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LETTER

Letter to the Editor

ORFEUS II echelle spectra: The scale height of interstellar O VI in the halo

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Abstract. FUV high resolution spectra of 18 stars, particularly chosen to observe the interstellar medium (ISM), were obtained during the second ORFEUS-SPAS free flight space shuttle mission in December 1996. Among these were 6 objects with a distance to the galactic plane larger than 1 kpc, one SMC and 4 LMC stars. This selction of targets is part of the ORFEUS program to explore the galactic halo. As the most important tracer of the hot gas we analyzed the stronger component of the important O VI doublet in all our ISM spectra. We found an average N(O VI)$\times \sin|b|$ of $\sim 3.5 \times 10^{14}$ cm^{-2} on the lines of sight to the 4 LMC stars. Assuming an exponential distribution of O VI we calculated a midplane density n_0 of $2.07^{+0.26}_{-0.24} \times 10^{-8}$ cm^{-3} and a scale height h_0 of $5.50^{+2.37}_{-2.09}$ kpc.

Key words: space Vehicles – ISM: general – ISM: structure – Galaxy: halo – Galaxy: structure – ultraviolet: ISM

1. Introduction

A hot galactic corona was first postulated by Spitzer (1956) as a medium to confine the high velocity clouds discovered by Münch (1952, 1957). Münch found absorption in the Ca II lines at 'high' velocities in spectra of stars at high galactic latitude.

Almost all information on the hot gas distribution within or surrounding the Galactic disk gathered since then derives from three different kinds of observation: the soft X-ray background at low and medium energies, the high-stage ion populations (C IV, N V and O VI) observed in absorption in the UV and Far UV, and on the detected FUV and EUV emission line backgrounds. Among the FUV absorption lines the O VI ion contributes the most important information to the understanding of the (hot) Galactic halo. It samples rather high temperature gas ($\sim 10^{5.5}$ K) with little contamination expected from photoionised gas and it has a line strength large enough that even nearby stars normally have detectable column densities. With the Copernicus satellite the first detection of O VI absorption lines (Rogerson et al. 1973) at 1031.92 Å ($\log gf = -0.58$) and 1037.61 Å ($\log gf = -0.88$) was made 25 years ago. These data were analyzed and summarized in a series of papers by Jenkins (1978a, b, c). Excluding a few lines of sight on the grounds of atypically high N(O VI), Jenkins found an average midplane density n_0 of about 2.8 $\times 10^{-8}$ cm^{-3} and a scale height h_0 of 300^{+200}_{-150} pc.

Since the wavelength region of the O VI resonance doublet is inaccessible for IUE and HST the last available observations with reasonable wavelength resolution were made with the Berkeley spectrometer in Sept. 1993 during the ORFEUS I mission launched on the Space Shuttle Discovery. The ORFEUS-SPAS mission is discussed in detail in Grewing et al. (1991). Hurwitz et al. (1995) present part of their spectrum of the SMC star NGC 346 No.1 near the O VI resonance line and a revisit of the ORFEUS spectrum of PKS 2155-304. They derived from this sparse data an upper limit for N(O VI) in the galactic halo of 2.0 $\times 10^{14}$ cm^{-2} toward NGC 346 No.1 and 2.2 $\times 10^{14}$ cm^{-2} towards PKS 2155-304. Hurwitz & Boywer (1996b) analyzed 14 early type halo stars (obtained with the Berkeley spectrometer) during the first mission. They derived a scale height for O VI between about 80 pc and 600 pc if the midplane density is between 1.5 and 5 $\times 10^{-8}$ cm^{-3}. These results were inconsistent with the comparativeley high column densities of N V reported by Sembach & Savage (1992) and the O VI/N V ratios measured in disk stars and predicted by various theories (see Spitzer 1996). New observations, performed with the Berkeley spectrograph aboard the ORFEUS II mission in Nov./Dec. 1996, yield to a N(O VI) of $(7 \pm 2) \times 10^{14}$ cm^{-2} toward the quasi-stellar object 3C 273 (Hurwitz et al. 1998).

Here we present first results from ORFEUS echelle spectra obtained during the mission of Nov./Dec. 1996. The strength of the absorption by the O VI line at 1031.92 Å has been determined and column densities have been calculated. The ensemble of

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Table 1. Basic properties of targets and parameters for O VI

Object	V [mag]	Sp. T.	l	b	z [kpc]	W_λ [Å]	N(O VI) $[10^{14}\mathrm{cm}^{-2}]$	Error	S/N	Exposure [ksec]	No. of star	Ref.[b]
HD 18100	8.46	B1 V	217.9	−62.7	2.67	0.177	1.42	0.64	11	2.9	0	1,3
HD 49798	8.29	sd O6 V	253.7	−19.1	0.21	0.044	0.35	0.11	17	1.3	6	2
HD 77770	7.53	B2.0 IV	169.3	41.9	0.77	0.086	0.69	0.14	9	1.9	8	3
HD 93521[a]	7.06	O9.5 V	183.1	62.2	1.50	0.125	0.99	0.15	18	1.7	10	1,3
HD 93840	7.76	B1 Ib	282.1	11.1	0.90	0.406	3.24	0.80	3	2.6	3	3
HD 116852	8.40	O9 III	304.9	−16.1	1.33	0.354	2.83	0.47	5	3.0	11	1
HD 146813	9.10	B1.5 IV	85.7	43.8	1.82	0.114	0.91	0.37	5	1.4	7	3
HD 214930	7.38	B2 VI	88.3	−30.1	0.50	0.080	0.64	0.12	3	1.0	9	3
HD 217505	9.15	B2 III	325.5	−52.6	2.38	0.234	1.87	0.66	5	1.9	5	4
HD 36402	11.50	OB+WC5, LMC	277.8	−33.0	30.0	0.740	5.91	2.46	2	1.6	4	5
HD 269546	11.30	B3+WN3, LMC	279.3	−32.8	29.8	0.871	6.96	3.25	3	6.4	2	6
LH 10:3120	12.80	O5.5 V, LMC	277.2	−36.1	32.4	0.840	6.71	3.82	1	6.5	12	7
Sk −67°166	12.27	O5e, LMC	277.8	−32.5	29.5	0.826	6.60	2.56	3	6.2	13	8
HD 5980	11.80	OB+WN3, SMC	302.1	−44.9	45.9	0.193	1.54	0.73	4	6.8	1	5

[a] Jenkins (1978a) found an N(O VI) of $7.24\times10^{13}\mathrm{cm}^{-2}$

[b] References: (1) Savage et al. (1997); (2) Jenkins & Wallerstein (1996); (3) Diplas & Savage (1994); (4) Hurrwitz & Boyer (1996b); (5) Sembach & Savage (1992); (6) Chu et al. (1994); (7) de Boer et al. (1998); (8) SIMBAD

data allows us to determine a substantially larger scale height of O VI in the galactic halo.

2. Instrumentation and observation

The ORFEUS 1m-telescope is equipped with two alternatively operating spectrometers. The details about the telescope and the Echelle spectrometer are discussed in Krämer et al. (1990) and in Barnstedt et al. (1998), the Berkeley spectrometer is described in Hurwitz & Boywer (1996a). The relevant properties of the Echelle spectrometer for the measurements discussed are: a spectral range from 912 Å to 1410 Å, spectral resolution of $\lambda/\Delta\lambda \leq 10,000$ and an effective collecting area of 1 cm^2.

Most of the stars on the ORFEUS II P.I. team target list were selected for interstellar and intergalactic medium research. We selected in particular high $|z|$ stars with large distances from the galactic plane. Discussed in this paper are 9 Galactic and 5 Magellanic Cloud objects; 6 of the Galactic targets have a $|z| >$ 1 kpc. Table 1 lists the targets and gives their basic properties.

3. Data reduction

3.1. Continuum fitting and identification of other spectral lines

We binned the data in the echelle order of the O VI line into elements containing 7 pixel (of optical resolution), equivalent to 0.21 Å and fitted a 5th order polynominal to define the interstellar continuum. For the galactic targets, a straight line is a good approach to the continuum of the narrow interstellar features (Fig. 1b). A multi gaussian or even single gaussian fit (see HD 93521 in Fig. 1a) was applied to the spectral structures, to define the equivalent width of the explored absorption.

In the vicinity of the O VI line at 1031.92 Å absorption structures due to H_2 Lyman P(3) at 1031.19 Å and H_2 Lyman R(4) at 1032.35 Å are present. However, these are well separable from the O VI line. Further possible interference may arise from the R(0) 6-0 interstellar line of HD at 1031.91 Å. We determined the contributions from this feature by looking for the 7-0 and 5-0 R(0) HD lines at 1021.453 and 1042.847 Å, respectively. Taking these results into account, an upper limit of 0.04 Å and 0.03 Å was subtracted from the O VI equivalent width to HD 116852 and HD 93840. HD 116852 and HD 93840 were the two only targets with measurable absorptions of HD. Following the data in Morton's (1991) list some metals may show here absorption lines, too. Since these particular elements have small intrinsic abundance and since these lines are from excited states we can ignore any contribution. In most of our spectra, the weaker component of the O VI doublet at 1037.61 Å is blended with the line of excited C II at 1037.02 Å and by two H_2 Lyman absorptions at 1037.15 Å and 1038.16 Å, both of level J = 1. Therefore, we used the weaker O VI line only to verify the result derived from the stronger component.

The velocity of the O VI absorption lines usually agree well with those of the C IV lines as seen in IUE and HST spectra. Apparently, the O VI ions exist in gas well related with the gas containing C IV. The complexity of the stellar background spectrum near the O VI absorption together with the intrinsic uncertainty in the IUE velocity scale does not warrant a more detailed comparison at this time.

3.2. Galactic targets

In all spectra of galactic stars which we have included to derive the O VI scaleheight, the H_2 Lyman P(3) line at 1031.19 Å was clearly separated from the O VI absorption. The H_2 Lyman R(4) at 1032.35 Å blended with O VI for several targets. A two-component fit was used to separate the H_2 contribution to the equivalent width for HD 77770, HD 93840 (Fig. 1b), HD 116852 and HDE 214930. In HD 93521 (Fig. 1a) and HD 49798

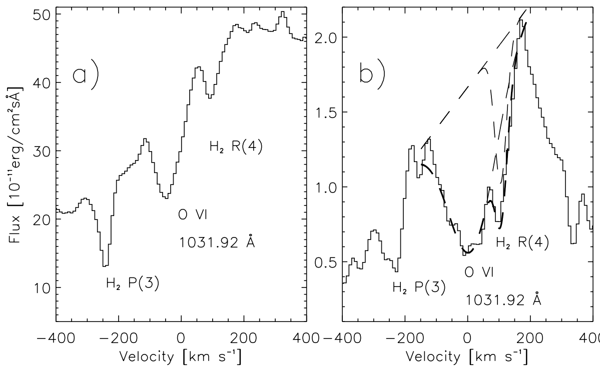

Fig. 1a and b. The O VI absorption in the spectrum of **a** the O9 Vp star HD 93521 and b) the B1 Ik star HD 93840. **a** The O VI feature has a radial velocity of about $-35\,\mathrm{km\,s^{-1}}$. Two neighbouring H_2 absorption lines are identified, too. **b** Here the H_2 R(4) line is not completely separated from O VI

the R(4) absorption is clearly separated. In these cases a single gaussian was used to determine the equivalent width.

For HD 18100, HD 146813 and HDE 217505 no measurable absorptions from neither H_2 Lyman P(3) nor H_2 Lyman R(4) was found between 990 and 1120 Å, hence the contribution of any H_2 to the O VI line can be neglected in these cases.

3.3. Magellanic Cloud targets

Magellanic Cloud spectra have a poorer signal to noise ratio than those of the galactic stars. Yet, three velocity components can be clearly identified in each absorption. This means, that the H_2 lines mentioned above will blend (due to the complex velocity structure of the gas on these lines of sight) with the O VI line, and decomposition may be problematic.

3.3.1. LMC stars

In the spectra of HD 36402, HDE 269546, and Sk $-67°166$ neither measurable galactic H_2 absorption with rotational levels $J \geqq 4$ nor an LMC component from any absorption with a level of $J \geqq 3$ are present. Thus, for these three targets the zero velocity component was used to derive the galactic O VI column density. We did not include the high negative velocity component we found in all our extragalactic stars. This feature seems to be composed of galactic H_2 Lyman P(3) absorption and a second component not yet defined (Fig. 2).

LH 10:3120 : In the O VI line region de Boer et al. (1998) found H_2-absorption at LSR velocity as well as at $+270\,\mathrm{km\,s^{-1}}$. The LMC component of H_2 P(3) 1031.19 Å and the galactic component of the H_2 R(4) 1032.35 Å line blend with O VI. Due to a lower S/N ratio, the separation of the galactic and LMC components of these two H_2 absorptions was very inaccurate. Therefore we just fitted the three velocity components mentioned above (negative velocity, zero velocity and LMC component) to the absorption profile. Referring to the results of de Boer et al. (1998) we subtracted 0.2 Å in equivalent width from our zero velocity component.

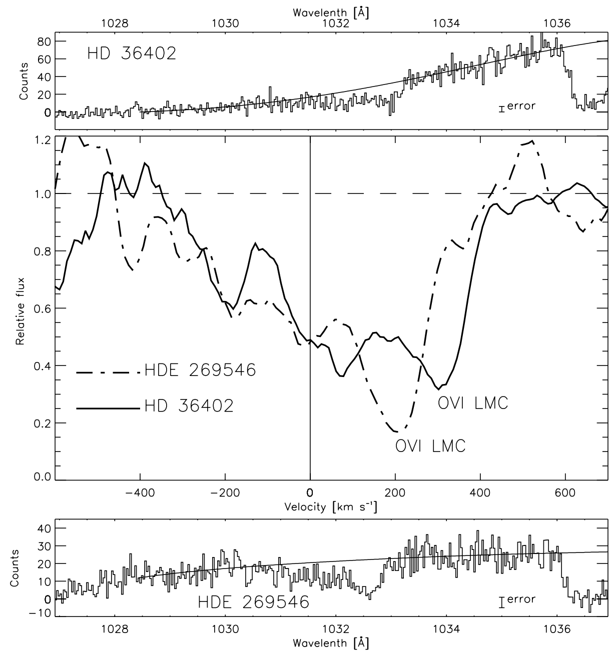

Fig. 2. Spectra of HD 36402 and HDE 269546 centered at 1031.92 Å. Relative flux is plotted against velocity shift. The spectrum has been filtered with a de-noising algorithm basing on a wavelet tranformation (Fligge & Solanki 1997). The indicated Magellanic Cloud components of the O VI absorption show almost the same velocity found for less ionized and neutral elements. Top and bottom panel show the original, unsmoothed spectra with their adopted continuum

3.3.2. HD 5980 in the SMC

The SMC star HD 5980 shows a first positive velocity component at $+147\,\mathrm{km\,s^{-1}}$, the velocity of the SMC (Westerlund 1997). In additon, we found at $+300\,\mathrm{km\,s^{-1}}$ a velocity component clearly separated from the normal SMC absorption. It has also been seen in many other ions in IUE spectra of this star (Fitzpatrick & Savage 1983) and the authors suggested an expanding SNR in the foreground to the SMC star as a possible origin of this feature. The equivalent width of our derived zero velocity component leads to an exceptionally small O VI column density. The FWHM of 0.35 Å is also exceptionally small compared to the LMC targets ($\sim$1.2 Å). It seems reasonable to suspect that galactic and SMC components are blended. However, given the uncertainties we decided not to include the O VI information from the line of sight to HD 5980 in the scale height fit procedure.

4. The spatial distribution of O VI

Our data allow to investigate the distribution of O VI in the galactic halo. The absorption equivalent widths have been calculated from the result of the fits. Assuming that absorption is optically thin, the column density can be calculated from

$$N(\mathrm{O\,VI})[\mathrm{cm^{-2}}] = 7.988 \times 10^{14} \times W_\lambda[\text{Å}] \quad (1)$$

The column densities for all targets are given in Table 1.

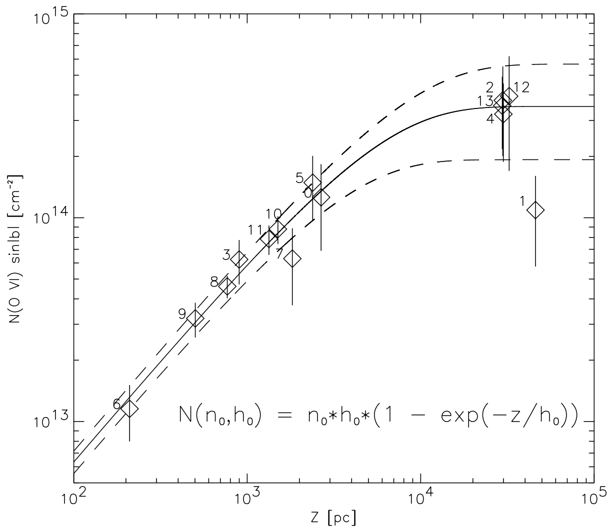

Fig. 3. Plot of galactic N(O VI)$\times \sin|b|$ versus $|z|$. The solid line is the best-fit exponential, the dashed line the $1\,\sigma$ deviation of the fit. The derived values are $n_0 = 2.07^{+0.26}_{-0.24} \times 10^{-8}$ cm^{-3} and $h_0 = 5.50^{+2.37}_{-2.09}$ kpc. Each entry is marked with the target number (Table 1)

If we assume a hydrostatic Galactic halo (corona) of the type postulated by Spitzer (1956), we have an exponential density distribution of O VI, described by the equation

$$n = n_0 \times \exp(-z/h_0) \qquad (2)$$

with the O VI midplane density n_0 and scale height h_0. The projected column density is then given by

$$N(\mathrm{O\,VI}) \times \sin|b| = n_0 \times h_0 \times (1 - \exp(-z/h_0)) \qquad (3)$$

Fig. 4 shows the result we found when fitting equation (3) to our column densities.

Best values for the parameters n_0 and h_0 resulting from our N(O VI)$\times \sin|b|$ fit are $n_0 = 2.07^{+0.26}_{-0.24} \times 10^{-8}$ cm^{-3} and $h_0 = 5.50^{+2.37}_{-2.09}$ kpc. Including the O VI column densities from the literature, we find the data point for 2C 273 to lie just above our 1σ upper limit and those for PKS 2155-304 and NGC 346 just below our 1σ lower limit. Therefore, inclusion of these data would not change our scaleheight value in a significant way.

We should note here that h_0 relies almost exclusively on the LMC measurements. To set an approximate lower limit for the scaleheight we applied the fit procedure to a dataset where the extragalactic stars are excluded. The result is $4.2^{+\cdots}_{-2.8}$ kpc, and points to a substantially larger scaleheight of O VI in the halo than previous measurements do. The upper $1\,\sigma$ limit is $>$20 kpc.

5. Concluding remarks

The O VI column densities derived from our ORFEUS II data are far too large to agree with the predictions of a photoionized model. These column densities clearly favour the hot halo concept as described by Spitzer (1956) and by Shapiro & Field (1976). The asymptotic column density of O VI in Fig. 3 of $10^{14.5}$ cm^{-2} can be compared with that of C IV and N V (Savage et al. 1997) of $10^{14.1}$ and $10^{13.4}$, respectiveley. If the O VI, N V and C IV were to coexist in space (the similar absorption velocities of O VI and C IV point to that) and ignoring the abundance of the other ionic stages of these elements, the equivalent gas column density is $N(\mathrm{H}) \simeq 10^{17.5}$ cm^{-2} (based on the solar abundances -3.4 dex for C, -4.1 dex for N and -3.2 dex for O). Such identical equivalent column densities can be understood in a simple exponential pressure model, the small scaleheight for O VI from previous measurements could not. However, without knowledge of the real gas distribution in the halo it is not possible to relate our findings with the consequences of the interplay of ionisation and cooling in the halo.

Due to its very high ionisation potential O VI remains the most likeley tracer of hot gas outflow from the Galaxy. A direct measure of this outflow is not possible at the present time and will be subject of further research and the scientific goal for future Far Ultraviolet missions like ORFEUS III or FUSE.

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