ABSORPTION SPECTRA OF DARK INTERSTELLAR CLOUDS – A LONG TERM PROJECT FOR THE TERSKOL OBSERVATORY

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We present the long-term project on investigation of the absorption spectral features originating in interstellar H I clouds. This project is being realized at the Terskol Observatory. The most important results and the world-largest database of spectra of interstellar clouds are described.

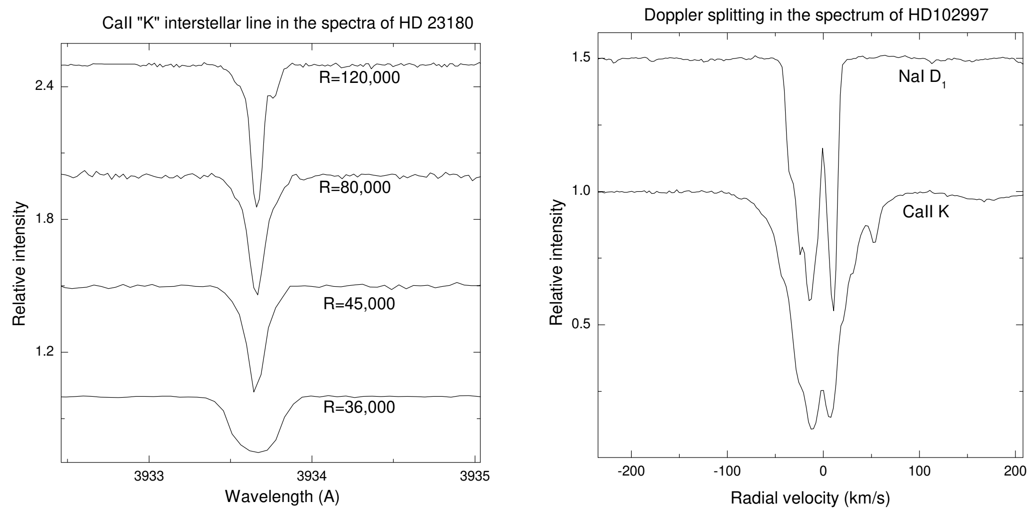
INTRODUCTION

The cold and dark interstellar medium, composed mostly of neutral (H I) and molecular hydrogen (H_2 clouds), can be revealed due to a variety of spectral features which may be detected in the light beams intersecting such regions. In the spectra of distant hot stars, one can find several kinds of absorption features:

- continuous extinction and polarization, which is closely related to the extinction (for a review see [11] or [15]);
- atomic resonance lines. A vast majority of them are situated in the vacuum-UV and thus are accessible only for space-born instruments. Ground-based observations allow to detect a few such lines: Ca II (discovered 100 years ago) as well as Na I, K I, Ca I, and Li I [2];
- absorption molecular features of simple species CN , CH , CH^+, C_2, and C_3; in the vacuum-UV several strong bands of CO and of the undoubtedly most abundant H_2 molecule, are observed. The latter was directly observed only onboard of two satellites: Copernicus [1] and FUSE [18] (for a review of the molecular research see [20]);
- numerous unidentified, diffuse interstellar bands. Due to the recent study [5] their number increased to about 300. Most of these interstellar features are barely visible even in high S/N spectra because of their shallowness (for a review see [9]).

The absorption spectra of dark interstellar clouds reveal the complexity of physico-chemical processes and variations of physical parameters which take place inside them [10]. The carriers of some observed interstellar absorption features are well-identified (atomic or molecular lines), some others are reasonably well-understood (dust grains). Diffuse interstellar bands still remain unidentified. When several clouds occupy a line of sight, spectral lines usually show the Doppler splitting. Absorption spectra of individual clouds differ considerably from object to object as a result of variations of physical parameters. This fact emphasized the importance of gathering many spectra of reddened stars in order to get a statistically meaningful sample of clouds to be studied.

For this research single cloud targets are the objects of basic importance. However, the requirement of selecting them is, in fact, very severe. Usually, heavily reddened stars are observed through several clouds. Spectra averaged along such lines of sight can hardly be physically interpreted. It seems more likely to find objects obscured by single clouds among slightly reddened stars; on the other hand, due to low reddenings all other interstellar features usually are weaker (their strengths are correlated reasonably with a colour excess – see, *e.g.*, [12]) and this makes their measurements not precise.



a) b)

Figure 1. (a) The Ca II K line observed in the spectrum of *o* Per in four resolutions. Note the systematic removal of the instrumental profile which dominates the feature in the lowest resolution. (b) Doppler splitting seen in interstellar sodium and ionized calcium lines. The latter are apparently more diffuse

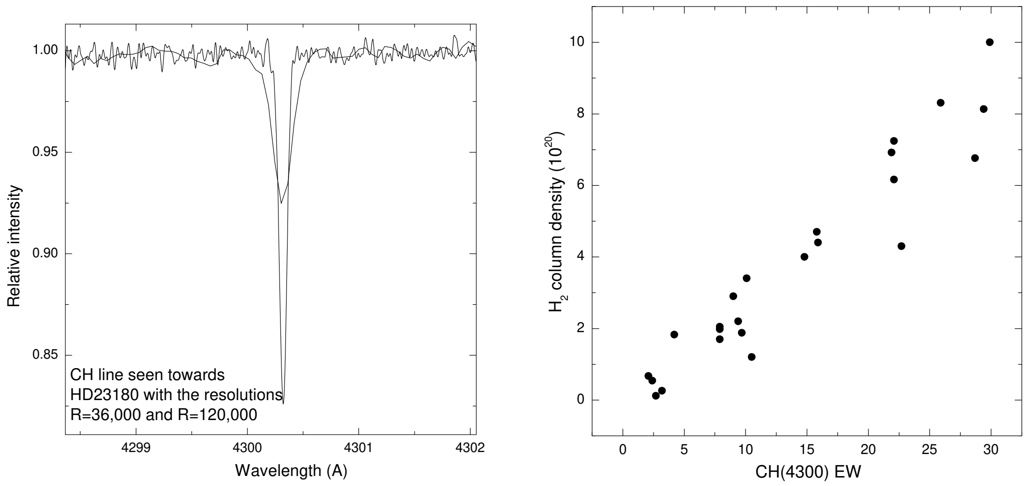


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Figure 2. (a) The profile of CH 4300 Å line in two resolutions observed in the same object. (b) Tight correlation between the H_2 column density (determined from extraterrestrial observations) and the equivalent width of the 4300 Å CH feature (the latter measurements have been performed using the high resolution Terskol spectra)

The simplest and the most abundant molecules, especially those bearing carbon – the component of a vast majority of identified interstellar molecules – are particularly appealing. Carbon plays undoubtedly a crucial role in the chemistry of interstellar clouds, due to its ability to form various bonds. According to existing models, chemical reaction chains, which most likely occur in interstellar clouds, in most of cases involve carbon atoms. Out of over 130 identified interstellar molecules, organic ones, in particular those built up on carbon chains (of up to 11 C atoms), make a vast majority. The already mentioned, detected simple chains (C_2 and C_3), are very likely building blocks for such complex compounds; the latter can be observed either as shorter or longer bare carbon chains or as polar molecules involving H and/or N atoms as well, observed already in radio wavelengths. C_2, C_3, and C_5 have been detected in the interstellar medium but the associated features are usually very weak [6, 14, 19] which leads to relatively low abundances of these species in the interstellar medium.

Spectral features of homonuclear compounds (like the above-mentioned carbon chains) are usually numerous but weak. This is why the history of interstellar molecules started from observations of polar species such as CH, CH^+, and/or CN. A spectrum of such a species contains few, but rather strong features [4]. Because of the very low density of interstellar clouds the interstellar spectral features are intrinsically very narrow and only very high resolution spectra allow to get rid of instrumental profiles in their cases.

It is to be mentioned that the well-known 4300 Å feature of CH is a very easy target. The spectral range is usually not too much attenuated by interstellar extinction which makes the achievement of a high S/N ratio in this spectral range quite easy (in a sharp contrast to, *e.g.*, CN). The 4300 Å feature seems to be a very important diagnostic tool for probing interiors of small, compact cloudlets where most likely molecular species (such as H_2 and/or DIB carriers) are formed and maintained [7].

OBSERVATIONS OF ABSORPTION SPECTRA OF INTERSTELLAR CLOUDS

Our poor understanding of the physical and chemical processes taking place in the interstellar medium follows a very scarce sample of observed objects. While compared to the early samples, like, *e.g.*, the HD atlas, of stellar spectra which led to to the stellar astrophysics, it contains barely ∼100 objects, in most of cases being not just single clouds. The problem follows the fact that low resolution spectra are hardly useful while observing either very sharp features (atomic lines) or those with some internal substructures (diffuse bands). It is thus of basic importance to extend the sample of high resolution spectra of more or less reddened stars.

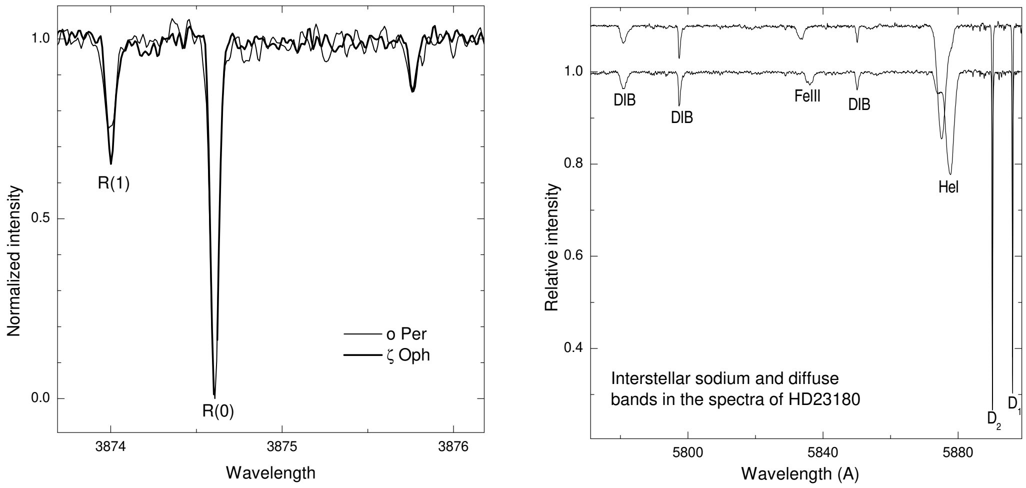
We conduct a broad survey of the spectra of interstellar clouds, obscuring reasonably bright OB stars since the Terskol 2-m telescope is commissioned. The details of the spectrograph attached to this telescope are described in contribution by Musaev *et al.* [17]. The spectrograph allows to cover in one exposure the range ∼3 500 Å ÷ 10 100 Å, divided into 92 orders, with a bunch of resolutions from $R = 45\,000$ through $R = 120\,000$ until $R = 500\,000$. The achieved resolutions allow the performing precise measurements of wavelengths and intensities of interstellar features. Unfortunately, the applied CCD camera, manufactured by Wright Instruments and equipped with 1242×1152 matrix (pixel size $22.5\,\mu$m× $22.5\,\mu$m) does not allow to cover the whole spectrum, formed in one exposure if R is greater than 45 000. In fact, three exposures with different positions of the grating are necessary to observe the whole available range in $R = 120\,000$.

Interstellar spectral lines, formed in a very low density and cold environments, are usually very narrow. The higher is the applied resolution the better is the chance to see the real profile of the feature, not the instrumental one. The change (with the applied resolution) of the observed profile of the Ca II K line, observed for the first time in 1904 by Hartmann, is demonstrated in Fig. 1a.

The figure clearly shows the importance of using high resolution spectra; they can reveal the structure of the interstellar medium along any considered line of sight. We conduct a long term project aimed to observe reddened stars using the resolution $R = 120\,000$ or more. Interstellar atomic lines are the best tool to check whether any of the chosen targets shines through a single cloud or, perhaps, through several clouds, characterized by a possibly different spectrum each (Fig. 1b).

The lines, depicted in Fig. 1b are the Ca II K line, known since 1904, and the Na I D_1 line discovered in 1919. Both show a similar Doppler splitting, proving that at least two clouds occupy the line of sight towards the chosen target. However, the Ca II K line profile seems to be more diffuse raising the question of whether both lines do originate in exactly the same space. A statistically meaningful sample of spectra, showing different Doppler structure in many interstellar lines is thus of basic importance. We continue the project of collecting such spectra, especially using the high resolution mode of the Terskol echelle spectrograph.

The design of the Terskol echelle spectrograph, especially while equipped with the new, back illuminated CCD camera, allows to investigate the spectral features originated in simple molecular species such as CN, CH, CH^+; also the homonuclear species like C_2 or C_3 can be investigated if a sufficiently high S/N ratio is achieved. The CH 4300 Å line is the oldest known interstellar molecular feature. Figure 2a demonstrates how narrow its



a) b)

Figure 3. (a) The variable strength ratio of the R(0) and R(1) features of the CN band – the determination of the rotational temperature of the molecule in two different clouds. (b) Diffuse interstellar bands (stationary features) in the spectrum of HD 23180 – the spectroscopic binary. Note also the presence of strong Na I lines

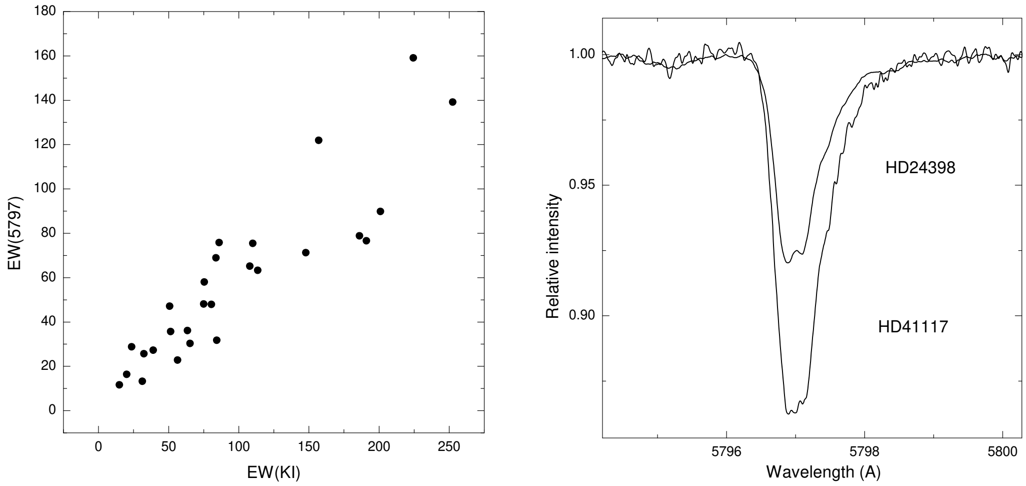


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Figure 4. (a) The close correlation between the K I strength and that of the 5797 DIB. The results were obtained from a Terskol echelle spectra. (b) The variable shape of the 5797 DIB observed towards two reddened stars (as obtained from the high resolution Terskol echelle spectra)

profile is. Its high strength follows the polar structure (the presence of the dipole momentum) which reduces the number of transitions but makes them strong.

The molecular feature demonstrated in Fig. 2b is the most easily accessible one; the spectral range allows high S/N observations from ground-based observatories. The latter contrasts sharply with the possibilities to observe the undoubtedly most abundant molecular species – H_2. The hydrogen molecule features can be investigated only with space-born instruments, which allow to observe in the extremely far-UV. Until now, only Copernicus in 1973 and, recently, FUSE, collected some direct data concerning the hydrogen column densities toward bright, reddened stars. The database, collected at the Terskol Observatory, allowed to correlate the hydrogen molecule column densities with the equivalent widths of the 4300 Å CH feature. Both values correlate very tightly, with the correlation coefficient of 0.97 which makes CH a very good H_2 tracer, apparently much better than the popularly used CO. Figure 2b presents the correlation between abundances of CH and H_2.

The CN molecule, discovered by the end of the 1930s offered the possibility for estimating its rotational temperature. McKellar found it to be 2.3 K, basing on the existing spectrum of ζ Oph. Currently, this result is being considered as the first determination of the temperature of the microwave background radiation. The recent spectra, acquired at Terskol with the resolution $R = 120\,000$ using the back illuminated CCD, allow to observe the CN band with a high precision. Figure 3a shows beyond a doubt that the rotational temperature of the CN molecule is not constant. Apparently, the molecule is being excited to a certain degree – various in different clouds. We intend to make a systematic survey of this effect in as many clouds as possible.

Despite atomic and molecular features, originating in H I interstellar clouds, one can observe a big group of the so-called *diffuse interstellar bands* – DIBs. These features are known since the first observation in 1921 by Miss Heger, but, despite numerous efforts, they remain unidentified until now. Their interstellar origin can be demonstrated in Fig. 3b where they apparently do not participate in the Doppler shifts caused by the variable radial velocities of the components of the depicted spectroscopic binary. One can also note their widths, clearly exceeding those of the interstellar sodium lines. Despite these, rather strong diffuse bands, almost ∼300, usually much weaker ones, have been found in spectra of reddened stars acquired at Terskol [5].

Diffuse interstellar bands are spread all over the spectrum, recorded from ground-based observations; the well-grounded shortest wavelength DIB is centered near 4430 Å while the longest wavelength one – around 9632 Å. The echelle spectrograph, attached to the 2-m telescope, is ideally designed to observe all these features in any single exposure. This facilitates the gathering the data concerning the whole spectra of interstellar clouds; let us mention that atomic and molecular lines are observed in the same spectra. The latter allows searching for possible relations between well-identified atomic or molecular lines and the unidentified DIBs. Our database allowed to establish a close correlation between some of the DIBs and K I line – Fig. 4a. This fact suggests that the DIB carriers may be ionized by the photons similar to those which are capable to ionize potassium; moreover one should use the K I lines to determine the rest wavelength velocity frame for the same DIBs. Let us mention that the Terskol echelle spectra allow the very precise (up to 0.003 Å) wavelength determination of any of the detectable features due to the applied global dispersion curve.

It is rather commonly believed that diffuse interstellar bands reveal the presence of some complex, carbon-bearing interstellar molecules. Only recently the experimenters found the methods to obtain spectra of such species in the gas phase. The method (Cavity Ring Down) is, however, very time consuming, while a lot of different species has already been proposed as DIB carriers. Generally, the proposed carriers fall into three categories:

- carbon (or hydrocarbon) chains first proposed by Douglas in 1977. Such species are likely abundant in the interstellar space due to high abundances of both hydrogen and carbon. However, the attempt to identify as DIB carriers some of the chain molecules known already from radio astronomical observations failed [16]; the attempt was done by means of comparing the CRD spectra from the laboratory in Basel with the Terskol echelle ones;

- polycyclic aromatic hydrocarbons (PAHs) proposed in 1984 because such molecules are especially resistant against photodestruction. The spectrum of the simplest PAH naphthalene was compared to the Terskol spectra [13] but the result remains uncertain. New spectra, both experimental and observational, are clearly necessary;

- fullerenes; the most promising species of this kind is the famous "soccer ball" – the C_{60} molecule. Two spectral features, found in our spectra in the near infrared (9577 and 9632 Å) may originate in this species. However, the only existing experimental spectra are acquired in the matrix isolation which does not allow a direct comparison. Anyway, fullerenes must not be the carriers of a vast majority of the observed DIBs.

It is to be emphasized that spectral features of many complex molecules occupy very broad spectral ranges. Echelle spectra of reddened stars allow to observe all of them together, this fact is of basic importance for a future identification. Our spectra allow to investigate mutual correlations between the strengths of many DIBs. However, the investigation of the profiles of diffuse bands seems to be a more promising direction. Strength correlations may always be uncertain because of, *e.g.*, stellar or telluric contaminations of certain features. Moreover, it is needed to measure weak DIBs with a relatively low precision. The profile shapes may be intrinsic to certain species but for the comparison with experimental data one needs a very high resolution and S/N ratio spectra.

Our Figure 4b compares the profiles of the 5797 DIB observed in the spectra of two reddened stars. Their shapes are apparently different. It is, of course, of basic importance to select for this kind of investigation only the objects where the interstellar atomic lines do not show any Doppler splitting.

The spectral database, collected using the Terskol 2-m telescope and the echelle spectrograph, is the world-largest one. It allows to conduct several projects using just the archived data; it is currently being extended to very high resolution spectra. It also allows to provide a very careful selection of objects and features to be observed using the largest and most modern telescopes of the leading observatories. Our recent observations, conducted at ESO and at the Mauna Kea Observatory were based on the samples selected using the Terskol database. It is to be emphasized that the comparing spectra from different instruments is a very important procedure as the published measurements do not coincide in every case.

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