The ORFEUS II Echelle Spectrum of HD 93521: A reference for interstellar molecular hydrogen

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Abstract. During the second flight of the ORFEUS-SPAS mission in November/December 1996, the Echelle spectrometer was used extensively by the Principal and Guest Investigator teams as one of the two focal plane instruments of the ORFEUS telescope. The spectrum of HD 93521 was obtained during this mission with a total integration time of 1740 s. This spectrum shows numerous sharp interstellar absorption lines. We identified 198 lines of molecular hydrogen including at least 7 lines with a high velocity component. Also most of the 67 identified interstellar metal lines are visible with a high velocity component.

We present the whole Echelle spectrum of HD 93521, obtained during the second ORFEUS-SPAS mission in November/December 1996. This spectrum has a good signal to noise ratio and the spectral resolution achieved is somewhat higher than the claimed resolution of $\lambda/\Delta\lambda = 10.000$ (Barnstedt et al. 1999).

The plots presented in the appendix show one Echelle order per plot for wavelengths above 1130 Å (Echelle orders 40 to 49), and half an Echelle order per plot for Echelle orders 50 to 61 ($\lambda < 1130$ Å) where all $\text{H}_2$-lines are included.

2. Data reduction and line identification

Two separate observations of HD 93521 were obtained during two successive orbits with a total integration time of 1740 s (ORFEUS observation IDs 2276,2 and 2276,3, observation date: day 333 of 1996, GMT 04:56:05 – 05:14:05 and GMT 06:28:05 – 06:39:05). The two echelle images were coadded and then the standard extraction procedure was applied (Barnstedt et al. 1999) without any smoothing. An additional radial velocity correction of $–10$ km s$^{-1}$ was applied, which corrects the wavelength scale for the fact that the star was not absolutely centered in the entrance diaphragm of the telescope. The maximum uncertainty due to the 20″ diameter of the diaphragm was ±36 km s$^{-1}$, so the deviation of $–10$ km s$^{-1}$ corresponds to a pointing offset of 3″, which is an excellent value for the ASTRO-SPAS satellite. The value of $–10$ km s$^{-1}$ was estimated by comparing the observed radial velocity components with those already published (Spitzer & Fitzpatrick 1992). The wavelength scale is he-
liocentric, a LSR scale would require an additional correction of $-1.6 \text{ km s}^{-1}$, which is negligible.

As with all echelle spectra, the signal to noise ratio is best in the centre of the echelle orders, while it is reduced by a factor of about 1.4 at both ends of each order. Due to the blaze curve being not fully centered, the signal to noise ratio at the short wavelength end of each order is significantly better than at the long wavelength end of each echelle order. There is also a slight deviation in the wavelength calibration at the short wavelength end of each echelle order, which affects a wavelength range of about 5% in each order.

For line identifications we used the following line catalogues:

1. H$_2$-lines:
   - Morton & Dinerstein (1974), except L10P1
   - Abgrall et al. (1993), correct wavelength for L10P1: 982.834 Å
2. Metal lines and H I:
   - Morton (1991)
   - Kurucz CD No. 23, web-page (Kurucz 1995)
   - Kelly (1968; and web-page)
   - Feibelman & Johannson (1994)

Identified lines from IUE spectra of HD 93521 above 1170 Å are listed by Ramella et al. (1980), with exception of two interstellar lines: λ1260.4, which is Si II and not Si III, and λ1304.4, which is also Si II and not O I.

The tables and plots show blended lines also, for which a non-ambiguous identification or estimate of the intensity is not possible.

Lines with a lower energy level greater than zero are marked with an asterisk, *. All stellar lines are marked with a bracketed asterisk, (*), and stellar wind lines are marked as (w) in the plots as well as in the tables.

### 3. Discussion of spectral features

The interstellar, stellar and wind absorption lines are visible in several or different radial velocity components. We therefore list and describe all occurring radial velocity components in Table 1.

We present tables of identified interstellar and stellar absorption lines. These tables show a running number for identification of the lines in the plots shown in the appendix, the vacuum wavelength, the log($gf$)-value, the number of the radial velocity component (VC) applied as given in Table 1, and some remarks or the transition for the H$_2$-lines. We will present and discuss the tables of molecular hydrogen lines, other interstellar lines, Lyman series lines and stellar absorption lines.

#### 3.1. Radial velocity components

Table 1 lists 7 components of radial velocities used to identify absorption lines and features in the spectrum. The first two components are the interstellar absorptions at $-12 \text{ km s}^{-1}$ and $-60 \text{ km s}^{-1}$, which are the two strongest of well known interstellar components (Grewing et al. 1978; Keenan et al. 1993; Spitzer & Fitzpatrick 1992). No. 3 gives the published value of the radial velocity of HD 93521 of $-16 \text{ km s}^{-1}$ (SIMBAD). No. 4 is the velocity of the emission of the geocoronal Ly-$\alpha$ line. This emission line results from a completely illuminated entrance aperture of the Echelle spectrometer which had a projected diameter of 20°. The velocity of 36.5 km s$^{-1}$ is the negative sum of two wavelength corrections applied to this spectrum: the heliocentric correction and the decentering correction (26.5 km s$^{-1}$ + 10 km s$^{-1}$).

Some stellar absorption lines show narrow absorption components resulting from winds, which have been observed previously (Bjorkman et al. 1994), but which are varying in time. We have identified two such components in several lines and they are listed as numbers 5 and 6 in Table 1. Component 7 represents the radial velocities of the strong Si III λλ1300 triplets, which are also due to stellar wind absorption (Massa 1993).

### Table 1. Table of radial velocity components (VC).

| VC No. | Rad.vel. [km/s] | Description |
|--------|----------------|-------------|
| 1      | $-12$          | first (main) interstellar component |
| 2      | $-60$          | high velocity interstellar component |
| 3      | $-16$          | radial velocity of HD 93521 |
| 4      | 36.5           | geocoronal Ly-$\alpha$ emission |
| 5      | $-270$         | 1. wind feature in stellar absorption lines |
| 6      | $-340$         | 2. wind feature in stellar absorption lines |
| 7      | $-50$          | wind feature in Si III triplets |

#### 3.2. Interstellar molecular hydrogen

For most of the H$_2$-lines only the main velocity component no. 1 was observed, but for some unblended lines the high velocity component could be seen also. A detailed discussion of column densities and curve of growths will be published in a separate paper (Gringel et al., in preparation).

Previous Copernicus measurements of selected H$_2$-lines only led to an upper limit of log $N$(H$_2$) < 18.54 (Savage et al. 1993). The high velocity components were not detected by Copernicus.

### Table 2. Table of identified or possible interstellar molecular hydrogen lines. VC is the velocity component as given in Table 1.

| No. | λ [Å]   | log($gf$) | VC  | Transition | Remarks |
|-----|---------|-----------|-----|------------|---------|
| 1   | 918.411 | $-2.795$  | 1   | L18P1      | blend   |
| 2   | 918.427 | $-1.889$  | 1   | W5Q3       | blend   |
| 3   | 919.410 | $-2.430$  | 1   | L18R2      | blend   |

Table 2, continued...
| No. | $\lambda$ [A] | log($f$) | VC | Transition | Remarks |
|-----|---------------|----------|----|------------|---------|
| 4   | 919.545       | −2.345   | W5P3 | blend      |         |
| 5   | 920.242       | −2.767   | L18P2 |            |         |
| 6   | 924.643       | −2.412   | L17R1 |            |         |
| 7   | 925.173       | −2.707   | L17P1 |            |         |
| 8   | 927.020       | −2.628   | L17P1 |            |         |
| 9   | 928.437       | −2.548   | L17R3 |            |         |
| 10  | 929.534       | −1.470   | W4R0 | blend      |         |
| 11  | 929.687       | −1.810   | W4R1 | blend      |         |
| 12  | 929.688       | −2.595   | L17P3 | blend      |         |
| 13  | 931.063       | −1.991   | L16R0 |            |         |
| 14  | 931.732       | −2.151   | L16R1 | blend      |         |
| 15  | 931.779       | −1.714   | W4Q2 | blend      |         |
| 16  | 931.811       | −1.979   | W4R3 | blend      |         |
| 17  | 932.270       | −2.621   | L16P1 |            |         |
| 18  | 932.606       | −3.318   | W4P2 |            |         |
| 19  | 933.185       | −2.563   | L17P4 | blend      |         |
| 20  | 933.243       | −2.202   | L16R2 | blend      |         |
| 21  | 933.581       | −1.714   | W4Q3 |            |         |
| 22  | 934.146       | −2.643   | L16P2 |            |         |
| 23  | 934.789       | −2.145   | W4P3 |            |         |
| 24  | 935.537       | −2.498   | L17R5 | blend      |         |
| 25  | 935.578       | −2.236   | L16R3 | blend      |         |
| 26  | 935.959       | −1.717   | W4Q4 |            |         |
| 27  | 936.859       | −2.679   | L16P3 |            |         |
| 28  | 938.468       | −2.036   | L15R0 |            |         |
| 29  | 939.124       | −2.207   | L15R1 |            |         |
| 30  | 939.710       | −2.536   | L15P1 |            |         |
| 31  | 940.627       | −2.256   | L15R2 |            |         |
| 32  | 941.601       | −2.471   | L15P2 |            |         |
| 33  | 942.966       | −2.293   | L15R3 |            |         |
| 34  | 944.331       | −2.451   | L15P3 |            |         |
| 35  | 946.129       | −2.342   | L15R4 | blend      |         |
| 36  | 946.170       | −2.958   | L14R0 | blend      |         |
| 37  | 946.386       | −1.889   | W3R1 |            |         |
| 38  | 946.425       | −1.207   | W3R0 | blend      |         |
| 39  | 946.986       | −2.728   | L14R1 | blend      |         |
| 40  | 947.113       | −1.876   | W3R2 |            |         |
| 41  | 947.425       | −1.564   | W3Q1 |            |         |
| 42  | 947.517       | −2.454   | L14P1 |            |         |
| 43  | 948.418       | −1.893   | W3R3 | blend      |         |
| 44  | 948.472       | −1.917   | L14R2 | blend      |         |
| 45  | 948.618       | −1.564   | W3Q2 | blend      |         |
| 46  | 949.355       | −2.041   | L14P2 |            |         |
| 47  | 950.316       | −1.903   | W3R4 | blend      |         |
| 48  | 950.401       | −1.564   | W3Q3 | blend      |         |
| 49  | 950.820       | −2.003   | L13R3 | blend      |         |
| 50  | 951.672       | −1.896   | W3P3 |            |         |
| 51  | 952.256       | −2.416   | L15P5 | blend      |         |
| 52  | 952.276       | −3.151   | L13P3 | blend      |         |
| 53  | 952.758       | −1.565   | W3Q4 | blend      |         |
| 54  | 952.802       | −1.762   | W3R5 | blend      |         |
| 55  | 954.149       | −1.860   | L13R0 | blend      |         |
| 56  | 954.475       | −1.873   | W3P4 | blend      |         |
| 57  | 955.067       | −2.024   | L13R1 |            |         |
| 58  | 955.682       | −1.567   | W3Q5 |            |         |
| 59  | 955.711       | −2.374   | L13P1 |            |         |
| 60  | 956.581       | −2.064   | L13R2 |            |         |
| 61  | 957.654       | −2.316   | L13P2 |            |         |

Table 2, continued ...
3.3. Interstellar metal lines

Most of the metal lines can be observed in both interstellar components with the second component being only slightly weaker than the main component. High resolution spectra do show more components (Spitzer & Fitzpatrick [1997]), but in the ORFEUS echelle spectra only two well separated components are seen. The separation is best seen in the Ar I lines λ1048 and λ1067 and the NI triplet λ1134. Interstellar O VI at λ1032 and λ1037 appears quite broad. Widmann estimated a N(OVI) = (0.99 ± 0.15) 10\(^{14}\) cm\(^{-2}\) from these ORFEUS echelle spectra (Widmann et al. [1998] Widmann [1999]).

Table 3. Table of identified interstellar metal lines. For unresolved doublets and triplets an average wavelength and a calculated effective log\((gf)\) are given. VC is the velocity component as given in Table 1.
3.4. Lyman series lines

Of the Lyman series 14 lines are detectable, from which the lines below the λ915.824 line are not separated, so that this line marks the interstellar Lyman limit towards HD 93521.

Table 4. Table of the identified interstellar Lyman-series (H I). All lines are doublets with a maximum separation of 5.4 mÅ (at λ1216). The resulting wavelength and log(gf) is given. VC is the velocity component as given in Table 1.

Table 5. Table of identified stellar (*) and stellar wind (w) lines. For the N II doublets only the stronger of the two lines is listed. VC is the velocity component as given in Table 1.
4. Conclusions

The presented ORFEUS II Echelle spectrum of HD 93521 shows an extraordinary rich variety of very sharp interstellar absorption lines, especially in the wavelength region between 900 Å and 1200 Å, which was not very well studied before the two ORFEUS missions and for which only now new observation possibilities exist. Particularly the nearly complete presence of very sharp (FWHM ≈ 100 mÅ) H₂ absorption lines in this spectrum – which will be analysed in detail in a forthcoming paper – makes it well suited as a reference spectrum for interstellar molecular hydrogen. Molecular hydrogen is partially visible in the interstellar high velocity component too. Additionally some stellar lines show narrow absorption components which are varying in time and which could be an indication for a disk.

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References

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Appendix: plots of the spectrum of HD 93521

The following plots show the complete ORFEUS II Echelle spectrum of HD 93521. The numbers shown in squared brackets correspond to the running numbers given in the Tables 2–5. Stellar lines are marked as (*), stellar wind lines as (w). Non-resonance lines are additionally marked with an asterisk, *.

The plots show one Echelle order per plot for wavelengths above 1130 Å (Echelle orders 40 to 49), and half an Echelle order per plot for Echelle orders 50 to 61 (λ < 1130 Å) which includes all H₂-lines. Thus the wavelength scale changes from order to order, but the relative wavelength scale (radial velocity scale) is nearly constant within these two wavelength ranges.

Addendum

H₂-line λ997.829 (no. 111) was erroneously identified with two velocity components. The more probable identification for the weaker component however is the H₂-line λ997.640 W1P5 with log(\(f\)) = −1.921.
J. Barnstedt et al.: The ORFEUS II Echelle Spectrum of HD 93521
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