Debris disks with multiple absorption features in metallic lines: circumstellar or interstellar origin?

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Debris disks are second generation dusty disks thought to be devoid of gas. However, this idea has been challenged in the last years by gas detections in some systems. We compiled a database of 301 debris disks and collected high-resolution optical spectra for ∼77% of them. From the analysis of these data we identified a group of 23 debris disks presenting several absorption features superimposed to the photospheric Ca\textsc{ii} and Na\textsc{i} doublets. These absorptions could be due to circumstellar material or interstellar clouds. In order to discriminate between the two scenarios, we characterized each feature in terms of its radial velocity, equivalent width and column density. Additionally, we searched in the literature for local clouds in the line of sight of the stars, and looked for the presence of similar absorption features in nearby stars. Our study concludes that while all the objects present interstellar absorptions in their spectra, three objects show features more compatible with circumstellar origin: HD 110058 presents a stable circumstellar absorption, while HR 4796 and c Aql present variable absorption features likely due to exocometary activity. The minute-scale variability we detect towards c Aql is the shortest of this kind detected so far. The detection of circumstellar features in these objects is consistent with their near edge-on inclinations. We also provide evidence challenging previous claims of circumstellar gas detections for HR 6507. Given the properties of the sample, we speculate that transient gaseous events must be a common phenomenon among debris disks.

Key words: planetary systems: formation – circumstellar matter – debris disks – ISM: clouds – objects: HR 4796 – c Aql – HD 110058 – HR 6507

1 INTRODUCTION

Planets are believed to form in protoplanetary disks. The mass of these disks is initially composed of 99% gas and 1% dust (ISM-like ratios, Bohlin et al. 1978; but see, among others, Williams & Best 2014). After a few Myrs (e.g. Hernández et al. 2007 and Fedele et al. 2010) these protoplanetary disks evolve from optically thick gas-rich systems into transition disks, and later, at a stellar age of about 10 Myrs, they are transformed into a collection of rocks, dust, planetesimals (and maybe gaseous giant planets) known as debris disks. At this stage, the disk is supposed to be fully depleted of gas due to gas removal processes such as photoevaporation, accretion and radiation pressure (e.g.Pontoppidan et al. 2014 and Alexander et al. 2006 for reviews on volatiles and photoevaporation in protoplanetary disks, respectively). Therefore, the current paradigm is that the majority of debris disks do not harbour gas and contain very little second generation dust produced by collisions among planetesimals; gas giants would have to form during the earlier gaseous stage of the disk; and rocky planets can form or

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continue to grow later during the gas-poor phase of the disk (Wyatt 2008).

The idea that debris disks should be gas free has been challenged in the past few years by the discovery of a number of debris disks containing some gas detected either in the far-infrared (FIR), infrared (IR), optical or UV wavelengths. These gaseous debris disks have been found mainly around young A type stars, like the well-studied \( \beta \) Pictoris (Brandeker et al. 2004), 49 Ceti (Roberge et al. 2014), HD 32297 (Redfield 2007), HD 172555 (Riviere-Marrach et al. 2012), HD 21997 (Moor et al. 2011), a few B type stars like \( \eta \) Her (Chen & Jura 2003) and 51 Oph (Thi et al. 2013), and very few F type stars, HD 181327 and \( \eta \) Corvi (Marino et al. 2016, Marino et al. 2017). Several tracers have been used to this end, for instance CO, C and O emissions at mm wavelengths (Greaves et al. 2016, Kral et al. 2017b), C\( \text{ii} \) and Na\( \text{i} \) absorptions in the optical (Kiefer et al. 2014a) and different C species (C\( \text{I} \), C\( \text{II} \)) and Fe I absorptions in the far UV, among others (Brandeker et al. 2004, Roberge et al. 2006, Roberge et al. 2014).

The possible origin of the gas detected in debris disks has been widely discussed (Moor et al. 2011, Wyatt et al. 2015, Köppl & Moor 2016, Kral et al. 2017a). In short, it could be residual gas that remained from the earlier gaseous stage of the disk, which would imply that the efficiency of gas removal processes may be lower than we thought. Or, it could be second generation gas, produced by icy comets that, either orbiting or as they approach the star, begin to “evaporate” (or, more correctly, sublimate) and release small amounts of gas. Gas of secondary origin could also be produced by collisions among volatile-rich dust grains or comet-like bodies (Higuchi et al. 2017 and references therein) or even by photon-stimulated desorption of solids (Matthews et al. 2014). These latter two processes could replenish the disk with a stable gaseous component likely to be located in the outer regions of the disk (Brandeker et al. 2004). On the other hand, the idea of the “falling evaporating bodies” (FEBs) has been gaining more acceptance in the last few years, since FEB-like events have been detected (mostly) around A-type stars with debris disks and some shell stars (e.g., Beust et al. 1998, Kiefer et al. 2014c, Eiroa et al. 2016). These events manifest as stochastic absorption features usually at redshifted velocities with respect to the radial velocity of the star. Variable absorption features have been detected over short time windows of hours or night to night as well as over months or years (Barnes et al. 2000, Thébault & Beust 2001, Welsh & Montgomery 2013). One interesting by-product of studying FEBs is posing the question on the cause of such instabilities in the debris disk. A possible cause for such instabilities could be the presence of a larger body like a planetesimal or a planet interfering with the dust transport and evolution of the disk (Beust et al. 1998).

Independently of its origin, the implications of the presence of gas in debris disks are many (see, for a recent review, Hughes et al. 2018). It can change our understanding of gas removal processes by setting new constraints on their efficiency (Williams & Cieza 2011). Particularly for photovaporation, thought to be the main cause of gas removal in protoplanetary disks (Alexander et al. 2006, Canovas et al. 2017). In addition, gas can influence the morphology of the dust in the disk providing us with a possible answer to the formation of the observed gaps in some debris disks (Lyra & Kuchner 2013). Gas can also imprint changes in the dynamics of the system since even small amounts of gas can drag dust and pebbles (Wyatt 2008); and dust grains can couple to the gas component which acts as a fluid affecting rocky planet formation processes (Fernández et al. 2006, Cleeves et al. 2016, Kenyon et al. 2016). Since the presence of gas can have a strong impact on the formation and evolution of planetary systems it is essential to understand its frequency and how gas detections relate to properties of debris disk systems, such as age, multiplicity, stellar type, metallicity, dust content and disk-planet interaction.

We are currently analysing a robust sample of 301 debris disk (Olofsson et al. in prep.) to learn what percentage of debris disks contain gas, how the gas is physically related to the dust and what properties characterize the stars that possess circumstellar gas in their surrounding debris disks. Instruments such as ALMA and APEX can provide us with a plethora of information about disks besides being able to detect gas emission. However, observing such a large sample with either facility would be extremely expensive in terms of telescope time. In comparison, the analysis of UV-optical ground-based spectra provides a very efficient way to find debris disks with gas to be followed up with other instruments (Montgomery & Welsh 2012, Welsh & Montgomery 2013, Kiefer et al. 2014a). Just as a simple illustration, integration times of CO surveys with ALMA or APEX are \( \sim 1 \) hour per target (Köppl et al. 2013, Hales et al. 2014), while optical high-resolution high-signal-to-noise-ratio spectroscopic observations of similar targets conforming our sample take only a few minutes or even seconds (in class 2 to 8 meter telescopes). Thus the number of spectra taken during one night ranges from \( \sim 50 \) to \( \sim 100 \), depending on the telescope/instrument and the targets.

In order to optimize the search for circumstellar gas in our sample, we have used the method described in Kiefer et al. (2014c), where the presence of gas in the line of sight of debris disks with near edge-on inclinations, is inferred by the identification of (narrow) extra absorption(s) in metallic lines in the UV/optical regime (Ca\( \text{II} \) H & K and Na\( \text{I} \) D1 and D2 being particularly good tracers). So far we have been able to collect data for about 77% of our sample and analysing those data, we have found a few particularly interesting objects with multiple gas features which are presented in this paper.

## 2 DEBRIS DISK SAMPLE

In this paper, we present a sub-sample of 23 gas-rich debris disk candidates characterized by showing gas detections at different radial velocities within our database of observations prior to December 2016. The full sample of debris disks we are observing consists of 301 systems selected from an original list compiled by Olofsson et al. (in prep). The original list, was assembled via a thorough literature search for debris disks that had been observed with the IRS instrument.
Gas in debris disks

(Houck et al. 2004) on board of the Spitzer space telescope (Werner et al. 2004). This search resulted in \( \sim 500 \) objects that were then filtered down to 301 imposing different criteria on the significance of the excess in the mid-infrared and excluding debris disks that display strong emission features in their IRS spectra (e.g., Oléron et al. 2012), as these objects are not really representative of “classical” debris disks. It follows then that the selection criteria applied to achieve our database of 301 debris disks are unbiased with respect to disk inclinations as the disks are optically thin and, since most inclinations are unknown, they can be assumed to be following a uniform distribution.

The ages of the systems in the full sample are mostly within the range 10–100 Myrs and most of them are located within distances of less than 200 pc. We are in the process of collecting high-resolution, high-signal-to-noise spectroscopic archival data and obtaining new observations of these objects to analyse the sample in the wavelength ranges covering the Ca \( ii \) H and K lines at 3968.5 and 3933.7\,Å, and the Na \( i \) D1 and D2 lines at 5895.9 and 5889.9\,Å. We have been able to collect adequate data for 234 objects in our sample, with \( \sim 55\% \) of the selected objects coming from our own observations and the rest from the ESO archive. As mentioned before, the sub-sample presented here was extracted from our database of observations updated up to December 2016.

The main properties of the sub-sample are detailed in Tables 1 and 2. Unless otherwise indicated, most of the stellar parameters reported in Table 2 were retrieved from the Simbad database (Wenger et al. 2000). In particular, distances came from the Tycho-Gaia Astrometric Solution (TGAS) from the Gaia data-release 1 (Gaia Collaboration et al. 2016) or from the Hipparcos new reduction of van Leeuwen (2007) when the former were not available. Luminosities are estimated via SED fitting (assuming the previously mentioned distances) with Kurucz models (Castelli et al. 1997) using VOSA (Bayo et al. 2008). Isochronal ages are estimated with VOSA based on the SED fitted parameters and different sets of isochrones (Siess et al. 2000, Baraffe et al. 1998). The multiplicity column highlights objects reported in the literature to be multiple systems. Note that the large uncertainties in isochronal ages are attributable to uncertainties in the distance to the objects and/or the set of isochrones assumed for the estimates (further discussion on the ages of the sample will be given in Oléron et al. in prep.). For those objects confirmed to belong to young moving groups (i.e. \( \beta \) Tuc, 66 Psc, \( \nu \) Hor, HD 24966, HD 54341, \( \eta \) Cha, HD 110058 and HR 6507), we have adopted the literature age commonly assigned to those moving groups (in principle more precise than isochronal dating).

As mentioned before, the 23 candidates presented in this paper have been chosen because they display particularly interesting gas absorption features: they all have not only one, but multiple absorptions at different radial velocities with respect to the star within the 12 years of baseline considered for this paper. Merely by statistical arguments, this multiplicity increases the chances of a circumstellar gas detection, and for the cases that a circumstellar origin for several simultaneous features could be confirmed, it would imply a very interesting disk configuration and/or geometry. For instance, a disk containing several gas rings at different distances from the star or different populations of exocomets, which would require further study and possible follow-up with high angular resolution instruments like ALMA.

### Table 1. Sub-sample of gas-rich debris disk candidates with multiple absorption features and their respective coordinates.

| Name     | HD Id     | R.A. [J2000] | Dec. [J2000] |
|----------|-----------|-------------|-------------|
| \( \beta \) Tuc  | HD 3003  | 00:32:43.9  | -63:01:53.4 |
| 66 Psc   | HD 5267  | 00:54:35.2  | +19:11:18.3 |
| \( \nu \) Hor  | HD 17848 | 02:49:01.5  | -62:48:23.5 |
| HD 24966 | HD 24966 | 03:56:29.4  | -38:57:43.8 |
| HD 290540 | HD 290540 | 05:31:31.4  | -01:49:33.3 |
| HD 36444 | HD 36444 | 05:31:40.5  | -01:07:33.3 |
| HD 290609 | HD 290609 | 05:33:05.6  | -01:43:15.5 |
| HR 1919  | HD 37306 | 05:37:08.8  | -11:46:31.9 |
| HD 54341 | HD 54341 | 07:06:20.9  | -43:36:38.7 |
| HD 60856 | HD 60856 | 07:35:56.9  | -14:42:39.0 |
| HR 3300  | HD 71043 | 08:22:55.2  | -52:07:25.4 |
| \( \eta \) Cha | HD 75146 | 08:41:19.5  | -78:57:48.1 |
| HD 92536 | HD 92536 | 10:39:22.8  | -64:06:42.4 |
| 3 Crv    | HD 105850 | 12:11:03.8  | -23:36:08.7 |
| HD 106036| HD 106036 | 12:12:10.3  | -63:27:14.8 |
| HR 4796  | HD 109573 | 12:36:01.0  | -39:52:10.2 |
| HD 110058 | HD 110058 | 12:39:46.2  | -49:11:55.5 |
| HD 112810 | HD 112810 | 12:59:59.9  | -50:23:22.5 |
| HD 126135 | HD 126135 | 14:24:43.9  | -40:45:18.6 |
| HD 141378 | HD 141378 | 15:48:56.8  | -03:49:06.6 |
| HD 141327 | HD 141327 | 15:49:43.1  | -32:48:29.8 |
| HR 6507  | HD 158352 | 17:28:49.7  | +00:19:50.3 |
| \( cAql \) | HD 183224 | 19:29:00.9  | +01:57:01.6 |

### 3 SPECTROSCOPIC DATA

We performed observations with FEROS (Kaufer et al. 1999) on the MPG/ESO 2.2m telescope at the La Silla Observatory in Chile and UVES (Dekker et al. 2000) on the VLT UT2 telescope at Paranal Observatory, Chile. We also queried the ESO archive searching for all relevant high-resolution spectra covering the blue-optical wavelength ranges. In particular data from HARPS (Mayor et al. 2003), UVES and FEROS instruments were searched for.

#### 3.1 New data

##### 3.1.1 FEROS observations

We performed observations with the FEROS \( \acute{E} \)chelle spectrograph for the objects listed in Table 3\(^2\). The instrument choice is motivated by its characteristics: large wavelength range (the complete optical spectral region from \( \sim 3500\,\text{Å} \) to

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1 The list of programme IDs can be found in the Acknowledgements.

2 Programme IDs: 094.A-9012(A), 096.A-9018(A) and 099.A-9004(A)
Table 2. Stellar parameters for the sample.

| Name         | vsini  | Type  | radv | distance | Isochronal Age | Literature Age | log($L_\text{bol}/L_\odot$) | Multiplicity |
|--------------|--------|-------|------|----------|----------------|----------------|---------------------------|--------------|
| Provisions   | 93     | A0V   | 7.70±0.60 | 45.65±0.394 | 115.48±0.17 | 45.48 | 30.07±0.60 | 1.94±0.01 | 2
| 66 Pas       | 144    | A1Vn  | 8.15±0.80 | 108.11±7.46  | 5.00±0.33 | 38.10 | 200.10 | 1.96±0.01 | 2
| ν Hor        | 143.7  | A2V   | 30.90±2.00 | 52.13±1.76  | 529.02±129.01 | 100 | 220.10 | 1.23±0.01 | 2
| HD 24966     | –      | A0V   | –      | 105.82±4.03  | 195.41±195.41 | 10 | 112 | 1.13±0.01 | 2
| HD 292540    | –      | A2    | –      | 357.32±54.90  | 11.57±19.74 | 101 | 1.23±0.01 | 2
| HD 36444     | –      | B9V   | –      | 458.20±98.20  | 4.33±0.20 | 1.33 | 1.13 | 0.01 | 2
| HD 29869β   | –      | A0    | –      | 23.86±11.43  | 28.52±110.17 | 453 | 1.13±0.01 | 2
| HR 1919      | 148.1  | A1V   | 23.00±0.70 | 70.76±4.15  | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 54341     | –      | A0V   | –      | 102.35±3.77  | 94.97±1.14  | 10 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 60856     | 44     | B5V   | 31.20±1.90 | 363.83±88.54  | 2.19±0.09 | 196 | 1.00 | 20.10 | 1.13±0.01 | 2
| HR 3300      | 224    | A0V   | 22.50±1.10 | 70.03±1.13  | 710.26±310.81 | 404 | 1.00 | 20.10 | 1.13±0.01 | 2
| 2001         | 296b   | B8V   | 10.00±1.00 | 145.13±8.75  | 4.04±0.49 | 231 | 1.00 | 20.10 | 1.13±0.01 | 2
| 3 Crv        | 126.8  | A1V   | 11.00±4.20 | 58.82±1.94  | 907.37±380.20 | 465 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 16036     | –      | A2V   | 7.70±1.30 | 99.09±3.87  | 463.25±263.25 | 17 | 1.00 | 20.10 | 1.13±0.01 | 2
| HR 4796      | 152.0  | A0V   | 7.10±1.10 | 72.78±1.75  | 69.50±20.98 | 375 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 110558    | –      | A0V   | 5.00±1.20 | 188.76±34.11 | 560.29±158.29 | 10 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 112810    | 82     | F3/5IV/V | 4.20±1.20 | 134.60±7.22  | 1997.74±1012.17 | 10 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 126135    | –      | B8V   | 12.00±6.00 | 165.02±16.34 | 5.00±0.60 | 104 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 141378    | 105    | A5IV-V | –      | 55.54±2.32  | 10.05±0.65 | 587 | 1.00 | 20.10 | 1.13±0.01 | 2
| HD 141327    | –      | B9V   | –      | 213.29±22.48 | 4.88±0.28 | 196 | 1.00 | 20.10 | 1.13±0.01 | 2
| HR 6507      | 180    | A8Vp  | –      | 59.63±1.93  | 7.83±0.12 | 600 | 1.00 | 20.10 | 1.13±0.01 | 2
| cAql         | 110    | A0IVp | 12.00±3.00 | 61.20±1.35  | 60.55±0.55 | 506 | 1.00 | 20.10 | 1.13±0.01 | 2

a Zorec & Royer (2012), b van Leeuwen (2007), cTGas, dTorres et al (in prep.), e Rhee et al. (2007), f Gontcharov (2012), g Hernández et al. (2006), h Mittal et al. (2015), i Ballering et al. (2013), j Dommanget & Nys (2002), k Docobo & Ling (2007), l Jura et al. (1993).

1 Distances reported for this object range from ~24 pc (van Leeuwen 2007) to ~775 pc (Kharchenko 2001); both of these estimates report huge uncertainties (above 50%), and propagate to unrealistic luminosities and thus isochronal ages. For this reason we do not include this object in any comparative analysis that involves age, luminosity and/or distance.

~9200Å in only one exposure), high resolution ($R = 48,000$) and high spectral coverage, which makes it suitable for detecting narrow absorption features in a wide variety of spectral lines. Spectra of these objects were taken on the nights listed in Table 3 with exposure times computed with the online FEROS Exposure Time Calculator to obtain a signal-to-noise ratio ($S/N$ hereafter) of about ~150 around the blue wavelength range. Standard calibrations were taken and the ESO pipeline with the default parameters was used to reduce the data. The reduced spectra were corrected for heliocentric velocity shifts and telluric contamination (see Sec. 3.3).

3 https://www.eso.org/observing/etc/bin/gen/form/INS.NAME =FEROS+INS.MODE=spectro
4 Programme ID: 096.C-0238(A)
5 Programme IDs: 097.C-0409(A) and 097.C-0409(B)

3.2 Archival data

We queried the ESO archive looking for optical spectra with resolution high enough to detect narrow absorption features with widths of ~0.1Å. This restricted the instruments to HARPS, UVES and FEROS. Our targets have been observed multiple times (e.g., searching for planets via radial velocity variations), hence we found a large number of spectra (from one spectrum up to 3000 spectra). Consequently, a considerable fraction of our dataset (~35% of the full sample) comes from different archives. In fact, 16 of our debris disks with multiple features were identified with these observations.

6 https://www.eso.org/observing/etc/bin/gen/form/INS.NAME =UVES+INS.MODE=spectro
Table 3. Number of spectra for each star per date, instrument, ESO observing period and dates of observations. Observations from our programmes are flagged with a *. 

| Name          | Number of Spectra | Instrument | Period | Observation dates               |
|---------------|-------------------|------------|--------|---------------------------------|
| β03 Tuc       | 6, 4, 2, 2, 2     | HARPS      | P73, P75, P77, P77, P77            | 2004-09-30, 2005-08-19, 2006-05-20, 2007-25, 26 |
| 66 Psc        | 1, 2              | UVES       | P96, P97                            | 2015-11-14*, 2016-07-23* |
| ν Hor         | 2, 2              | HARPS      | P75, P77                            | 2005-08-19, 2005-09-09, 2006-09-11 |
| HD 24966      | 1                 | FEROS      | P96                                 | 2016-01-04* |
| 66 Psc        | 1, 2              | UVES       | P97, P97, P97                        | 2016-07-23*, 2016-08-21, 29* |
| HD 290540     | 1                 | FEROS      | P96                                 | 2016-01-03, 04* |
| HD 36444      | 1                 | FEROS      | P96                                 | 2016-01-04* |
| HD 290609     | 1                 | FEROS      | P96                                 | 2016-01-04* |
| HR 1919       | 4, 2, 2, 2, 2     | HARPS      | P76, P76, P76, P76, P76             | 2006-02-08, 09, 10, 11, 13, 2006-03-12 |
| HD 54341      | 3                 | HARPS      | P94, P94                            | 2015-10-23*, 2016-03-29, 29* |
| HD 60856      | 1                 | FEROS      | P96                                 | 2016-01-04* |
| HR 3300       | 6, 2              | HARPS      | P94, P4, P94                         | 2015-01-18, 20, 21 |
| η Cha         | 1, 2, 3, 3        | FEROS      | P82, P82, P82, P88                  | 2008-11-18, 21, 22, 2011-07-07 |
| HD 92536      | 3, 3, 2, 1        | HARPS      | P94, P94, P94, P94                  | 2005-02-12, 2015-01-19, 20 |
| 3 Crv         | 4, 2, 2, 2        | HARPS      | P77, P77, P77, P80                  | 2006-05-20, 21, 25, 2007-12-10, 2009-12-05 |
| 2, 2, 2, 2    | 1                 | FEROS      | P90, P96, P96, P96                  | 2006-10-24, 2006-05-12, 2007-01-01 |
| HD 110058     | 1, 1, 1           | FEROS      | P84, P84, P84, P85, P85             | 2010-01-27, 28, 29, 30, 2010-06-01, 14 |
| 4796          | 74, 152, 76, 92, 16 | UVES       | P68, P79, P79, P79, P79, P79        | 2002-01-19, 2007-05-07, 08, 13, 14, 15 |
| HD 112810     | 2                 | UVES       | P96                                 | 2016-02-21* |
| HR 6507       | 4, 2, 2, 2        | HARPS      | P75, P77, P77, P80                  | 2005-08-20, 2006-05-20, 25, 2006-09-12 |
| 2, 5, 2, 2    | 6                 | UVES       | P80, P80, P84, P84                  | 2008-03-17, 21, 2010-07-08, 09, 09 |
| c Aql         | 10, 38            | UVES       | P79, P87                            | 2007-06-30, 2011-05-27 |
| 1, 1, 1       | FEROS             | P83, P83, P83 | 2009-06-02, 03, 03, 2009-08-24 |
| 1, 1, 1       | FEROS             | P86, P85, P85 | 2010-07-22, 2010-08-23, 31 |

3.2.1 HARPS data

HARPS is an echelle spectrograph fed by a pair of fibres, one of them collects the star light, while the second is used to either record simultaneously a Th-Ar reference spectrum or the background sky. HARPS spectra covers the wavelength range 3780–6910Å, has a spectral resolution of 120,000 and has been optimised for mechanical stability, which makes it ideal for our study. We retrieved several epochs of HARPS data for the debris disks listed in Table 3. All these observations were already reduced with the ESO pipelines and corrected for heliocentric radial velocity shifts, and we then corrected for telluric contamination (see Sec. 3.3).

3.2.2 UVES data

Additional to the HARPS data, we found a considerable number of UVES observations for our sample (see Table 3). UVES is a two-arm cross-dispersed echelle spectrograph, its blue arm covers the wavelength range 3000–5000Å and the red arm covers 4200–11000Å. Overall, the spectral coverage depends on the instrumental set-up used for the observations since UVES allows the use of dichroic beam splitters, but in general we have spectra covering the ranges 3043–3916Å, 3236–4563Å, 3731–4999Å, 4549–6686Å, 4726–6835Å and 6650–10426Å. These UVES data had already been reduced with dedicated ESO pipelines but additional corrections of...
heliocentric radial velocity shifts and telluric contamination were necessary.

3.2.3 FEROS data

We also retrieved FEROS archival data for some of our targets (Table 3). Similarly to the HARPS data, the FEROS observations were reduced with the available instrument pipelines and corrected for heliocentric radial velocity shifts. Posterior corrections for telluric contamination were performed.

3.3 Telluric lines correction

The red domain of the spectra contains many telluric absorption features mostly due to water vapour, $O_2$ and $O_3$. Since one of our main tracers is the sodium doublet at 5895.9 and 5889.9Å, it is imperative to perform a correct subtraction of telluric contamination. To this end, we used Molecfit\(^7\)\(^{}\)(Smette et al. 2015, Kausch et al. 2015), a tool developed to correct observations for telluric absorption which can be used for any kind of spectra without the need to observe a standard star. We used the wavelength range 5902.5-5927.0Å to fit the continuum but excluded gas absorption features to ensure that they do not affect our best-fitting result. We applied these corrections to every epoch for all the objects except for HD 106036 and HD 112810 which spectra did not cover the red wavelength range. We successfully removed telluric absorptions and reduced them to the noise level (i.e. they were reduced by about 99%). An example of the telluric correction is shown in Figure 1.

4 METHODS AND RESULTS

We analysed the calcium H & K lines at 3968.47 and 3933.66Å and the sodium D1 & D2 lines at 5895.92 and 5889.95Å, respectively. The aim is to detect narrow absorption lines superimposed on the photospheric line. These “extra” absorption lines indicate the presence of gas in the line of sight of the star. To determine the nature of the gas we followed different approaches, that we detail in the following sub-sections.

The first step in our analysis is to measure the radial velocity of the stars. Afterwards, we determined the photospheric contribution for each line either by performing spectral synthesis or by finding a “spectral twin”. Then, we identified additional (stable or transient) components by removing the photospheric contribution before characterizing their properties.

Additionally, we also searched for signatures of Diffuse Interstellar Bands (DIBs), compared the radial velocity of the absorption features to the radial velocities of known local clouds and searched for similar extra absorption lines in nearby stars to better assess their nature.

4.1 Radial velocities

Since five of our objects did not have any reported radial velocity measurements in the literature, we performed our own estimates for all objects aiming at a homogeneously determined set of values and to assess the accuracy of our results.

In a first attempt to obtain the radial velocities, we computed the cross correlation function for every epoch of each object using a synthetic model as a template. Unfortunately, since most of our objects are fast rotators, their absorption lines have very wide profiles, and we did not obtain consistent results between all the epochs, with dispersions up to 30 km s\(^{-1}\). Therefore, we decided to take a different approach and use a simpler but, in this case, more suitable technique. For every epoch of each object we fit Lorentzian profiles to the most prominent absorption lines in our spectra: H\(_\alpha\), H\(_\beta\), H\(_\gamma\) and H\(_\delta\). We excluded H\(_\epsilon\) because it is blended with the Ca\(_{II}\) H line. We used a range of 1000 km s\(^{-1}\) for the profile fitting of each (previously normalized) line in velocity space and obtained the radial velocity of the line from the position of the profile with respect to the rest frame.

In order to address possible changes in the estimates of radial velocities due to activity, we checked all our objects for emission features in the Balmer lines (not only for emission dominated lines, but also for shallow core emissions). Only one object, namely HD 60856, presents emission features in these lines. This emission is dominating the full line in the...
case of Hα and thus it was not possible to model the photospheric profile. Therefore, only for this object, we decided to exclude Hα from the radial velocity measurements. In addition, we bootstrapped each of the remaining Balmer lines to estimate the impact of a core emission in our fitting procedure. The standard deviation for the radial velocity from this procedure with 1000 realizations was 2 km.s\(^{-1}\). However, if there are more than 2 epochs, for objects with only one epoch of observations, therefore our estimated uncertainty for the radial velocity takes into account the individual line fitting uncertainties and the dispersion found among the different lines.

For all the other objects, since the cores of the lines appeared purely photospheric, we averaged over all the epochs and lines, and the uncertainties were derived propagating the estimated errors.

In most cases, our radial velocity measurements are in good agreement with the ones found in the literature (see Table 2), having average differences of ∼3 km.s\(^{-1}\). However, the radial velocity value we determined for ν Hor differed by ∼17 km.s\(^{-1}\) with respect to the literature. We computed both radial velocity values when fitting Kurucz (Castelli et al. 1997) models and concluded that our estimate provides a better match to our data. In general, although differences with the literature were relatively small, in the model fitting process we always obtained a better fit when shifting the model to our own estimates of radial velocity. In any case, the large difference found for ν Hor is not that surprising given the high dispersion in the measurements provided from different datasets in Wilson (1953), the reference adopted in Simbad. Finally, we must also note that, for the whole sample, no significant shifts were found between epochs, obtaining velocity dispersions per object of the order of ∼2 km.s\(^{-1}\). Our resulting radial velocity estimates are shown in Table 4.

### 4.2 Spectral synthesis

For most objects (except HD 112810, see Sec. 4.3), we used Kurucz models (Castelli et al. 1997) to fit and normalize the photospheric absorption, thus isolating the additional absorption lines. The models were computed using the spectral synthesis codes SYNTH and ATLAS 9 (Sbordone et al. 2004).

For each line we computed the normalized median spectrum from all the epochs, to use it as a robust reference for the fitting process. Since the radial velocity dispersion along all the epochs is small, the median can be used as a good reference. For each of the median spectrum, the uncertainties are derived using the standard deviation of all epochs if there are more than 2 epochs. For objects with only one or two epochs, the pipelines do not always provide uncertainties. Therefore, for each wavelength point, we estimate the uncertainty for the radial velocity that takes into account the individual line fitting uncertainties and the dispersion found among the different lines.

| Name         | v\(_{\text{ini}}\) [km.s\(^{-1}\)] | radV [km.s\(^{-1}\)] | T\(_{\text{eff}}\) (Ca \(_{\text{ii}}\) K) [K] | log g [dex] | [Fe/H] |
|--------------|----------------------------------|----------------------|------------------------------------------|-------------|---------|
| β03 Tuc      | 100                              | 6.05 ± 1.60*         | 9550                                     | 4.00 ± 0.50 | +0.17 ± 0.20 |
| 66 Psc       | 150                              | 4.32 ± 2.66*         | 10750                                    | 3.90 ± 0.23 | -0.38 ± 0.54 |
| ν Hor        | 140                              | 13.58 ± 1.67         | 8300                                     | 4.25 ± 0.25 | -0.20 ± 0.31 |
| HD 24966     | 210                              | 15.70 ± 3.15         | 9250                                     | 4.38 ± 0.22 | -0.03 ± 0.58 |
| HD 290540    | 200                              | 27.26 ± 3.12         | 10500                                    | 4.25 ± 0.25 | -0.88 ± 0.22 |
| HD 36444     | 360                              | 26.72 ± 4.50         | 10250                                    | 4.00 ± 0.35 | -0.62 ± 0.65 |
| HD 290609    | 100                              | 25.87 ± 1.65         | 10500                                    | 3.88 ± 0.41 | -0.07 ± 0.26 |
| HR 1919      | 140                              | 23.49 ± 1.28         | 8800                                     | 4.15 ± 0.38 | -0.12 ± 0.22 |
| HD 54341     | 140                              | 41.03 ± 0.95         | 10500                                    | 4.50 ± 0.25 | -0.12 ± 0.22 |
| HD 60856     | 40                               | 34.78 ± 3.58         | 14000                                    | 4.12 ± 0.22 | -0.38 ± 0.41 |
| HR 3300      | 210                              | 22.35 ± 0.72         | 9550                                     | 4.25 ± 0.25 | +0.10 ± 0.37 |
| HR 4796      | 150                              | 15.21 ± 1.41         | 11750                                    | 3.75 ± 0.25 | -0.88 ± 0.22 |
| HD 92536     | 180                              | 15.45 ± 0.44         | 11150                                    | 3.88 ± 0.41 | -0.45 ± 0.35 |
| 3 Crv        | 130                              | 14.41 ± 1.09         | 8500                                     | 4.12 ± 0.22 | +0.17 ± 0.41 |
| HD 106036    | 160                              | 9.37 ± 2.34          | 9000                                     | 4.50 ± 0.25 | +0.00 ± 0.25 |
| HR 4796      | 150                              | 5.35 ± 2.94*         | 9800                                     | 4.25 ± 0.25 | -0.07 ± 0.26 |
| HD 110058    | 150                              | 11.20 ± 0.81         | 9000                                     | 4.03 ± 0.36 | -0.33 ± 0.47 |
| HD 112810    |                    | 5.25 ± 2.24          |                               | 5.25 ± 2.24 |         |
| HD 126135    | 310                              | 11.73 ± 0.67         | 11250                                    | 3.88 ± 0.41 | -0.62 ± 0.65 |
| HD 141378    | 80                               | -14.68 ± 2.62        | 8750                                     | 4.50 ± 0.25 | +0.42 ± 0.13 |
| HD 141327    | 250                              | -4.65 ± 2.40         | 10550                                    | 4.00 ± 0.35 | -0.50 ± 0.50 |
| HR 6507      | 140                              | -36.13 ± 2.49        | 7750                                     | 4.25 ± 0.25 | +0.28 ± 0.13 |
| c Aql        | 90                               | 17.29 ± 2.61         | 9700                                     | 4.35 ± 0.26 | -0.57 ± 0.49 |
the remaining parameters: \(T_{\text{eff}}\), \(\log g\), [Fe/H] and \(\text{vsini}\). Table 5 summarizes the fixed values and range of parameters that we explored in the fitting process. Those ranges were chosen according to previous estimates available in the literature. Our model fitting procedure consists of a simple two-step \(\chi^2\) minimization. The fits were performed for each line independently since, possibly due to non-Local Thermodynamic Equilibrium (non-LTE) effects (Przybilla et al. 2011, Plez 2013 and Sitnova et al. 2017), it is hardly possible to obtain good matches for all of them simultaneously.

The only parameter determined using all the lines at once is \(\chi^2\) of the parameter space that yielded similar (a factor 2 with respect to the minimum) \(\chi^2\) values for all the parameters, within a coarse grid of models. The step sizes are reported in Table 5. Afterwards, we used a simplex downhill method with finer interpolations for \(T_{\text{eff}}\) and \(\log g\), with steps of 50 K and 0.1 dex, respectively.

To avoid local minima, we repeated the simplex downhill algorithm several times, initializing it from different regions of the parameter space that yielded similar (a factor 2 with respect to the minimum) \(\chi^2\) values in the coarse grid. The convergence criterion for the downhill algorithm was set to an improvement in the goodness of fit by 10\(^{-4}\). Given that Ca II K is the most sensitive photospheric temperature tracer among all the lines studied (Gray & Corbally 2009), in Table 4 we report as the best fitting temperature the one obtained for that line. A rather conservative confidence interval is estimated from all the models that returned a relative change in \(\chi^2\) smaller than 50% compared to the best fitting model. On the other hand, for \(\log g\) and [Fe/H], we provide an average of the values obtained for the four lines, and the associated uncertainties correspond to their standard deviations.

Once the best fitting model per line is found, it is used to isolate the extra absorption lines from the photospheric profile. The best fits for each objects and lines are displayed in Figures A1 to A4.

We were able to find matching photospheric models for all the objects, and the resulting parameters are consistent with their spectral types from the literature. The only exception is HD 112810, which is an F3/5IV/V spectral type according to the literature and the only F-type star within the sample presented in this paper (we further discuss this object in Section 4.3). Otherwise, for each individual object, the dispersion in \(T_{\text{eff}}\) for the four different lines is of the order of \(\sim 300\) K, which is expected when accounting for non-LTE effects (Przybilla et al. 2011, Plez 2013 and Sitnova et al. 2017).

#### 4.3 Spectral twins

As an alternative to the synthetic spectrum, we also performed a search for the closest spectral match within all the objects in our sample for which we have spectra (i.e. 234 objects). In particular, we compared the median spectrum (the same as the reference spectrum) of each candidate against the median spectrum of each object in the sample with similar spectral types. We used a range of 11 subtypes (e.g. between A0 and F0 for an A5 candidate) for the spectral twin search.

Similar to the synthetic model fit, we selected the best fitting “template” in terms of minimum \(\chi^2\). The only difference is that in the \(\chi^2\) calculation we neglected the wavelength regions containing the 10% most distant data points between the two spectra being compared, in order to avoid a bias induced by the presence of extra features in either spectra.

In the case of HD 112810, since we were not able to find a satisfactory Kurucz model, we used the spectral twin we found for the object as a photospheric model to integrate the absorption feature. As can be seen in Fig. 2, HD 15115 is a good match to the spectrum of HD 112810.

#### 4.4 Identification and characterization of features

We started by normalizing the reference (median) spectrum by the synthetic model (or spectral twin for HD 112810) to isolate the extra absorption features. In some cases when the model is not a perfect match (often the case in the wings of the photospheric lines), the normalized spectrum shows a “wavy” pattern, that makes the characterization of the extra features more challenging. In those cases we performed a polynomial fit to the normalized spectrum to remove this wavy pattern.

Afterwards, we performed Gaussian fitting to each of the extra absorption features in order to derive radial velocities, equivalent widths and apparent column densities. In the case of blended absorption lines, we modelled a combined Gaussian profile with the minimum number of Gaussians that would finely fit the profile. We only considered as “real absorption features” those with significance above \(3\sigma\) over the residual spectrum. We considered a feature to be “the same” as that present in another line of the same object when the absolute difference of the radial velocity of both features is \(\leq 2\sigma\), where \(\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}\), being \(\sigma_1\) and \(\sigma_2\) the uncertainty of the radial velocity of each feature.

Radial velocities and equivalent widths were estimated from the best Gaussian(s) fit. In addition, apparent column densities were estimated following Savage & Sembach (1991) and using the oscillator strength values \(f\) from Morton (1991). We checked our own estimates for three stars against results produced by the Vapid code (Voigt Absorption Profile Interstellar Dabbler Howarth et al. 2002, which can model interstellar absorption lines) and they agreed within the uncertainties. Apparent column density (CaII/NaI) ra-

| Parameter                | Values                          |
|--------------------------|---------------------------------|
| Turbulent Velocity       | 2.0 km.s\(^{-1}\)               |
| Additional Turbulence    | 0.0 km.s\(^{-1}\)               |
| Opacity Threshold        | 0.001                           |
| \(T_{\text{eff}}\)       | 6000–13000 K, with \(\Delta=250\) K |
| \(\log g\)               | [3.5, 4.0, 4.5]                 |
| [Fe/H]                   | [-1.0, -0.5, 0.0, +0.2, +0.5]   |
| \(\text{vsini}\)         | 20–400 km.s\(^{-1}\), with \(\Delta=10\) km.s\(^{-1}\) |
Gas in debris disks

Figure 2. Spectral twin found for HD 112810 (in black): the F4IV type star HD 15115 (in red). The radial velocities of both stars have been shifted to zero for a better comparison. No additional broadening has been added to the spectra of any of the two objects.

The parameters for each line and feature are presented in Table 6. The average radial velocity of each feature and their N(Ca\textsc{ii}/Na\textsc{i}) are shown in Table 8. As can be seen in the Tables, the range of properties is very wide, including blue and red-shifted components, weak and intense features, either Ca\textsc{ii} or Na\textsc{i} rich. The detailed discussion on the impact of these parameter in determining the origin of the gas responsible for the feature is left to Section 5.
Table 6: Absorption feature parameters. Heliocentric radial velocity, apparent column density and equivalent width of the features present in each line. Uncertainties for the radial velocities are in the order of 2.3 km s\(^{-1}\) for the Ca\(ii\) lines and 1.5 km s\(^{-1}\) for the Na\(i\) lines. Apparent column densities and equivalent widths have uncertainties of 3–4\% for the Ca\(ii\) lines and 1–2\% for the Na\(i\) lines.

| Name      | radV \(\text{km s}^{-1}\) | \(\text{log}_{10} N\) \(\text{cm}^{-2}\) | EW \(\text{mA}\) | radV \(\text{km s}^{-1}\) | \(\text{log}_{10} N\) \(\text{cm}^{-2}\) | EW \(\text{mA}\) | radV \(\text{km s}^{-1}\) | \(\text{log}_{10} N\) \(\text{cm}^{-2}\) | EW \(\text{mA}\) | radV \(\text{km s}^{-1}\) | \(\text{log}_{10} N\) \(\text{cm}^{-2}\) | EW \(\text{mA}\) |
|-----------|---------------------------|-----------------|---------|---------------------------|-----------------|---------|---------------------------|-----------------|---------|---------------------------|-----------------|---------|
| \(\beta\) Tri | -12.23 | 9.78 0.52 | – | – | -3.50 | 10.14 0.60 | -3.50 | 10.50 3.10 | -3.51 | 10.51 6.25 | 3.18 | 9.64 0.85 |
| 66 Psc   | -5.14 | 11.10 10.38 | -6.01 | 11.05 4.72 | -5.83 | 11.28 17.49 | -5.85 | 11.27 31.64 | – | – | – | – |
| \(\nu\) Hor | 5.41 | 10.55 3.04 | 4.18 | 10.35 0.96 | 3.86 | 9.52 0.33 | 2.97 | 9.78 1.20 | – | – | – | – |
| HD 24966 | -13.10 | 10.52 2.79 | – | – | – | – | – | – | – | – | – | – |
| HD 290540 | 9.51 | 11.61 32.77 | 9.27 | 11.50 13.29 | 9.09 | 11.45 26.23 | 9.26 | 11.44 49.67 | 23.56 | 11.96 123.98 | 35.30 | 11.29 35.55 |
| HD 36444 | 7.27 | 11.16 12.03 | 6.91 | 11.28 7.96 | 9.02 | 11.44 25.95 | 8.79 | 11.30 36.31 | 22.13 | 11.95 72.57 | 22.15 | 11.87 109.98 |
| HR 1919  | 10.92 | 11.70 38.88 | 21.72 | 11.82 27.16 | 22.13 | 11.95 72.57 | 22.13 | 11.87 109.98 | 21.18 | 11.96 27.16 | 21.18 | 11.87 109.98 |
| HD 54341 | 30.11 | 11.10 10.57 | 31.98 | 11.13 5.79 | 30.81 | 11.23 16.26 | 31.00 | 10.98 18.06 | – | – | – | – |
| HD 290609 | -9.23 | 10.91 6.86 | – | – | – | – | – | – | – | – | – | – |
| HD 60856 | 20.39 | 11.69 36.77 | 20.14 | 11.82 26.63 | 20.38 | 12.25 118.41 | 20.38 | 12.03 134.94 | 23.02 | 12.08 149.96 | 35.22 | 11.12 24.87 |
| HR 3300  | 5.62 | 10.77 4.99 | 4.95 | 10.50 1.38 | 7.52 | 10.18 1.49 | 5.72 | 10.19 3.01 | 30.51 | 10.44 4.42 | 30.51 | 10.44 4.42 |
| \(\eta\) Cha | -3.37 | 10.13 1.16 | -3.46 | 10.11 0.55 | -1.05 | 9.57 0.36 | -3.46 | 9.84 1.36 | – | – | – | – |
| HD 92536 | 2.81 | 10.60 3.36 | 1.57 | 10.22 0.72 | -0.23 | 9.50 0.31 | -0.56 | 9.74 1.07 | – | – | – | – |
| 3 Crv    | -6.64 | 11.05 9.23 | -7.69 | 10.83 2.89 | -6.81 | 10.76 5.53 | -6.86 | 10.71 9.60 | – | – | – | – |
| HD 106036 | -6.17 | 11.03 9.13 | -3.40 | 11.20 6.78 | – | – | – | – | – | – | – |
| HR 4796  | -14.40 | 10.41 2.18 | -14.60 | 10.49 1.33 | -11.10 | 9.89 0.76 | -11.76 | 9.85 1.40 | -5.11 | 10.54 6.75 | 3.42 | 9.78 0.52 |
| HD 110058 | 1.85 | 11.47 24.98 | 0.97 | 11.45 12.04 | 0.56 | 11.23 16.31 | 0.42 | 11.24 32.67 | 12.34 | 11.49 43.52 | 0.00 | 10.00 0.00 |

Continued on next page.
Table 6 – continued from previous page

| Name      | radV [km.s\(^{-1}\)] | Ca\(\text{ii}\) K log\(_{10}\) N [cm\(^{-2}\)] \(EW\) [mÅ] | Ca\(\text{ii}\) H log\(_{10}\) N [cm\(^{-2}\)] \(EW\) [mÅ] | Na\(\text{i}\) D\(_1\) \(EW\) [mÅ] | Na\(\text{i}\) D\(_2\) \(EW\) [mÅ] |
|-----------|----------------------|-------------------------------------------------|-------------------------------------------------|-----------------|-----------------|
| HD 112810 | -12.11               | 11.07,  9.76                                     | -10.86,  10.88,  3.23                           | -                | -                |
|           | -3.76                | 11.60,  29.69                                    | -4.49,  11.57,  14.99                           | -                | -                |
|           | 3.77                 | 11.01,  8.46                                     | 2.28,  11.25,  7.58                            | -                | -                |
| HD 126135 | -22.78               | 10.25,  1.51                                     | -                                              | -22.49,  10.01,  1.01 | -22.12,  10.06,  2.23 |
|           | -14.89               | 10.73,  4.45                                     | -15.59,  10.60,  1.71                           | -13.47,  10.84,  6.73 | -14.36,  10.67,  9.03 |
|           | -8.32                | 10.59,  3.27                                     | -9.90,  10.56,  1.57                           | -7.83,  10.02,  1.04 | -10.23,  10.46,  5.64 |
|           | 4.16                 | 10.92,  6.83                                     | 3.83,  10.85,  3.05                            | 4.25,  11.59,  33.50 | 4.36,  11.57,  58.21 |
| HD 141378 | -30.03               | 10.79,  5.16                                     | -                                              | -                | -                |
|           | -15.02               | 10.36,  1.93                                     | -                                              | -                | -                |
| HD 141327 | -18.37               | 11.33,  18.11                                    | -21.23,  11.22,  7.07                           | -23.48,  10.42,  2.58 | -23.69,  10.41,  4.97 |
|           | -1.43                | 11.95,  66.92                                    | -2.40,  11.97,  37.57                           | -4.17,  12.51,  203.27 | -4.20,  12.43,  260.97 |
|           | 14.78                | 11.80,  47.59                                    | 14.23,  11.82,  26.94                           | 14.66,  10.77,  5.73 | 14.16,  10.77,  11.18 |
|           | 22.92                | 11.04,  9.25                                     | 21.83,  10.97,  4.06                           | 23.11,  10.60,  3.90 | 22.75,  10.75,  10.90 |
| HR 6507   | -38.93               | 10.32,  1.78                                     | -39.26,  11.02,  4.49                           | -38.62,  10.39,  2.40 | -39.01,  9.97,  1.82 |
|           | -30.41               | 11.12,  10.98                                    | -29.52,  11.29,  8.22                           | -29.80,  10.26,  1.80 | -29.10,  10.42,  5.09 |
|           | -24.86               | 11.25,  14.00                                    | -25.05,  11.22,  6.84                           | -25.08,  10.97,  8.71 | -25.09,  10.91,  14.68 |
| c Aql     | -31.19               | 10.49,  2.64                                     | -31.67,  10.52,  1.44                           | -                | -                |
|           | -19.67               | 10.34,  1.88                                     | -19.88,  10.44,  1.21                           | -                | -                |
4.5 Variability of the extra absorption features

We investigated the variability of additional absorption lines in two ways: first by analysing their stability when they are detected in all the epochs and second by looking for transient absorption features that appear in a handful of epochs. For the first method, we performed the same Gaussian fitting described above, but on each individual epoch and we searched for variations in flux and velocity of those ‘stable’ components (since they are present in all the epochs they also appear in the reference spectrum). For the second method, we searched for additional variable detections above a 3σ level that might appear in some of the epochs. Such transient detections could be related to FEB-like events.

We found variable absorption features attributable to FEB-like events in specific epochs of the objects c Aql and HR 4796. In particular, in the case of c Aql we detected very short-term variations from within a few nights to within a few minutes. Variations detected on the night of 2011-05-27 are shown in Fig. 3 for the Ca ii K line, and they are also present in the Ca ii H and Na i lines for some of the observations. These variations, likely attributable to intense exo-cometary activity, are detected at ~35 km.s$^{-1}$, red-shifted with respect to the radial velocity of the star.

We have also detected variability in the Ca ii K line of HR 4796. The observed variations appear as a small feature detected at 5.30 km.s$^{-1}$, matching the radial velocity of the star (5.35 km.s$^{-1}$). Since we have collected over 200 individual spectra of HR 4796, in Fig. 3 we only show a selection of a few epochs as examples of the variability observed around this star. These detections are narrow and only slightly over 3σ. Since the strength of Ca ii H line is roughly half that of the Ca ii K line, we do not expect to have a significant detection in the latter (as was the case). However, it is reassuring (in the circumstellar gas scenario) that all the detections in the Ca ii K line match the radial velocity of the star.

In addition, we have detected low-level (~ 2σ) variability in the residual spectra of HR 6507. However, this variability presents itself as a very broad component covering the full range of velocities of the photospheric line, as can be seen in Fig. 4. In order to determine if this variability was produced by circumstellar gas or the star itself, we also analysed the Hα line. Neither narrow emission nor absorption were detected in this line. However, the same broad variability was found, more consistent with photospheric variation. This star is classified as a shell star in (Hauck & Jaschek 2000, Jaschek et al. 1991), but even the shell classification is questioned in Jaschek et al. (1988) and Jaschek & Andrillat (1998). From the velocity field involved, this variability is more likely due to the presence of spots (as described in Figueira 2013).

4.6 Local Interstellar Medium features

4.6.1 Objects with known clouds in the line of sight

We looked for local interstellar clouds in the line of sight of the stars, as this clouds could explain the presence of the extra absorption lines that we observe. We used the online Local Interstellar Medium (LISM) Kinematic Calculator8 (Redfield & Linsky 2008) which predicts the radial and transverse velocities of LISM clouds in any direction and calculates which clouds are traversed by any given line of sight.

We found traversing known clouds from the Redfield & Linsky (2008) catalogue for 18 of our objects and, in most cases, the radial velocity of the clouds matched the velocity of some of the absorption features. In Table 8 we present the clouds traversing the line of sight of each object, their heliocentric radial velocities and whether they match one of the absorption lines or not. As can be seen in the Table, a significant number of our features are attributable to gas located in the G cloud, which is an interstellar cloud located next to the Local Interstellar Cloud (LIC).

4.6.2 Objects with Diffuse Interstellar Bands

We have analysed the Diffuse Interstellar Bands (DIBs) at wavelengths 5780.5Å and 5797.1Å. DIBs are absorption features caused by the ISM and they can be detected in the UV, optical and IR wavelengths. DIBs are much broader than the atomic interstellar lines, having full width at half maximum ranging from ~0.8-30 Å, presumably due to unresolved rotational structure of large carbon-bearing molecules, which are common in the interstellar medium (Herbig 1995). The DIBs we have chosen to analyse are some of the strongest DIBs detectable in optical spectra. The presence of absorption features at any of these particular wavelengths might indicate the presence of ISM in the line of sight of the star, as DIBs are hardly attributable to circumstellar gas around pre-main sequence or main sequence stars (as opposed to objects that have departed the main sequence, see for e.g. Diaz-Luis et al. 2015).

We detected the presence of absorption lines likely to be due to DIBs in the 12 objects listed in Table 7. These absorption lines are broad and diffuse, making it difficult to obtain precise measurements of their radial velocities. Therefore we use this criteria mostly to confirm the presence of ISM within a certain velocity range. We note that although in most cases we have identified diffuse bands at both wavelength locations, for HR 3300, HD 92536, and HD 126135 we have detected DIBs at only one of the wavelengths. This can be explained by the fact that the intensity of the bands detected for those three sources is much lower than in the other cases; therefore we interpret the difference as a sensitivity issue rather than a physical one.

8 http://lism.wesleyan.edu/LISMdynamics.html
Gas in debris disks

Figure 3. Left: Variability in the Ca\textsc{ii} K line of c Aql during the night of 2011-05-27, the UT of each observation is shown in the legend. Right: Example of variability detected in HR 4796 at the stellar radial velocity along a selection of spectra taken on 2002-01-19. The thick black line in each Figure shows the median spectrum for comparison. The radial velocity of the star is marked with a dashed black line in both Figures.

Figure 4. Variability in the residuals of the Ca\textsc{ii} K line of HR 6507 after normalizing all the epochs by the reference spectrum. The date of each observation is shown. The radial velocity of the star is marked with a dashed black line.

4.6.3 Nearby stars analysis

Similarly to the analysis performed on the objects in our sample, we analysed the Ca\textsc{ii} K lines of nearby stars searching for the presence of absorption features at similar velocities to the ones observed in our objects. Finding these similar absorption lines in the line of sight towards nearby stars would strongly suggest an ISM origin for the gas feature(s). We chose to analyse the Ca\textsc{ii} K line since its absorption is more intense and easier to detect than the H line and it is the main tracer of circumstellar gas in the optical.

For each star of our sample, we searched for high resolution spectra of nearby stars within a search-box of up to 6 degrees (~3 degrees radius). Considering the distances of the objects, the equivalent projected separations between the targets and their neighbours range between ~0.1 pc and ~30 pc. From the gathered data, we only considered objects having early spectral types, ideally between B0 and F5, since absorption features are harder to detect in later spectral types. Non-photospheric gas absorptions are easily spotted when superimposed on fast rotators having wider (and fewer) spectral lines.

We found suitable nearby stars for all the candidates except for 66 Psc and HD 24966. The observations used for this analysis are described in Table C1. We found absorption

Table 7. Summary of the detection of absorptions consistent with DIBs at either 5780.5 Å or 5797.1 Å.

| Name     | DIB at 5780.5 Å | DIB at 5797.1 Å |
|----------|----------------|-----------------|
| β03 Tuc  | ✓              | ×               |
| 66 Psc   | ×              | ×               |
| ν Hor    | ×              | ×               |
| HD 24966 | ×              | ×               |
| HD 290540| ✓              | ✓               |
| HD 36544 | ✓              | ✓               |
| HD 290609| ✓              | ✓               |
| HR 1919  | ×              | ×               |
| HD 54341 | ×              | ×               |
| HD 60856 | ✓              | ✓               |
| HR 3300  | ×              | ✓               |
| η Cha    | ×              | ×               |
| HD 92536 | ✓              | ×               |
| 3 Crv    | ×              | ×               |
| HD 106036| ✓              | ×               |
| HR 4796  | ×              | ×               |
| HD 110058| ×              | ×               |
| HD 112810| ×              | ×               |
| HD 126135| ✓              | ✓               |
| HD 141378| ×              | ✓               |
| HD 141327| ✓              | ✓               |
| HR 6507  | ×              | ×               |
| c Aql    | ×              | ×               |
features present in all the nearby stars and they match most of the absorption features found in our objects, confirming the interstellar origin for the majority of the features. In the case of HD 110058, we found that three nearby stars presented one absorption feature matching HD 110058 absorption line at $\sim 1 \text{ km.s}^{-1}$, one star shows a weak absorption matching the radial velocity of the G cloud, but none of the nearby stars shows any signs of absorption lines matching the one at $\sim 12 \text{ km.s}^{-1}$, which also happens to be near the estimated radial velocity of this star. Therefore we propose a circumstellar origin for this feature.

A comparison of the nearby stars absorption lines against our objects and their respective angular separations are shown in Figs. C1 to C4.

4.7 General results

We present a summary of our results regarding stable features in Table 8, in which we report the radial velocity of the star, the traversing clouds, their radial velocities and whether they match one of the observed features, the average velocities of each absorption feature, its Ca\textsuperscript{ii}/Na\textsuperscript{i} density ratio, whether it has a matching absorption in a nearby star and our verdict on its origin; ISM (InterStellar Medium) or CS (CircumStellar).

Most of the stable features are likely produced by clouds in the line of sight and not by the circumstellar medium, except in the cases of HR 4796 and HD 110058. We find that two objects present variability: HR 4796 shows flux variations in its feature located at the same velocity as the star and c Aql exhibits transient red-shifted absorption lines with characteristics of FEB-like events. Another interesting case is that of HR 6507, for which a clear diagnostic cannot be attained with the available data as discussed in Sec. 5.2.2.
Table 8: Absorption components and their mean radial velocity, CaT/NaI density ratio, absorption feature detection in a nearby star and proposed origin.

| Name        | Stellar RV [km.s$^{-1}$] | Cloud Name | Cloud RV [km.s$^{-1}$] | Matching Feature? | Feature RV [km.s$^{-1}$] | $X_{NaI}$/CaT | Nearby star Origin |
|-------------|---------------------------|------------|-------------------------|--------------------|---------------------------|--------------|-------------------|
| β03 Tuc     | 6.05 ± 1.60               | –          | –                       | –                  | -11.22                    | 3.47         | ISM               |
|             |                           | Dor        | 13.85 ± 0.65            | x                  | -3.74                     | 0.38         | ISM               |
|             |                           | Vel        | 2.54 ± 0.78             | ✓                  | 2.26                      | 13.08        | ISM               |
| 66 Psc      | 4.32 ± 2.66               | –          | –                       | –                  | -5.71                     | 0.63         | ISM               |
|             |                           | –          | –                       | –                  | 0.49                      | 0.40         | –                 |
| ν Hor       | 13.58 ± 1.67              | LIC        | 11.44 ± 1.29            | ✓                  | 11.49                     | 7.03         | – ISM             |
|             |                           | G          | 5.33 ± 1.52             | ✓                  | 4.11                      | 6.16         | ISM               |
|             |                           | Vel        | 12.65 ± 0.93            | ✓                  | 12.74                     | 2.94         | ISM               |
|             |                           | Cet        | 9.85 ± 0.63             | x                  | -9.09                     | < 1          | ISM               |
| HD 24966    | 15.70 ± 3.15              | Blue       | 10.59 ± 1.30            | x                  | -13.10                    | > 5          | ISM               |
|             |                           | G          | 17.51 ± 1.38            | ✓                  | 15.68                     | 8.40         | – ISM             |
|             |                           | Dor        | 32.11 ± 0.85            | ✓                  | 32.15                     | 6.58         | – ISM             |
| HD 290540   | 27.26 ± 3.12              | –          | –                       | –                  | 9.28                      | 1.31         | ISM               |
|             |                           | –          | –                       | –                  | 23.78                     | 1.04         | ISM               |
|             |                           | –          | –                       | –                  | 35.51                     | 0.46         | ISM               |
|             |                           | –          | –                       | –                  | -3.99                     | < 1          | ISM               |
| HD 36444    | 26.72 ± 4.50              | LIC        | 22.75 ± 0.96            | ✓                  | 21.99                     | 0.72         | ISM               |
|             |                           | –          | –                       | –                  | 31.30                     | 1.00         | ISM               |
|             |                           | –          | –                       | –                  | 40.51                     | > 5          | ISM               |
| HD 290609   | 25.87 ± 1.65              | –          | –                       | –                  | -8.89                     | 3.05         | ISM               |
|             |                           | –          | –                       | –                  | 8.99                      | 2.70         | ISM               |
|             |                           | –          | –                       | –                  | 23.50                     | 0.73         | ISM               |
|             |                           | –          | –                       | –                  | 34.90                     | 3.24         | ISM               |
| HR 1919     | 23.49 ± 1.28              | –          | –                       | –                  | 10.63                     | 5.59         | ISM               |
|             |                           | –          | –                       | –                  | 31.11                     | 11.97        | ISM               |
| HD 54341    | 41.03 ± 0.95              | –          | –                       | –                  | 3.31                      | < 1          | ISM               |
|             |                           | Blue       | 9.59 ± 0.93             | ✓                  | 10.32                     | > 5          | ISM               |
| HD 60856    | 31.89 ± 1.59              | LIC        | 16.37 ± 1.18            | x                  | 20.32                     | 0.40         | ISM               |
|             |                           | –          | –                       | –                  | 25.38                     | 2.80         | ISM               |
| HR 3300     | 22.35 ± 0.72              | –          | –                       | –                  | 29.98                     | 1.55         | ISM               |
|             |                           | G          | 4.62 ± 0.94             | ✓                  | 5.95                      | 2.97         | ISM               |
|             |                           | Vel        | 15.00 ± 0.97            | ✓                  | 16.75                     | 1.08         | ISM               |
|             |                           | Cet        | 20.50 ± 0.87            | ✓                  | 20.82                     | > 5          | ISM               |
| η Cha       | 15.21 ± 1.41              | G          | -4.07 ± 1.17            | ✓                  | -2.84                     | 2.47         | ISM               |
|             |                           | Vel        | 0.02 ± 0.75             | x                  | 10.94                     | 2.07         | ISM               |
| HD 92536    | 15.45 ± 0.44              | G          | -6.09 ± 0.97            | x                  | 0.90                      | 6.52         | ISM               |
|             |                           | –          | –                       | –                  | 9.47                      | 0.77         | ISM               |
|             |                           | –          | –                       | –                  | 17.84                     | 2.21         | ISM               |
| 3 Crv       | 14.41 ± 1.09              | Leo        | -5.36 ± 1.05            | ✓                  | -7.00                     | 1.65         | ISM               |
|             |                           | –          | –                       | –                  | -1.89                     | 9.91         | ISM               |
| HD 106036   | 9.37 ± 2.34               | Gem        | 2.54 ± 0.95             | ✓                  | 2.96                      | > 5          | ISM               |
|             |                           | G          | -11.13 ± 0.98           | x                  | -4.78                     | –           | ISM               |
|             |                           | –          | –                       | –                  | 10.18                     | –           | ISM               |
| HR 4796     | 5.35 ± 2.94               | –          | –                       | –                  | -12.97                    | 3.79         | ISM               |
|             |                           | –          | –                       | –                  | -5.38                     | 0.64         | ISM               |
|             |                           | –          | –                       | –                  | 5.20                      | > 5          | X CS              |
| HD 110058   | 11.20 ± 0.81              | G          | -14.46 ± 0.97           | x                  | 0.95                      | 1.68         | ISM               |
|             |                           | –          | –                       | –                  | 12.35                     | 1.02         | X CS              |
| HD 112810   | 5.25 ± 2.24               | G          | -15.70 ± 0.97           | x                  | -11.48                    | –           | ISM               |
|             |                           | –          | –                       | –                  | -4.12                     | –           | ISM               |
|             |                           | –          | –                       | –                  | 3.02                      | –           | ISM               |
| HD 126135   | 11.73 ± 0.67              | NGP        | -24.28 ± 1.22           | ✓                  | -22.46                    | 0.82         | ISM               |

Continued on next page

Gas in debris disks
Table 8 – continued from previous page

| Name     | Stellar RV [km.s\(^{-1}\)] | Cloud Name | Cloud RV [km.s\(^{-1}\)] | Matching Feature? | Feature RV [km.s\(^{-1}\)] | \(\text{N(Ca}^{\text{ii}}\) | \(\text{N(Na}^{\text{i}}\) | Nearby star | Origin |
|----------|-----------------------------|------------|--------------------------|--------------------|----------------------------|-------------------|-----------------|------------|--------|
| Gem      | -14.33 ± 1.01               |            | -14.58                   | ✓                  | 0.80                       | ✓                | ✓               | ISM       |
| –        | –                           | –          | -9.07                    | 1.89               | ✓                          | ISM              |
| –        | –                           | –          | 4.15                     | 0.20               | ✓                          | ISM              |
| –        | –                           | –          | 26.30                    | < 1                | ✓                          | ISM              |
| HD 141378 | -14.68 ± 2.62               | G          | -28.37 ± 1.18            | ✓                  | -30.03                     | > 5              | ✓               | ISM       |
| –        | –                           | –          | -15.02                   | > 5                | ✓                          | ISM              |
| HD 141327 | -4.65 ± 2.40                | G          | -27.31 ± 1.08            | X                  | -21.69                     | 7.32             | ✓               | ISM       |
| –        | –                           | –          | -3.05                    | 0.31               | ✓                          | ISM              |
| –        | –                           | –          | 14.46                    | 11.08              | ✓                          | ISM              |
| –        | –                           | –          | 22.65                    | 2.12               | ✓                          | ISM              |
| HR 6507  | -36.13 ± 2.49               | –          | -38.95                   | 3.72               | ✓                          | ISM              |
| –        | –                           | –          | -29.71                   | 7.33               | ✓                          | ISM              |
| –        | –                           | –          | -25.02                   | 1.99               | ✓                          | ISM              |
| c Aql    | 17.29 ± 2.61                | Mic, Aql   | -26.86, -25.26           | X                  | -31.43                     | > 5              | X              | ISM       |
| Eri      | -20.11 ± 1.14               | ✓          | -19.77                   | > 5                | ✓                          | ISM              |

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5 DISCUSSION

Gas absorption features superimposed on photospheric lines look fairly similar whether they are caused by clouds in the line of sight of the star or by the presence of stable gas in the circumstellar environment. Therefore, a detailed analysis, involving multiple criteria, has to be performed in order to discriminate between the two scenarios. Below we discuss our results regarding the origin of the features in “interstellar” and “circumstellar” categories.

5.1 Interstellar-like features

Most of the absorption features found in this study are classified as “interstellar” as they do not present significant time variability beyond the noise level or attributable to different instrument or resolution. In addition, all these features possess other characteristics such as having a composition consistent with typical ISM values, matching clouds in their line of sight, or detection of a similar feature in a nearby star with velocities matching within 3σ.

Overall, we found 21 absorption features matching the radial velocity of known clouds traversing the lines of sight of the stars. A summary of the traversing clouds, their radial velocities and the matching absorptions is provided in Table 8. The evidence for these features to be caused by those clouds in the line of sight, is strengthened by the fact that they are also detected in nearby stars around our science targets. A particular case of this phenomenon is observed in the objects HD 290540, HD 36444 and HD 290609.

These three stars are located within an angular separation of 0.7◦ of each other. As can be seen in Fig. C1, the three objects present similar absorption features at similar velocities, which are also detected for three other nearby stars within an angular radius of 1◦. We obtained comparable radial velocities for these three objects, around 26 km.s−1. As noticeable in Fig. C1, they all have a deep absorption line close to 23 km.s−1, which corresponds to the Local Interstellar Cloud (LIC, Redfield & Linsky 2008). Although this absorption line is found to be close to the radial velocity of the stars, its interstellar origin is clear as it is confirmed by being present in other three stars with a similar line of sight and having a N(Ca/Na) ratio consistent with ISM (≤1). The other absorption lines seen in the three objects at ~ 9 and ~ 34 km.s−1 also seem to have a common interstellar origin. The one at ~ 9 km.s−1 is possibly attributable to the Hyades cloud at ~ 11 km.s−1, which according to Redfield & Linsky (2008) crosses near (< 20◦) the line of sight of these three stars. We did not find any known cloud traversing a similar line of sight at a radial velocity close to ~ 34 km.s−1, however, since this absorption line is present in several stars at a similar velocity we also conclude that it is of interstellar origin.

There is a fourth feature at ~ 41 km.s−1 for HD 36444 detected only in the Ca II lines which, due to its mostly Calcium composition (N(Ca/Na) > 5) could be consistent with having a circumstellar origin. However, a similar feature is observed in the nearby star HR 1863, and therefore it is likely to be another feature of interstellar origin, possibly warm ISM, which has been reported to have a composition richer in Calcium than cold ISM (Bertin et al. 1993). Unfortunately we have obtained only one epoch for HD 36444 therefore we were not able to investigate the variability of this feature. Further data is thus necessary in order to fully rule out circumstellar origin.

HD 290609 also presents a fourth feature, but it is detected around ~ 51 km.s−1. However, we point out that this group of stars is located within the Orion OB1 association (Hernández et al. 2006) making it likely that environmental nebular gas is observed at different velocities (Brown et al. 1994). In any case, although we conclude an ISM origin for HD 290609’s fourth feature because of the high frequency of interstellar clouds observed in the surroundings; as in the previous case, there is only one spectrum available for HD 290609 and it would be interesting to perform further analysis gathering more epochs in order to better assess the origin of this feature.

5.2 Circumstellar-like features

5.2.1 Stable features with no matching absorptions in nearby stars

In the case of HD 110058, we found that three nearby stars present one absorption feature matching HD 110058’s absorption at ~ 1 km.s−1, thus we propose an interstellar origin for this feature. This interstellar feature was also reported by Hales et al. (2017), who analysed MIKE spectra of HD 110058 and three nearby stars (at angular separations between 1.2” and 2.8”) and found matching features for the absorption at ~ 1 km.s−1. We obtained further spectra for four different nearby stars in the ESO archive (at angular separations between 0.74” and 2.16”) and confirmed the matching absorption lines in three stars, in agreement with the findings by Hales et al. (2017). Given the distance to this star (188 ± 34.1 pc), both studies cover a region of 2.4 – 9.2 pc in radius. Considering a typical radius of 1.5 pc for the warm local ISM material located within 15 pc from the Sun (Redfield & Linsky 2008), the projected coverage at the distance of HD 110058 would be about 19 pc, thus the local ISM material would likely cover the region in which the nearby stars are located. On the other hand, our measurements of the equivalent widths of this feature is in agreement with a more recent work by Rebollido et al. (2018), where the authors report that the strength measured for this blue-shifted component varies with respect to Hales et al. (2017) measurement, proposing a possible circumstellar origin for the blue-shifted feature at ~ 1 km.s−1. Considering the scenario of variability in the blue-shifted component and a possible overlap of circumstellar feature over the interstellar it would be worth performing follow-up observations of this object to better assess the origin of this feature. There is a fourth nearby star analyzed which does not present a feature at said velocity, but shows a weak absorption line at ~ −15 km.s−1 matching the radial velocity of the G cloud. HD 110058 presents an additional absorption feature at ~
12 km s$^{-1}$ which is very near our estimate of the radial velocity of this star (11.20 km s$^{-1}$). None of the nearby stars analyzed show any sign of absorption matching HD 110058’s absorption line at $\sim 12$ km s$^{-1}$. Therefore we propose a circumstellar origin for this feature. This circumstellar feature was also proposed by Hales et al. (2017) and confirmed by Rebollido et al. (2018), thus our analysis is in agreement with their conclusions.

5.2.2 Variable features

We detected variable absorption features attributable to FEB-like events in the objects c Aql and HR 4796. The detection of FEB-like events in c Aql was previously reported by Montgomery & Welsh (2017), where they detected high variations from night to night and attributed them to exocometary activity. Furthermore Welsh & Montgomery (2013) reported some nightly changes but no FEB-like events. With the data collected from the ESO archive we found, in addition to night to night variations, strong variability within very short time scales of only a couple of minutes. To our knowledge, this is the shortest-term variability detected to date in such systems. This object is known to be a pulsating star with a period of 30.39 minutes (Kuschnig et al. 1994) but a phase analysis of the Cati K and the Hα lines does not indicate any such periodicity. In addition, the residual absorption events are not associated with a counterpart in emission at a mirroring velocity with respect to the radial velocity of the star (even taking into account the uncertainty in the latter), as one would expect from pulsations. In the left panel of Fig. 3, we show the variability detected in c Aql through eight individual spectra taken within a time span of $\sim 20$ minutes. Similar short term variability has only been observed so far in $\beta$ Pictoris (Kiefer et al. 2014b) and the shell star $\phi$ Leo (Eiroa et al. 2016), with reported variability within hours.

Variability in the Cati K line of HR 4796 at the same radial velocity of the star is reported here for the first time. Previously, only a sporadic absorption at $\sim 60$ km s$^{-1}$ during the night of 2007-05-04 was reported by Welsh & Montgomery (2015). A more detailed analysis of the variability detected in these two objects will be presented in Iglesias et al. (in prep).

Regarding other objects in our sample with claims of variability in the literature, there are also HR 6507 (Welsh & Montgomery 2015) and HD 24966 (Welsh & Montgomery 2018). In the case of HR 6507, Welsh & Montgomery (2015) modeled the absorption lines using two components at radial velocities $\sim 37$ km s$^{-1}$ and $\sim 28$ km s$^{-1}$. The observations were taken with the Sandiford Echelle Spectrograph at the McDonald Observatory, Texas, with $\sim 60000$ resolution. We combined HARPS and UVES spectra (with higher resolution, $\sim 100000$ and $\sim 80000$, respectively) and were able to distinguish and fit three absorption features at radial velocities $\sim 39$ km s$^{-1}$, $\sim 29$ km s$^{-1}$ and $\sim 25$ km s$^{-1}$. Welsh & Montgomery (2015) attributed a circumstellar origin for the feature observed at $\sim 37$ km s$^{-1}$ because of its proximity to the radial velocity of the star ($\sim 36$ km s$^{-1}$). However, for the corresponding feature, which we measure at $\sim -39$ km s$^{-1}$, we found absorption lines of similar velocity and intensity in nearby stars, suggesting ISM origin.

HR 6507 has also been reported to possess shell star signatures (Hauck & Jaschek 2000, Jaschek et al. 1991), although in other works no clear indication of a shell has been found, attributing this to a weakening or disappearing of the shell (Jaschek et al. 1988, Jaschek & Andrillat 1998). Nevertheless, considering the possibility of HR 6507 being a shell star, it is likely that it possesses circumstellar gas and therefore shows gas signatures at its radial velocity. As mentioned in 4.5, we found small variability in the overall residuals of all the lines observed for HR 6507. In Hauck & Jaschek (2000), they report the star as variable and possibly micro-variable, which might explain the observed variations. Taking all this into account, we do not attribute the variability to FEBs-like events, but a more detailed study of this source is needed to achieve stronger conclusions.

In the case of HD 24966, Welsh & Montgomery (2018) recently proposed the detection of exocomet at different velocity ranges in two out of three observations. The significance and interpretation of such variable transient FEB absorption features will be further investigated in Iglesias et al. (in prep).

5.2.3 Relationship between circumstellar-like features and system properties

Gas absorptions features of presumed circumstellar origin were found in the systems HD 110058, HR 4796 and c Aql.

The debris disk around HD 110058 has been resolved with SPHERE by Kasper et al. (2015), where they determined an inclination of $\sim 90^\circ$. This edge-on orientation reinforces the circumstellar verdict on the gas origin, as this is the most favourable orientation for potentially detecting gas lines in absorption. Since the absorption line that we detect is deep, narrow, stable, and close to the radial velocity of the star, it is consistent with a stable gas component, possibly located in the outer regions of the disk (Beust et al. 1998, Brandeker et al. 2004).

HR 4796 has an inclination of $76.5^\circ$ (Milli et al. 2017, Kennedy et al. 2018) which is fairly close to edge-on. Since somewhat small misalignments in cometary orbits with respect to the parental disk are common (Nesvorný et al. 2017), it is not necessarily unlikely to detect FEB events.

Regarding the disk around c Aql, it has only been marginally resolved with Herschel by Morales et al. (2016). They estimated an inclination of $21^\circ \pm 42^\circ$. Although this inclination does not seem favourable for circumstellar gas detections using optical spectroscopy, the estimated uncertainty on the inclination is very large as the disk was only marginally resolved. The possibility of a much higher inclination cannot be ruled out. Even if the shallower inclination is confirmed, we could still be spotting the activity of bodies with highly inclined orbits. Overall, it is reassuring that two
of our candidates with gas detections are close to edge-on, with very robust inclination determinations.

Regarding the rest of the sample, only two other objects have been marginally resolved (with Herschel): ν Hor, modelled with 73.4° ± 6.5° inclination (Moór et al. 2015), and HD 141378, with an estimated inclination of 60° ± 37° (Morales et al. 2016). We did not detect signs of circumstellar gas in these objects. Nevertheless, it would be worth performing follow-up studies to be able to analyze more epochs and therefore increase the chances of detecting stochastic activity or provide more robust evidence of the lack of such activity.

6 CONCLUSIONS

In this work we have analysed the multiple absorption features present in the Ca ii H & K and Na i D1 and D2 lines of 23 debris disks systems using optical high-resolution spectroscopy in order to determine if their origin is of circumstellar or interstellar nature.

We found gas absorptions of circumstellar nature in three objects: HD 110058, HR 4796 and c Aql. HD 110058 presents a strong stable absorption consistent with a gaseous disk, possibly residual gas leftover from the earlier gas-rich stage of the disk or from very active planetesimal collision episodes.

Variable absorption features were found in the spectra of HR 4796 and c Aql. A weak circumstellar absorption was found in HR 4796 at the same radial velocity as the star with flux variations over 3σ, possibly due to photo-dissociation processes or collisions of icy bodies producing changes in the gas content of the disk. Highly variable red-shifted absorptions were detected in c Aql, with substantial variations observed on time scales shorter than two minutes, which is the shortest variablity detected so far in this type of lines. These fast changing signatures are likely due to exocometary activity within the disk surrounding c Aql. For these two objects, HR 4796 and c Aql, we will present a more detailed analysis of the variable features in a future work. The circumstellar gas detections are in agreement with the near edge-on inclinations of the two objects with robust inclination measurements: HD 110058 with an inclination of ∼ 90° and HR 4796 with an inclination of 76.5°.

Given h, r and i the scale-height, radial distance and inclination of a circumstellar disk, respectively, and assuming a typical scale-height/distance ratio of h/r ∼0.1 for debris disks (Thébault 2009), the typical angle subtended by the disk should be ∼ 5.7°. For a uniform distribution of sin(i) between 0 and 1, the probability of i > (90° − 5.7°) is ∼10%, and therefore the probability for a randomly inclined system to be found close to edge-on or with an inclination suitable to detect circumstellar gas absorptions is ∼10%.

However, the sample analyzed in this paper cannot, a priori, be considered “random” because of the selection criterion of “having multiple absorption features” (that may bias the sample towards objects with circumstellar gas on close to edge-on orientation). On the other hand, this sample is actually unbiased with respect to stochastic detections such as FEBs (we remind the reader that the selection function was performed on the reference spectra, i.e. only stable components are considered).

Bearing in mind that the inclination constraints could be more relaxed regarding the detection of FEBs (as discussed in Sec. 5.2.3); that FEBs, given their stochastic nature, may not be detected by mere chance at our epochs of observations; and that, in any case, we do detect circumstellar gas in three cases out of 23 objects (one stable and two variables); our results definitely point towards gas in debris disks not being a rare phenomenon. We will, however, have more quantitative and robust results on this matter once the full sample of 301 debris disks is analyzed.

ACKNOWLEDGEMENTS

DI would like to thank Iván Lacerna, support astronomer at the MPG/ESO 2.2m telescope, La Silla Observatory, for his significant help and support during the observing runs with FEROS and Alain Smette, the author of Molecfit, for his great help on improving telluric corrections. AB and DI acknowledge financial support from the Proyecto Fondecyt Iniciación 11140572. DI, AB and JO acknowledge support from the Millennium Science Initiative (Chilean Ministry of Economy), through grant Núcleo Milenio de Formación Planetaria. This work has made use of data from the ESA space mission Gaia (http://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, http://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This publication makes use of VOSA, developed under the Spanish Virtual Observatory project supported from the Spanish MICINN through grant AYA2011-24052. Data from the following programmes have been used in this work: CNTAC 096.A-9018(A) and 094.A-9012(A); and ESO 096.C-0238(A), 097.C-0409(A), 097.C-0409(B), 073.C-0733(E), 075.C-0689(A), 077.C-0295(A), 077.C-0295(B), 184.C-0815(A), 184.C-0815(E), 184.C-0815(F), 096.C-0238(A), 075.C-0689(B), 077.C-0295(D), 080.C-0712(A), 094.C-0946(A), 076.C-0279(A), 076.C-0279(B), 076.C-0279(C), 078.C-0290(A), 082.A-9004(A), 088.A-9029(A), 66.D-0284(A), 60.A-9036(A), 60.A-9120(B), 60.A-9122(B), 084.A-9003(A), 085.A-9027(G), 184.C-0815(C), 68.C-0548(A), 078.A-9059(A), 079.A-9007(A), 079.A-9009(A), 079.C-0789(A), 085.A-9027(B), 084.D-0067(A), 087.A-9013(A), 092.A-9006(A), 179.C-0197(A), 179.C-0197(C), 082.D-0061(A), 077.C-0295(C), 083.C-0679(A), 079.D-0567(A), 083.A-9014(A), 083.A-9014(B), 087.B-0308(A), 073.C-0733(E), 075.C-0689(A), 077.C-0295(A), 077.C-0295(B), 094.A-9012(A), 179.C-0197(B), 088.C-0408(A), 074.B-0455(A), 266.D-5655(A), 194.C-0833(C), 096.A-9030(A), 096.A-9024(A), 082.C-0831(A), 084.C-1008(A), 084.A-9004(B), 091.D-0414(B), 088.A-9003(A), 072.D-0410(A), 098.C-0463(A),
APPENDIX A: PHOTOSPHERIC LINE FITS

In this appendix we provide the Figures illustrating the Kurucz models that best reproduce each one of the lines of the reference spectrum for each star in the sample. In all cases the reference spectrum is displayed in black and the best fitting model in red. Please note that the parameters are allowed to vary between different lines for the same object (as these models do not include non-LTE effects).

APPENDIX B: RESIDUAL COMPONENTS

In this appendix we provide the Figures showing every isolated component and the multi-gaussian fit obtained to reproduce and characterize those features.

APPENDIX C: NEIGHBOURING STARS

In this appendix we show the analysis performed with neighbouring stars looking for features of similar characteristics to those detected in each “science” target (paying particular attention to the velocity). The detection of the same feature in several stars does automatically support an ISM origin of the feature.
Figure A1. Best-fit models for β03 Tuc’s, 66 Psc’s, ν Hor’s, HD 24966’s, HD 290540’s and HD 36444’s CaII H&K and NaI D1&D2 lines. Median from the real spectra in black, synthetic spectrum in red.
Figure A2. Best-fit models for HD 290609’s, HR 1919’s, HD 54341’s, HD 60856’s, HR 3300’s and η Cha’s CaII H&K and NaI D1&D2 lines. Median from the real spectra in black, synthetic spectrum in red.
Figure A3. Best-fit models for HD 92536’s, 3 Crv’s, HD 106036’s, HR 4796’s, HD 110058’s and HD 126135’s Ca II H&K and Na I D1&D2 lines. Median from the real spectra in black, synthetic spectrum in red.
Figure A4. Best-fit models for HD 141378’s, HD 141327’s, HR 6507 and c Aql’s Ca\textsc{ii} H&K and Na\textsc{i} D1&D2 lines. Median from the real spectra in black, synthetic spectrum in red.
Figure B1. Absorption profiles of the Ca$\text{ii}$ H & K and Na$\text{I}$ D1 & D2 lines for β03 Tuc, 66 Psc and ν Hor. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B2. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HD 24966, HD 290540 and HD 36444. Photospheric absorptions have been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B3. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HD 290609, HR 1919 and HD 54341. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B4. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HD 60856, HR 3300 and $\eta$ Cha. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B5. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HD 92536, 3 Crv and HD 106036. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B6. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HR 4796, HD 110058 and HD 112810. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B7. Absorption profiles of the Ca\textit{ii} H & K and Na\textit{i} D1 & D2 lines for HD 126135, HD 141378 and HD 141327. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure B8. Absorption profiles of the Ca\textsc{ii} H & K and Na\textsc{i} D1 & D2 lines for HR 6507 and c Aql. Photospheric absorptions has been subtracted and the remaining extra components have been modelled by gaussian profiles. Individual gaussian fits are shown in dotted magenta lines and the combined profile is shown in red. Dashed black line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure C1. Nearby stars around β Tuc, ν Hor, HD 290540 (along with HD 36444 and HD 290609), HR1919, HD 54341 and HD 60856. Dashed line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure C2. Nearby stars around HR 3300, η Cha, HD 92536, 3 Crv, HD 106036 and HR 4796. Dashed line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure C3. Nearby stars around HD 110058, HD 112810, HD 126135, HD 141378, HD 141327 and HR 6507. Dashed line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Figure C4. Nearby stars around c Aql. Dashed line marks the estimated radial velocity of the star and cyan lines mark the velocity of the traversing clouds in the line of sight with their respective errors as their line widths.
Table C1: All nearby stars used in the analysis per each object of science, their number of spectra, instrument and ESO program ID. Note that HD 290540, HD 36444 and HD 290609 are each other’s nearby stars and in addition have three other common nearby stars.

| Object           | Nearby star     | Number of Spectra | Instrument | Program ID       |
|------------------|-----------------|-------------------|------------|------------------|
| β03 Tuc          | β01 Tuc         | 6                 | HARPS      | 073.C-0733(E)    |
|                  |                 | 2                 | HARPS      | 075.C-0689(A)    |
|                  |                 | 2                 | HARPS      | 077.C-0295(A)    |
|                  |                 | 2                 | HARPS      | 077.C-0295(B)    |
|                  |                 | 3                 | FEROS      | 094.A-9012(A)    |
| ν Hor            | HR 798          | 1                 | FEROS      | 179.C-0197(B)    |
|                  | HR 762          | 4                 | FEROS      | 088.C-0498(A)    |
| HD 290540, HD 36444 and HD 290609 | HR 1861 | 1 | FEROS | 074.B-0455(A) |
|                  |                 | 12                | UVES       | 266.D-5655(A)    |
|                  | VVV Ori         | 98                | UVES       | 194.C-0833(C)    |
|                  |                 | 6                 | FEROS      | 096.A-9030(A)    |
|                  |                 | 2                 | FEROS      | 096.A-9024(A)    |
| HR 1919          | VV350 Ori       | 2                 | UVES       | 082.C-0831(A)    |
|                  | HD 38735        | 79                | FEROS      | 084.C-1008(A)    |
|                  |                 | 24                | FEROS      | 084.A-9004(B)    |

Continued on next page
| Object | Nearby star | Number of Spectra | Instrument | Program ID     |
|--------|-------------|-------------------|------------|---------------|
| HD 54341 | L01 Pup | 4 | FEROS | 091.D-0414(B) |
| HD 60856 | HD 61045 | 8 | UVES | 072.D-0410(A) |
| HR 3300 | HD 70731 | 7 | UVES | 093.D-0852(A) |
|          | HD 71722 | 5 | HARPS | 094.C-0946(A) |
|          |          | 12 | FEROS | 094.A-9012(A) |
| η Cha   | HD 75505 | 7 | FEROS | 084.A-9003(A) |
|          |          | 1 | FEROS | 086.A-9006(A) |
|          | 9 Cha | 310 | FEROS | 078.D-0549(A) |
|          |          | 3 | FEROS | 084.A-9003(A) |
| HD 92536 | tet Car | 1 | FEROS | 073.D-0291(A) |
|          |          | 1 | FEROS | 074.D-0300(A) |
|          |          | 15 | UVES | 076.C-0503(A) |
|          |          | 80 | UVES | 077.C-0547(A) |
|          |          | 1 | FEROS | 078.D-0080(A) |
|          |          | 125 | UVES | 194.C-0833(A) |
|          | VV407 Car | 9 | FEROS | 086.D-0449(A) |
|          | HD 93738 | 2 | FEROS | 096.A-9018(A) |
|          | VV364 Car | 6 | FEROS | 086.D-0449(A) |
| 3 Crv   | zet Crv | 1 | FEROS | 179.C-0197(D) |
| HD 106036 | zet Cru | 1 | FEROS | 090.D-0358(A) |
| HR 4796 | u Cen | 30 | FEROS | 60.A-9700(A) |
|          |          | 121 | HARPS | 60.A-9036(A) |
|          |          | 120 | HARPS | 60.A-9700(G) |
| HD 110058 | tau Cen | 8 | HARPS | 076.C-0279(A) |
|          |          | 4 | HARPS | 076.C-0279(C) |
|          |          | 1 | FEROS | 078.D-0080(A) |
|          |          | 20 | UVES | 087.D-0010(A) |
| HD 110484 | 3 | FEROS | 083.C-0139(A) |
| HR 4871 | 1 | FEROS | 078.D-0080(A) |
|          | 1 | FEROS | 087.C-0227(C) |
|          | 13 | HARPS | 088.C-0353(A) |
|          | 13 | HARPS | 089.C-0000(A) |
| sig Cen | 1 | FEROS | 082.B-0484(A) |
| HD 112810 | H Cen | 10 | UVES | 266.D-5555(A) |
|          | 2 | HARPS | 185.D-0056(A) |
|          | 1 | HARPS | 185.D-0056(C) |
| HD 126135 | a Cen | 14 | UVES | 266.D-5555(A) |
|          | 64 | UVES | 073.D-0504(A) |
|          | 3 | HARPS | 075.C-0234(A) |
|          | 3 | HARPS | 079.C-0170(A) |
|          | 18 | UVES | 081.C-0475(A) |
|          | 4 | UVES | 097.D-0035(A) |
| HD 124961 | 2 | FEROS | 072.D-0021(A) |
|          | 2 | FEROS | 073.D-0049(A) |
|          | 2 | FEROS | 082.D-0061(A) |
| HD 141378 | HD 141569 | 1 | UVES | 075.C-0637(A) |
|          | 109 | UVES | 079.C-0789(A) |
|          | 1 | FEROS | 083.A-9003(A) |
|          | 7 | FEROS | 085.A-9027(B) |
| b Ser   | 10 | UVES | 076.B-0055(A) |
|          | 8 | HARPS | 077.C-0295(A) |
|          | 2 | HARPS | 077.C-0295(C) |
|          | 2 | FEROS | 083.A-9014(A) |
|          | 2 | FEROS | 083.A-9011(B) |
|          | 1 | FEROS | 083.A-9014(B) |
|          | 3 | FEROS | 084.A-9011(B) |

Continued on next page
| Object   | Nearby star | Number of Spectra | Instrument | Program ID     |
|----------|-------------|-------------------|------------|----------------|
| HD 141327| HD 142426   | 3                 | FEROS      | 085.A-9027(G)  |
|          |             | 6                 | FEROS      | 089.D-0097(B)  |
|          |             | 2                 | FEROS      | 090.D-0061(B)  |
|          |             | 2                 | FEROS      | 091.D-0145(A)  |
| HD 140037|             | 1                 | FEROS      | 179.C-0197(C)  |
|          |             | 1                 | FEROS      | 091.C-0713(A)  |
| ksi01 Lup|             | 11                | FEROS      | 075.D-0342(A)  |
|          |             | 6                 | HARPS      | 075.C-0689(A)  |
|          |             | 2                 | HARPS      | 075.C-0689(B)  |
|          |             | 2                 | HARPS      | 077.C-0295(D)  |
| ksi02 Lup|             | 2                 | HARPS      | 075.C-0689(B)  |
|          |             | 2                 | HARPS      | 077.C-0295(D)  |
|          |             | 2                 | HARPS      | 077.C-0295(C)  |
|          |             | 12                | HARPS      | 184.C-0815(F)  |
| HR 6051  | HD 146029   | 1                 | FEROS      | 179.C-0197(A)  |
|          | HD 144822   | 1                 | FEROS      | 077.C-0138(A)  |
| HR 6507  | V2373 Oph   | 9                 | FEROS      | 091.D-0122(A)  |
|          | HD 156208   | 8                 | FEROS      | 081.D-2002(A)  |
| c Aql    | BD+01 3992  | 10                | UVES       | 293.D-5036(A)  |
|          | HD 183735   | 1                 | FEROS      | 083.D-0034(A)  |

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