A&A 416, L5–L8 (2004)
DOI: 10.1051/0004-6361:20040026

Astronomy & Astrophysics

Far Ultraviolet Spectroscopy of HD 76534

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Received 22 December 2003 / Accepted 22 January 2004

Abstract. We present the first Far Ultraviolet Spectroscopic Explorer (*FUSE*) spectrum of HD 76534, a Herbig Be star. Here we focus on the analysis of the H_2 absorption lines which allow to quantify the gaseous content along the line of sight. This analysis evidences large amounts of cold and warm H_2 toward the star. We demonstrate that the H_2 is bound to HD 76534 and we argue that it is likely distributed in a circumstellar envelope. In addition, the present study gives clues for the existence of common properties for the circumstellar H_2 of Herbig Ae/Be stars.

Key words. stars: circumstellar matter – stars: pre-main sequence – stars: individual: HD 76534

1. Introduction

Herbig Ae/Be stars (HAeBes) are the likely precursor of the β-Pictoris and Vega-type stars, whose circumstellar (CS) debris disks are believed to host planetary bodies. In the past four years, millimeter-wave interferometry as well as coronagraphic imaging have evidenced the presence of massive CS disks around Herbig Ae (HAe) stars (Mannings & Sargent 2000; Pantin et al. 2000; Augereau et al. 2001; Grady et al. 2001; Roberge et al. 2001). In addition, the spectral energy distribution (SED) of HAeBes (especially the dip that occurs at 10 μm) cannot be explained by normal dust-removal processes, such as the Poynting-Robertson effect and radiation pressure due to the star. Rather, it suggests that the dust structure is evolving because of a break-up of the disk, possibly caused by planet formation.

However, while HAe stars are now relatively well documented, the nature and evolutionary status of the CS environment of Herbig Be (HBe) stars is still largely unknown. Natta et al. (2000) emphasized structural differences between HAe and HBe stars, based on their findings that a large number of HAe stars appear to be associated with CS disks while the HBe stars generally lack clear evidence of disks. Indeed, those authors showed that the latter are often found inside large cavities, depleted of dust and gas. They interpreted these observations by the faster evolution of the circumstellar environment of HBe stars, due to their higher masses.

HD 76534 is a bright (V = 8.02 mag) B2.5 star (Valenti et al. 2000). It illuminates a reflection nebula in which it is embedded, and it is a member of the Vela R2 Association (Herbst 1975). Finkenzeller & Mundt (1984) were the first to classify HD 76534 as a Herbig star, but this status has been questioned by Thé et al. (1985) due to its low near-infrared (NIR) excess, which differs from the whole class of Herbig Ae/Be stars. Since then, authors agreed to classify it as a Herbig Be star (Hillenbrand et al. 1992; Thé et al. 1994; Valenti et al. 2000; Maheswar et al. 2002). The low NIR excess in the SED of HD 76534 could easily be explained by the clearing of the dusty material from the close CS environment of the star by the strong stellar radiation field. Alternatively, this clearing of dust in the inner region of the circumstellar environment of HD 76534 may represent a very early phase of planet formation.

In this Letter, we focus on an analysis of the molecular hydrogen absorption lines in the *FUSE* spectrum of HD 76534 which allows us to quantify the gaseous content of the CS environment of the star. In Sect. 2, we present the observational material. Section 3 is devoted to the analysis of the circumstellar gas and especially the analysis of H_2 absorption lines whose results are discussed in Sect. 4.

2. Observations and data reduction

HD 76534 was included in the *FUSE* Cycle 2 Guest Investigator Program, B038 (P.I. C. Catala; see Bouret et al. 2003), and was observed on March 11, 2002, with the *FUSE* 30″ × 30″ LWRS aperture. The observation covers the wavelength spectral range 905–1187 Å at a spectral resolution of $R \simeq 15\,000$. The data were processed with the version 2.4.1 of the *FUSE* pipeline, CalFUSE. The total exposure time of 5711 seconds was split into 10 subexposures, although for 6 of

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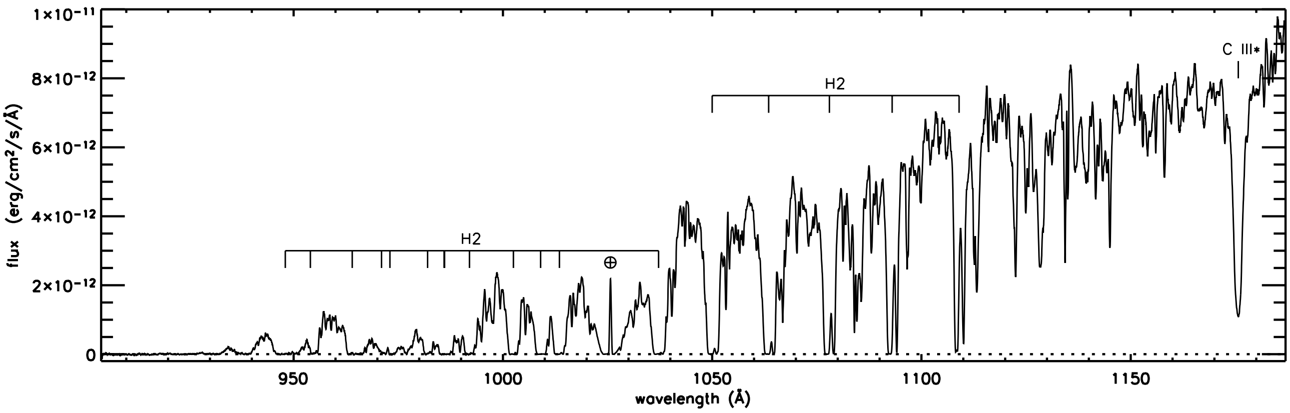

Fig. 1. Observed *FUSE* spectrum of HD 76534. For the sake of clarity, the spectrum has been binned by 5 pixels and smoothed. As expected for a B2.5 star such as HD 76534, the stellar continuum is detected down to 930 Å. The principal broad absorption lines of H_2 are indicated throughout the spectrum. Airglow lines are labeled with ⊕ symbol. Note the presence of the absorption line due to the C III multiplet UV 4 at 1175 Å.

them the target was not in the aperture. Thus, only the other 4 subexposures, which represent about 2200 s, were used. This was sufficient to ensure a good flux level in each segment of the spectrum because of the early spectral type of the star.

The LiF 1b segment was affected by the so-called "worm artifact" in the detector which artificially decreases the flux level. Thus, for the spectral lines analysis we used the LiF 2a segment, which covers the same wavelength range as the LiF 1b.

The co-added spectra in each detector channel were rebinned in wavelength by a factor 5 in order to increase the S/N ratio to 35 per spectral element resolution at 1150 Å, without degrading the resolution. An overview of the whole *FUSE* spectra is shown in Fig. 1.

The absolute wavelength calibration of each segment in the rest frame of the star was done by comparing the spectrum with a photospheric model using the stellar parameters in Table 1 (discussed hereafter). The age and mass were kindly calculated for us by Dr. L. Testi from the Palla & Stahler (1999) tracks using the interpolation routines written for the Testi et al. (1998) study.

To help disentangle circumstellar and/or interstellar (CS/IS) spectral lines from the purely photospheric ones, we undertook a modeling of the photosphere of HD 76534, using the TLUSTY and SYNSPEC codes (Hubeny & Lanz 1995). Previously, we used the same method to determine photospheric parameters in our analysis of the Herbig stars HD 259431 and HD 250550 (Bouret et al. 2003). We refer the reader to that paper for more details.

Table 1. Astrophysical parameters of HD 76534. $v_{\rm rad}$ is measured in the heliocentric rest frame.

Spectral Type	B2.5	(3)
$T_{\rm eff}$ (K)	20 000 ± 1000	(1)
log$g$	4.0	(1)
LogL_* ($L_\odot$)	2.83	(1)
R_* ($R_\odot$)	2.16	(1)
M_* ($M_\odot$)	≥5	(2)
$v \sin i$ (km s^{-1})	110 ± 10	(1)
$A_{\rm v}$ (m)	0.80	(3)
Age (Myr)	≥0.5	(2)
$v_{\rm rad}$ (km s^{-1})	+17	(4)

(1) This work; (2) Dr. L. Testi (private communication); (3) Valenti et al. (2000); (4) Finkenzeller & Jankovics (1984).

3. Gaseous content

3.1. Analysis of the atomic gas

As expected for a B2.5 star such as HD 76534, the stellar continuum is detected down to 930 Å (Fig. 1). No hot emission lines or wind lines are detected, but the purely photospheric C III multiplet UV 4 at 1175 Å is seen in absorption. This demonstrates that HD 76534 is not an active star and is not in an accretion phase. Numerous CS/IS lines of H_2 and atomic species are seen in absorption. The analysis of those lines has been performed using the OWENS profile fitting procedure, which was written by Dr. M. Lemoine (for details see Lemoine et al. 2002; Bouret et al. 2003). One example of its use is illustrated in Fig. 2. Measuring the radial velocities of atomic and ionic species, we find that two distinct media are present along the line of sight.

Lines of N I, N II, and Fe II corresponding to electronic transitions from ground level as well as fine structure levels are found at the velocity of the star, which suggests that the gas is bound to the star. We have also identified lines of C I, N I, P II, and Ar I, whose radial velocities differ from that of the star by $\Delta v_{\rm rad} \sim +15$ km s^{-1} in the star's rest frame. This radial velocity is close to that measured by Cha & Sembach (2000) for the interstellar Na I toward HD 76534. Thus, these elements appear to be related to interstellar gas in the line of sight.

3.2. Analysis of molecular hydrogen

Molecular hydrogen being the most abundant element in the circumstellar environment of young stars, the analysis of the H_2 lines present in the spectrum allows us to quantify the amount of gas surrounding the star.

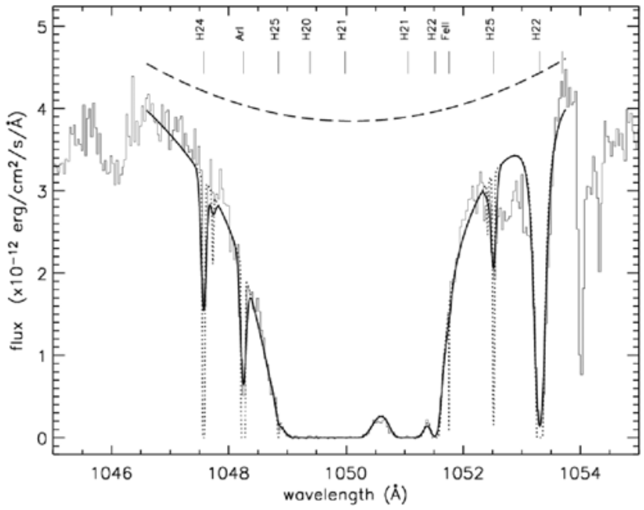

Fig. 2. Example of fit of H_2 lines obtained with the OWENS profile fitting procedure in the observed *FUSE* spectrum of HD 76534. Stellar continuum: dashed line; Intrinsic line profile: dotted line; Resulting profile: thick line.

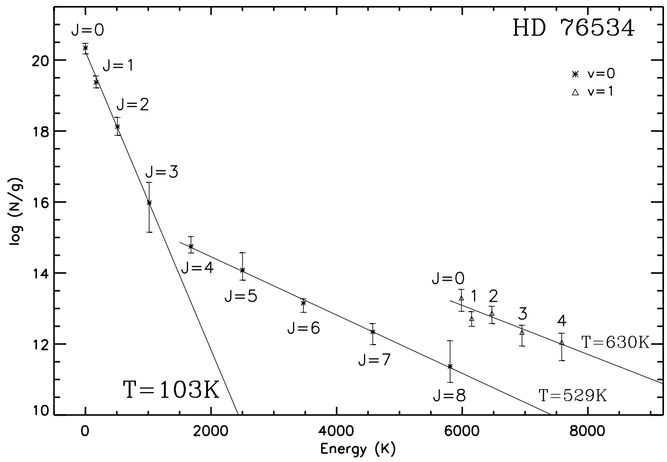

Fig. 3. Excitation diagram for H_2 in HD 76534. The slope for the column densities of the low J-levels ($J = 0-3$) is much steeper than for the higher ($v = 0$, $J = 4-8$) levels and vibrationally excited levels. This reveals both cold and warm components with three different kinetic temperatures (see text).

Table 2. Summary of the column densities of the different energy levels of H_2 in the spectrum of HD 76534.

H_2	v	g	Energy (cm^{-1})	N (cm^{-2})
$J = 0$	0	1	0.00	$2.19^{+0.77}_{-0.71} \times 10^{20}$
$J = 1$	0	9	118.49	$2.09^{+1.08}_{-0.62} \times 10^{20}$
$J = 2$	0	5	354.39	$6.61^{+5.49}_{-2.82} \times 10^{18}$
$J = 3$	0	21	705.50	$1.99^{+5.44}_{-1.69} \times 10^{17}$
$J = 4$	0	9	1168.53	$5.01^{+4.50}_{-1.74} \times 10^{15}$
$J = 5$	0	33	1739.11	$3.98^{+8.42}_{-1.90} \times 10^{15}$
$J = 6$	0	13	2411.77	$1.82^{+0.60}_{-0.82} \times 10^{14}$
$J = 7$	0	45	3179.93	$9.77^{+7.03}_{-5.49} \times 10^{13}$
$J = 8$	0	17	4035.93	$3.98^{+16.92}_{-2.57} \times 10^{12}$
$J = 0$	1	1	4161.00	$1.99^{+1.47}_{-1.16} \times 10^{13}$
$J = 1$	1	9	4274.00	$4.79^{+2.62}_{-1.93} \times 10^{13}$
$J = 2$	1	5	4498.00	$3.71^{+2.06}_{-1.83} \times 10^{13}$
$J = 3$	1	21	4831.00	$4.47^{+2.56}_{-2.63} \times 10^{13}$
$J = 4$	1	9	5271.00	$1.00^{+0.79}_{-0.70} \times 10^{13}$
total				$4.35^{+1.91}_{-1.36} \times 10^{20}$

As shown in Figs. 1 and 2, the *FUSE* spectrum of HD 76534 is rich in broad H_2 absorption lines. We have identified H_2 lines corresponding to $J = 0$ to $J = 8$ in the ground vibrational state ($v = 0$), and rotational levels up to $J = 4$ in the first excited vibrational state ($v = 1$) of the ground electronic state. Column densities were derived from χ^2 fitting of unsaturated and/or damped lines. The results from this process are tabulated in Table 2.

Using these column densities, we have plotted the excitation diagram of H_2 in Fig. 3. This diagram shows that the H_2 is thermalized up to $J = 3$, with a temperature about $T_{03} = 103 \pm 11$ K, while the higher J-levels column densities are consistent with kinetic temperatures of $T_{48} = 529 \pm 68$ K for the $v = 0$, $J = 4-8$ levels, and $T_{(v=1)} = 630 \pm 229$ K for the $v = 1$, $J = 0-4$ levels. These temperatures are higher than the typical temperature of the IS medium (Rachford et al. 2002), thus suggesting that the gas is located close to the star. Moreover, the H_2 radial velocity we measured at $v_{\rm rad} = 0.0^{+0.27}_{-1.35}$ km s^{-1} in the star's rest-frame clearly confirms the circumstellar origin of gas we detect toward HD 76534.

4. Discussion

The total H_2 column density in the CS environment of HD 76534 is comparable to what is generally measured in dense IS molecular clouds, although very different physical conditions prevail in the latter. Indeed, in those clouds H_2 is known to be thermalized up to $J = 1$ with a kinetic temperature about ~50 K (Rachford et al. 2002). In opposite, in the circumstellar environment of HD 76534, the H_2 is thermalized up to $J = 3$ with a kinetic temperature of 103 ± 11 K. These differences between properties of circumstellar H_2 and interstellar H_2 are confirmed by previous studies of the close CS environment of HAeBes. Published results regarding HAeBes observed with *FUSE* have shown that the circumstellar H_2 is thermalized up to $J = 3$ or $J = 4$, with kinetic temperatures in the range of 90 K to 800 K (Bouret et al. 2003; Lecavelier des Etangs et al. 2003). These results concern a sample of Herbig stars that span the spectral range A1–B2 (including HD 76534). Some of them, like HD 100546, are known to host a CS disk (Lecavelier des Etangs et al. 2003), while earlier stars, like HD 259431 (Bouret et al. 2003), most likely possess CS envelopes. The present study is a clue for the existence of common properties for the circumstellar H_2 of HAeBes, that differ from those of the interstellar H_2. This behaviour is further confirmed by our preliminary analysis of the circumstellar H_2 in the *FUSE* spectrum of the Herbig Be star HD 176386.

The amount of H_2 we have measured in the CS environment of HD 76534 represents a significant reservoir for the possible formation of gas giant planets. However, most of the models of giant planet formation predict timescales that are far longer than the pre-main sequence evolutionary lifetimes of B-type star and require a solid core to form first, onto which gas is accreted. This scenario is unlikely in the hostile circumstellar environment of HD 76534. Indeed, due to the strong stellar radiation field, molecular gas and dust are dissociated, thus leaving a cavity with low opacity to the UV flux, up to the radius where the warm H_2 component at $T_{(\upsilon=1)} = 630$ K is located. We have determined this radius by assuming flux conservation and a blackbody temperature of 630 K for the gas. We find that the warm H_2 component should be located outside ~11.5 AU from the star. However, because we observe absorption lines, we only detect the gas in front of the star, which prevents us from deriving informations on its exact spatial distribution.

We note that although the SED of HD 76534 presents a strong excess at far-infrared wavelengths, it shows only a tiny excess at NIR wavelengths ($\lambda \leq 5\ \mu$m), which suggests that most of the dust very close to the star has been dissipated. Indeed, Natta et al. (2000) have shown that the NIR and mid-IR excesses in the SEDs of HAeBes – when such excesses are evident – are due to the presence of a CS disk, while the far-IR excess represents the flux contribution of a CS envelope. Moreover, those authors concluded that the CS environment of HBe stars evolves very quickly due to their strong radiation field, with a short phase of disk-like structure that is rapidly destroyed. Finally, in their analysis of the SED of HD 76534, Hillenbrand et al. (1992) noted the similarity of its NIR excess with those of the classical Be stars, which is generally thought to be due to free-free emission in an ionised envelope rather than to CS dust (Hamann & Persson 1992). Similar conclusions were reached by Tovmassian et al. (1997), based on the *IRAS* and *Glazar space telescope* data.

Summarising the entire set of results, we argue that the presence of a disk around HD 76534 is unlikely. Nevertheless, CO observations and interferometry (at infrared and/or radio wavelengths) will be required to really answer the question of the spatial distribution of the gas. In a forthcoming paper we will present a systematic analysis of the properties of H_2 in the circumstellar environments of the whole sample of Herbig stars from the *FUSE Circumstellar Disk Team Program*.

Acknowledgements. This research is based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. FUSE is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985. We thank B. Godard at J.H.U for reprocessing data for us.

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