HIGH-RESOLUTION SPECTRA OF DARK INTERSTELLAR CLOUDS

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СПЕКТРЫ ВЫСОКОГО РАЗРЕШЕНИЯ ТЕМНЫХ МЕЖЗВЕЗДНЫХ ОБЛАКОВ, Креловски Я., Галазутдинов Г., Мусаев Ф. – В работе представлен ряд новых спектров, полученных с помощью кудэ-эшеле-спектрографа, установленного в фокусе кудэ 2-м телескопа на пике Терскол. Достигнутое недавно очень высокое разрешение ($R = 500\,000$) позволяет анализировать формы профилей особенностей спектров межзвездного поглощения. Особенности проявляются или резко очерченными (если происходят от атомов газа или простых молекул), или очень сложными профилями (неидентифицированные диффузные межзвездные полосы – DIBs). Предполагается, что DIBs происходят от сложных углеродосодержащих молекул, которые могут содержаться в темных межзвездных облаках. Анализ их профилей высокого разрешения является, по-видимому, наиболее перспективным путем для идентификации производителей этих загадочных спектральных особенностей.

The paper presents brand new spectra acquired with the aid of the coude echelle spectrometer installed at the coude focus of the 2-m telescope at Terskol Peak. Very high resolution ($R = 500\,000$), available since very recently, allows analysis of profile shapes of interstellar absorption spectral features. The latter are either very sharp (if originated in gas atoms or simple molecules) or show very complicated profiles (unidentified diffuse interstellar bands – DIBs). DIBs are believed to originate in complex, carbon–bearing molecules, possibly present in dark interstellar clouds. An analysis of their high-resolution profiles seems to be the most prospective way to identify the carriers of these puzzling spectral features.

INTRODUCTION

Various interstellar absorptions may originate in dark, interstellar H I clouds (ISM clouds). Some of them are well–identified atomic lines or bands carried by simple 2–3 atom molecules, some others remain unidentified (diffuse interstellar bands – DIBs). The whole spectrum of a dark, interstellar cloud may be composed of:

- continuous extinction – the selective attenuation of the light of stars shining through ISM clouds; the most interesting part of the extinction curve is situated in the vacuum–UV. For a review see [13, 17],
- polarization – closely related to extinction and probably caused by the same dust grains but partially aligned, most probably by the galactic magnetic field,
- atomic lines of Fe I (3719.937, 3859.913 Å), Ca II (H – 3968.468 & K – 3933.663 Å), Ca I (4226.728 Å), Na I (D_1 – 5895.9236 & D_2 – 5889.9504 Å), Li I (6707.83 Å), K I (4044.136, 4047.206 & 7698.959 Å) and others, observed only in extraterrestrial ultraviolet – see [2, 18]. In many cases these features show several Doppler components because of different radial velocities of clouds situated along the same sightline,
- molecular features of CN (3873.37, 3873.998, 3874.608, 3875.763 Å), CH (3878.768, 3886.41, 3890.213 & 4300.321 Å), CH^+ (4232.54 Å & 3957.70 Å), C_2 (8750 – 8775Å) and C_3 (near 4052 Å); in the vacuum–UV strong bands of CO and H_2 are observed. For a review see [20],

- numerous unidentified, diffuse interstellar bands. The recent surveys [3, 8, 14] have grown their number to about 300. Most of these interstellar features are barely visible even in high S/N spectra. For a review see [7].

The absorption spectra of ISM HI clouds reveal the complexity of physical processes which take place inside them. The behaviour of spectral features reflects variations of physical parameters characterizing the intervening clouds [12]. Apparently this causes the observed variations of DIB intensities and profiles. Relating the DIB behaviour to that of the identified interstellar features one can try to understand how the DIB carriers react to variations of temperature or density. To do this it is necessary to search for targets obscured by only one cloud to avoid confusion caused by ill–defined averages. A reliable description of physical processes inside the ISM should be restricted to such individual clouds.

The latter requirement is, in fact, very severe. Usually heavily reddened stars are observed through several clouds. Any physical parameter averaged along such a line of sight hardly makes any sense. On the other hand, low reddenings are usually connected with weak DIBs (DIB strengths are correlated reasonably tightly with a colour excess – see, *e.g.*, [16]). It is very difficult to record spectra in which the noise does not contaminate seriously profiles of weak features.

PROFILES OF ATOMIC GAS INTERSTELLAR LINES

The ground–based observations can cover only a few spectral lines, originating in atoms of neutral interstellar gases. Among them the Na I lines are usually saturated and thus their intensities (equivalent widths) cannot be directly correlated with those of diffuse interstellar bands as the latter are far from the saturation level. The line which is always observed but very rarely saturated is that of K I (7699 Å). Krełowski, Galazutdinov & Musaev [15] proved that narrow diffuse bands, such as 5797 or 6379 are well–correlated with this line. The observed relation may suggest that intensities of some DIBs depend on the ionization conditions inside certain clouds. To interpret observed profiles of K I lines we need, however, high-resolution profiles – free of possible contamination by the instrumental profile. Fig. 1 shows how the growing resolution in spectra from CEGS (SAO) and the MAESTRO spectrometer fed with the 2-m Terskol telescope changes the observed shape of the K I line profile.

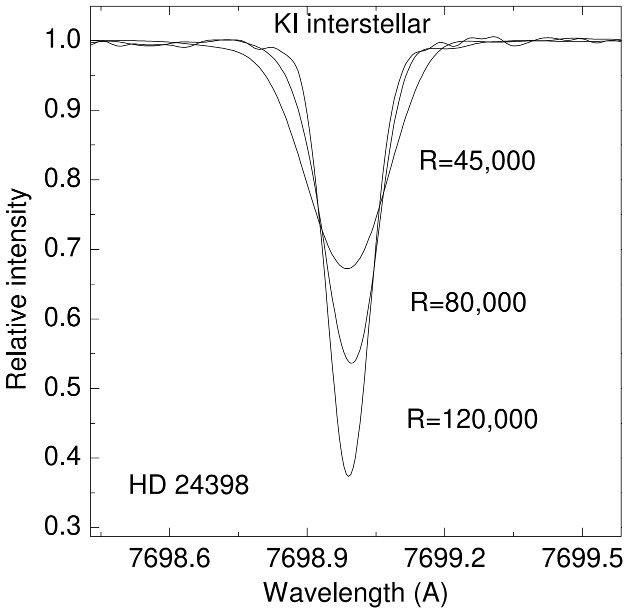

Figure 1. The effect of growing resolution. The interstellar line was observed in the spectrum of ζ Per at SAO and Terskol with three different resolutions

SPECTRAL ABSORPTION FEATURES OF SIMPLE MOLECULES

Currently it is rather commonly accepted that diffuse bands originate in some interstellar molecules, most probably complex, carbon–bearing ones. It may be thus interesting to relate the DIB intensities to those of the features originating in some well–identified, simple molecules, such as CH, CN or CO. The latter spectral features are also very sharp because of the very low density of ISM. The presence of free radicals, like CH, brings the evidence supporting the above phrase. The latter molecule cannot exist in any denser environment.

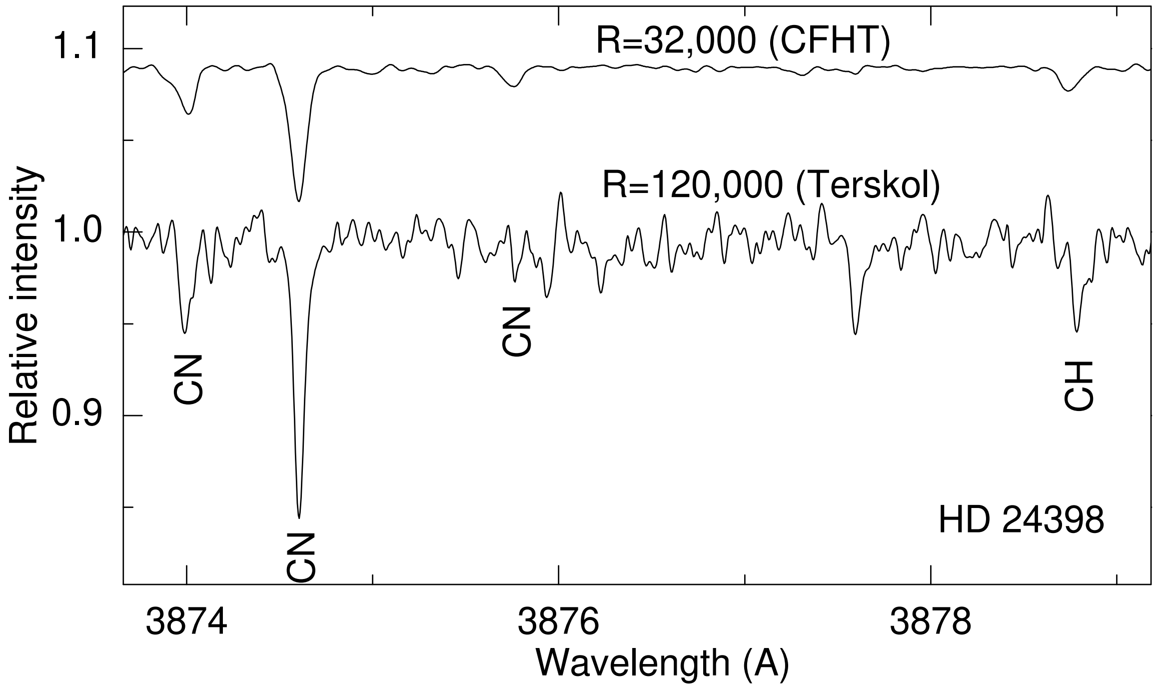

Figure 2. The effect of growing resolution observed in the CN band. The spectra are from CFHT ($R = 32\,000$) and Terskol ($R = 120\,000$)

Homonuclear molecules such as H_2, C_2 or C_3 have been discovered much later. The hydrogen molecule is difficult to be observed as its spectral features are situated in far–UV and thus available only to extraterrestrial observations. The other two above mentioned species reveal their presence by absorption bands available to ground based observations. However, as typical bands originating in homonuclear molecules contain many features, the absorbed energy is quite evenly distributed among them which leads to their shallowness and makes their detection difficult. Currently the MAESTRO spectrometer is capable of recording the infrared spectra of C_2, (Phillips 2–0 band) but the C_3 band near 4052 Å is out of reach as in this wavelength range the quantum efficiency of the applied CCD sensor is too low. Let's add that the first images of the Phillips 2–0 band with the resolution of $R = 120\,000$ are those from the MAESTRO spectrograph. The above mentioned resolution is absolutely necessary to observe the C_3 band as the latter contains many densely packed narrow features [5].

DIFFUSE INTERSTELLAR BANDS

For most of their history DIBs were not observed in individual ISM clouds, in spite of the fact that since the observations of Beals [1], who discovered the Doppler splitting in interstellar atomic lines, it is commonly accepted that the interstellar medium is not homogeneous, but contains many separate clumps. Krełowski & Walker [10] and Krełowski & Westerlund [11] have demonstrated convincingly that spectra of interstellar clouds are not identical. The strength ratios of many different pairs of DIBs vary substantially from object to object which proves they are carried by different species reacting in different ways to varying physical conditions inside the intervening clouds. These variations seem to be related to those of another spectral characteristics of ISM clouds: intensities of atomic and molecular features or shapes of interstellar extinction curves [12].

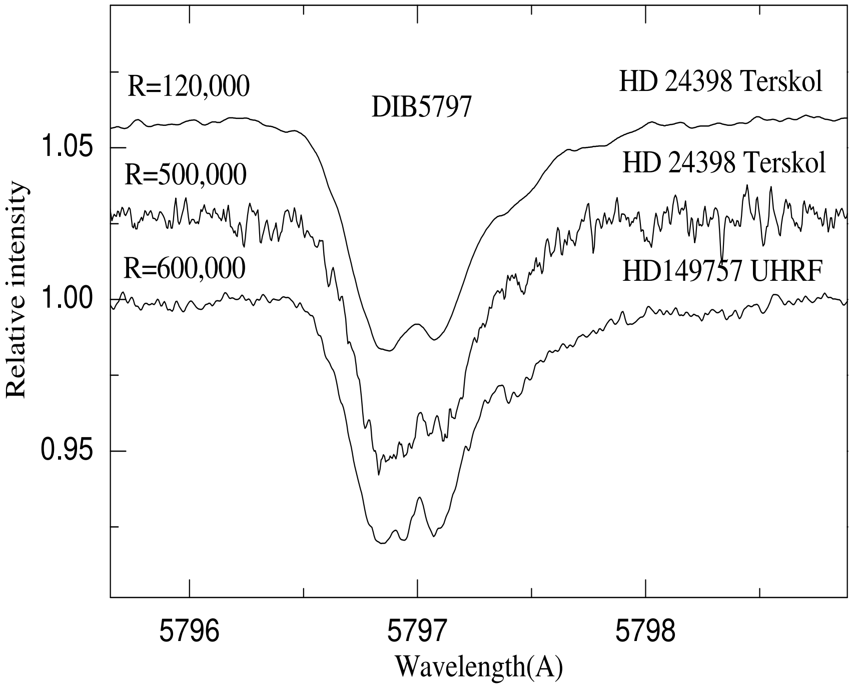

Figure 3. The profile of 5797 DIB observed at UHRF (the Siding Spring Observatory) with $R = 600\,000$ and at the Terskol Observatory with $R = 120\,000$ and $R = 500\,000$. The observed object is HD24398

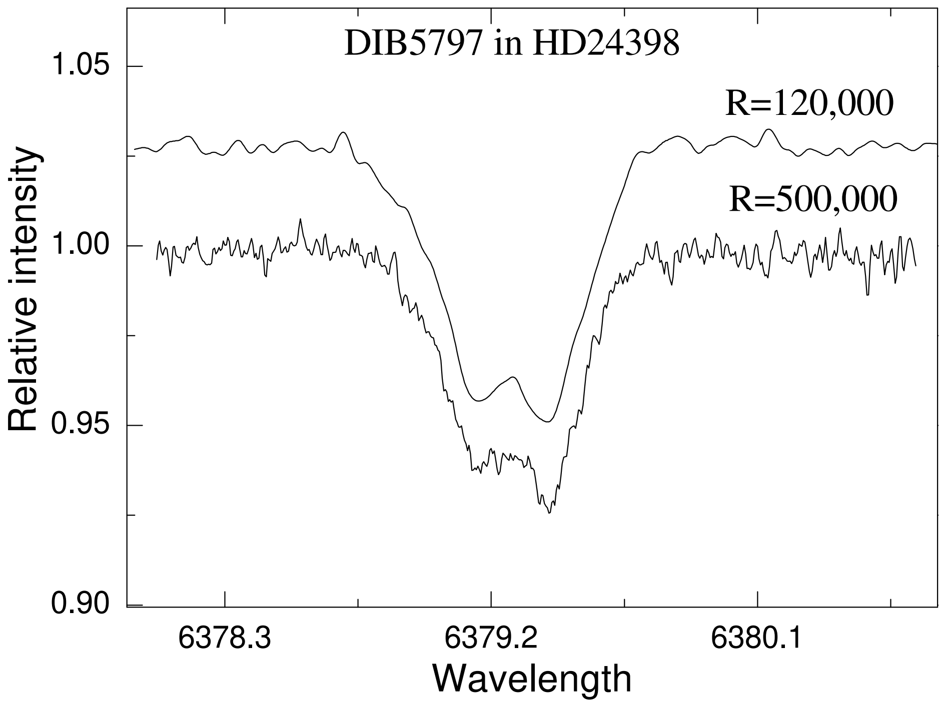

Figure 4. The first ultra high-resolution profile of the 6379 DIB acquired at Terskol; $R = 500\,000$

Herbig & Soderblom [6] demonstrated convincingly that the profiles of DIBs, as well as those of interstellar atomic lines, can be modified by the Doppler splitting. These observations created the problem of the intrinsic profiles of DIBs, *i.e.*, profiles not modified by the Doppler effect. Such profiles can be observed only in individual clouds, *i.e.*, in the cases of low to moderate reddening (single clouds of very high reddening are not common). It is commonly believed now that DIBs originate in some large, carbon–bearing molecules. The latter can be responsible both for DIBs and some segments of the interstellar extinction curve. Their internal structure can be very complicated and the possible presence of many species in every cloud makes the task of identification very difficult. During the decade of 1990s the number of unidentified spectral features, found in the interstellar medium, has grown up to nearly 300 [3].

Westerlund & Krełowski [22] were the first to investigate systematically the intrinsic profiles of five DIBs. Their spectra contained the interstellar Na I lines which allowed to select for the profile analysis only the targets which are very likely to be obscured by single, individual clouds. The analysis showed that all DIB profiles are non–gaussian and that some substructures exist inside the relatively narrow DIBs (5797 and 6379). During the last decade it was convincingly demonstrated that the profiles of diffuse bands are really not gaussians but show some internal structure which may be intrinsic to certain molecules [9, 19, 21]. However, despite many efforts, none of the possible carriers have been identified yet. Fig. 3 shows how the substructures of the strong 5797 DIB are getting revealed with the growing resolution of spectra.

High resolution, high S/N profiles of strong DIBs may allow identification of carriers. The vibrational-rotational transitions, while taking place in complex molecules, are very unlikely to show the rotational features separated – they rather form bandheads (large molecules are typically characterized by small rotational constants; the latter should thus blend and allow only to recognize the P, R, and Q branches inside a profile). The profile shapes may be thus specific to a given molecule(s).

The highest resolution DIB profiles, published until now are those of Sarre *et al.* [19] and Kerr *et al.* [9]. The Ultra High Resolution Facility allowed to see some very fine details of the 5797 and 6614 profiles. It is characteristic that the 5797 profile contains three features which could be the P, R and Q branches of a molecular band. The complicated DIB profiles can also follow the isotopic abundances of carbon [21]. As the wavelength differences between the substructures, seen inside certain DIBs (5797, 6614) are nearly constant, it seems possible that the observed profiles are composed of the features (of nearly gaussian profiles) originating in molecules containing 0, 1, 2, *etc.* ^{13}C atoms. The presence of ^{13}C causes a wavelength shift which is directly proportional to the number of ^{13}C atoms in the carrier molecule.

High-resolution profiles of some DIBs may be so characteristic to a given carrier that their comparison with high-resolution laboratory spectra (acquired in gas phase) may allow identification. It is to be emphasized, however, that the spectra used to determine the profiles must be of very high resolution ($R > 200\,000$) and very high S/N (>1000). This fact creates observational problems as such tasks are usually very time consuming. The procedure requires also a very careful analysis of possible stellar contaminations which could have very likely avoided any attention while spectra of lower S/N have been analyzed. The profiles of diffuse bands may differ from object to object, not only in width or wavelength but also in the pattern of weak substructures seen in the bottom of some broad features [4].

The new setting of the echelle spectrometer on top of Terskol Peak allows three resolutions: 120 000; 250 000; and 500 000. The latter offers evidently one of the few possibilities to acquire ultra high-resolution spectra and allows analyzing profiles of either sharp or very complex interstellar absorption features. It has to be mentioned that the highest resolution has been applied only to a very bright star: ζ Per. A possible sample of objects may be efficiently extended only if a back–illuminated CCD sensor is installed instead of the currently exploited front–illuminated one. While rising the quantum efficiency by a factor of three one can expect to be able to observe with $R = 500\,000$ stars as faint as four apparent magnitude. This should allow profile analysis of several DIBs originated along different sight–lines.

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