 1.2 $\mu$m. This is necessary to obtain physically consistent values for the surface gravity and the calibration factor. The direct retrieval of the surface gravity and the brown dwarf radius from medium-resolution emission spectra is known to be problematic (e.g. Kitzmann et al. 2020; Oreshenko et al. 2020). The spectrum around 1 $\mu$m, which is dominated by the alkali resonance line wings, plays an important role in the determination of log $g$. Inaccuracies in the measured data, but also the theoretical description of the line wings can strongly influence the retrieved values of the surface gravity. We, therefore, did not use this problematic region for the spectral retrieval. However, for comparison, we add a retrieval using the entire available spectral range in the Appendix.

The resulting posterior distributions are shown in Fig. 11, while derived quantities and the posterior spectra are presented in Fig. 12. The retrieved values for the surface gravity log $g$ are quite high, while the calibration factor $f$ is smaller than unity. On the other hand, the obtained value of log $g = 5.44 \pm 0.05$ dex is within the confidence interval of the estimates based on the BT-Settl models, where a value of 5 $\pm$ 0.5 dex is found (see Section 4.2). By assuming that $f$ only describes deviations with
respect to assumed radius of 1 $R_{\text{Jup}}$, it can be converted into a posterior for the brown dwarf radius, shown in Fig. 12. In reality, however, $f$ also includes other sources of errors, for example, inaccuracies in the calibration of the spectrum, systematic errors of the instruments and detector, or errors in the distance measurements. The retrieved value for $f$ of 0.69 $\pm$ 0.09 results in a radius estimate of 0.83 $\pm$ 0.06 $R_{\text{Jup}}$, which is consistent with evolutionary calculations by Saumon & Marley (2008) for such an old object.

The retrieved abundances of H$_2$O, CH$_4$, and K are all well constrained. As mentioned above, adding NH$_3$, CO, and CO$_2$ as free parameters will result in unconstrained, prior-dominated posterior distributions. Based on the retrieved abundances, we estimate the C/O ratio and metallicity in Fig. 12. Both, the C/O ratio and the overall metallicity are subsolar. Within its confidence intervals, this is consistent with the values found for the host star (Maire et al. 2020). We note, however, that both quantities are only estimates based on the H$_2$O, CH$_4$, and K values (H$_2$ and He are assumed to form the background of the atmosphere) and that other molecules that are not detected in the available part of the spectrum might change these estimates.

All cloud parameters are essentially unconstrained which suggests that the presence of a grey cloud layer is not favoured by the data. The temperature profile, on the other hand, is well constrained as evidenced by the small uncertainties shown by the shaded area in the right-hand panel of Fig. 11.

The effective temperature presented in Fig. 12 has been obtained by integrating the posterior spectra over wavelengths and converting the flux to an effective temperature using the Stefan–Boltzmann law. Its value of about 900 K agrees well with the estimates derived from BT-Settl models (see Section 4.2).

Due to the small radius and high surface gravity, the derived mass shown in Fig. 12 is also quite large. The obtained value of 78.1 $^{+1.6}_{-3.1}$ $M_J$ is almost at the edge of the usually assumed upper mass limit for brown dwarfs (80 $M_J$). As can be seen in Fig. 12, the posterior distribution is also cut at higher masses. Within the retrieval, we reject all masses larger than 80 $M_J$ to not allow the nested sampling to move into an unrealistic mass regime. Without that cut-off, the retrieved mass would even be a bit higher than the value we obtain here.

The posterior spectra shown on the bottom panel of Fig. 12 suggest that overall the retrieval matches the measured spectrum.
indices linked to the H\textsubscript{2}O molecule, the first in the second in the simultaneously. Indeed, performing a fit separately in the Y\textsubscript{H} and the J\textsubscript{H} yields satisfactory fits both in the Y\textsubscript{H} and the J\textsubscript{H} bands. We defer this to a future paper.}

This last result has an important consequence on the age (and then on the mass) of HD 1160 B. Indeed according to the atmospheric models, a stellar mass for this object, implied if we assume the older ages (120 Myr) proposed for the system, would require a surface gravity of the order of 5.0 dex that seems to be ruled out by our analysis. Instead, the surface gravity that we have defined for this object favour the younger ages (10–20 Myr) and lower masses (around 20 M\textsubscript{Jup}) in the proposed ranges. In any case, uncertainties on the fit with the models and in the determination of the spectral indices do not allow to fully exclude the possibility of an older age. Further analysis at higher spectral resolution and with different instruments will be necessary to completely solve these uncertainties.

HD 19467 B is instead an old object and its mass can be defined with small uncertainties confirming that it is at the edge between the brown dwarfs and the low stellar mass regimes. We derived a T\textsubscript{6} spectral type, through the comparison with templates and using appropriate spectral indices. This is in good agreement with the T\textsubscript{eff} of the order of \( \approx 1000 \) K that we found from the comparison of its spectrum with BT-Settl atmospheric models. Finally, we derived a large variation of the surface gravity (log \( g \) = 5.0 dex) that confirms the old age of this fully evolved object.

Finally, we performed on the latter object spectral retrieval to further define its physical and chemical characteristics. T\textsubscript{eff} and surface gravity were in good agreement with what we found using the evolutive models while the mass of the object tends to be higher than what we found with the models. From the point of view of the chemical abundances, we were able to put strong constraints on the abundances of H\textsubscript{2}O, CH\textsubscript{4}, and K while this was not possible for other molecules like NH\textsubscript{3}, CO, and CO\textsubscript{2}. Furthermore, our analysis does not favour the presence in the atmosphere of this object of a grey cloud layer.

It was not possible to apply the spectral retrieval analysis to the case of HD 1160 B due to the fact that these models are at the moment optimized to the case of cold objects and require to be adapted for the case of higher T\textsubscript{eff}. We defer this to a future work.

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APPENDIX: ATMOSPHERIC RETRIEVAL OF HD 19467 B USING THE FULL SPECTRUM

In this Appendix, we show the retrieval for HD 19467 B using the entire spectrum, i.e. without cutting it below 1.2 μm. The derived quantities and the posterior spectra are presented in Fig. A1 while the resulting posterior distributions are shown in Fig. A2.

The results suggest that without removing the problematic region below 1.2 μm, we obtain much higher surface gravities and too small calibration factors and, therefore, radii. With a value of only 0.6 R_Jup, the derived median radius is probably too small for a brown dwarf. While we still obtain subsolar C/O ratios, the overall metallicity is now supersolar. The posterior spectra shown in bottom panel of Fig. A1 corroborate our previous approach of removing the peak around 1 μm from our retrieval analysis. It is clear, that the model has problems fitting this spectral region.

Figure A1. Top: Posterior distributions of derived quantities for the retrieval of HD 19467 B. The posteriors are shown for the brown dwarf radius R, its mass M, effective temperature T_{eff}, the C/O ratio, and the overall metallicity [M/H]. Bottom: Posterior spectra and residuals. The solid lines refer to the median of all posterior spectra. The shaded areas signify the 3σ confidence intervals of the spectra. The measured spectrum is indicated by the red data points.
Figure A2. Posterior distributions for the retrieval of HD 19467 B using the full available spectrum. See caption of Fig. 11 for details on the posterior plots.

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