Very high resolution profiles of four diffuse interstellar bands

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ABSTRACT
Ultra-high-resolution ($R \sim 300\,000$) profiles of four diffuse interstellar bands (DIBs) are presented. The $\lambda \lambda$ 5797-, 5850-, 6196- and 6379-Å DIBs were observed towards the reddened supergiant HD 24398, a line of sight free of Doppler splitting; thus the observed profiles can be considered as intrinsic to the DIB carriers. Three of the profiles show substructure which supports the hypothesis of a molecular origin for these DIBs.

Key words: ISM: clouds – ISM: molecules.

1 INTRODUCTION
Since their discovery by Heger (1921), the carriers of diffuse interstellar bands (DIBs) remain unidentified despite much effort. Soon after their interstellar origin had been established (Merrill 1934), the hypothesis of their molecular origin was formulated (McKellar 1941). The set of known features (almost 300 entries: Herbig 1975; Galazutdinov et al. 2000a) contains the following.

(i) Very narrow ones, like 6196 Å, for which Herbig & Soderblom (1982) demonstrated the presence of Doppler splitting while reddened stars are observed through two or more clouds situated along their lines of sight; their intrinsic profiles vary apparently from object to object (Galazutdinov et al. 2002a) and contain weak substructures.

(ii) Narrow ones, like 5797, 6379 or 6614 Å, for which high-resolution spectra usually reveal some substructures (Sarre et al. 1995; Krełowski & Schmidt 1997; Kerr et al. 1998; Walker et al. 2001; Galazutdinov et al. 2002a); their intrinsic profiles are also apparently sensitive to variations in environmental conditions.

(iii) Broad features, like 5780 or 6284 Å; their profiles are apparently only slightly asymmetric (Westerlund & Krełowski 1989); no substructures have been discovered as yet.

(iv) Very broad DIBs, like 4430 or 6177 Å (Beals & Blanchet 1937; Herbig 1975; Chlewicki et al. 1986); evidently, their profiles are rather featureless (Snow 2002).

A common origin of all these features seems very unlikely; most probably, the whole DIB spectrum reveals the presence of many different carriers. The most often proposed species are complex interstellar molecules, usually some carbon-bearing ones (for a review see e.g. Fulara & Krełowski 2000) such as linear hydrocarbons or bare carbon chains, polycyclic aromatic hydrocarbons and fullerenes. Spectra of linear molecules contain usually one strong and several quite weak features each, distributed evenly (energy scale) in a very broad spectral range (Weselak et al. 2001). It is an attractive proposition that DIBs are carried by these species: generally, the interstellar spectra contain a bit more than 10 strong DIBs and up to 300 weak ones. Also, the strengths of the strong features are usually not very well correlated (Moutou et al. 1999), except for 6614 and 6196 Å. However, even these two were proved not to be of the same origin (Galazutdinov et al. 2002a). Analyses of mutual relations between strong and weak DIBs hardly lead to evident conclusions (Weselak et al. 2001). This is because strengths of weak features are necessarily measured with a much lower precision: in any case, the signal-to-noise (S/N) ratios inside profiles of the spectral features as shallow as $\sim 1$ per cent of the continuum are below 10. It is also to be mentioned that measurements of intensities are also uncertain in the case of strong DIBs because of blending and because of doubts as to how their borders should be defined. This is why the recently published equivalent widths of 5780 and 5797 Å (Thorburn et al. 2003) do not agree with those of Herbig (1993), which makes the existing considerations based on mutual correlations between DIBs hardly conclusive. This motivates a search for fine structure, which should be detectable if the features originate in molecular carriers. To identify some of the DIBs, it seems necessary to analyse their high-resolution profiles, especially those revealing possible rotational contours which are likely to be specific to any of the carriers. In order to accomplish this, both ultra-high spectral resolution and high S/N are required. The resolving power of $\sim 60\,000$ used by Krełowski & Schmidt (1997) only suggests the presence of fine structure in most of the reasonably narrow DIBs as well as at $R = 45\,000$ (Galazutdinov et al. 2001), but does not allow the substructures to be seen separated. Such substructures, as well as their pattern, which is variable from object to object, have been recently demonstrated in $R = 220\,000$ spectra from ESO (Galazutdinov et al. 2002a). The substructures inside the profiles of strong DIBs are very narrow and shallow (Sarre et al. 1995;
Kerr et al. 1998). These papers also proved that some of them are extremely sharp, which makes them invisible in lower resolutions (Fig. 1). This creates an ill-defined average of spectra of all these clouds, which can be hardly interpreted as any of the components involved possibly being of different intrinsic profile as well as being of different radial velocity. This fact is rather fortunate, as the stars observed through single clouds are very likely to be nearby and thus to be bright. The apparent brightness is a necessary property of a target to be observed in an ultra-high resolution. Recently, the MAESTRO (Matrix Echelle Spectrometer of Terskol Observatory) instrument installed at the coudé focus of the 2-m telescope of the Terskol Observatory was reconfigured to allow ultra-high-resolution spectral observations. It is natural that we attempted to obtain precise profiles of several reasonably narrow DIBs in the spectra of a bright, reddened star.

2 THE OBSERVATIONAL DATA

We have acquired our spectra with the aid of the coudé echelle spectrometer (Musaev et al. 1999) fed by the 2-m telescope at the observatory on the Terskol Peak in Northern Caucasus to determine the fine structure of the selected DIB profiles. In contrast to the published optical layout (Musaev et al. 1999), we replaced the main disperser – a mosaic of two R2 echelle gratings (200 × 250 mm, 37.5 groove mm⁻¹) – with a mosaic built from three R6 (80.5° blaze angle) echelle gratings (220 × 320 mm, 37.5 groove mm⁻¹), which allows us to reach a nominal spectral resolution of R = 500 000 corresponding to 2 pixels on the available CCD chip (see below) when the slit width is 0.5 arcsec. Other components of the spectrometer are exactly the same: the collimator is an off-axis f/36 parabolic mirror with a diameter of 200 mm, the camera is a Schmidt one with outer focus, f = 1900 mm and the cross-disperser is a 45° crown prism. A spectrum consists of 50 to 52 spectral orders formed on the 1242 × 1152 pixel CCD matrix (pixel size 22.5 μm × 22.5 μm) of the camera, manufactured by Wright Instruments. The spectrometer forms the spectrum in the range ∼3500 to ∼10 100 Å with the resolution R = 300 000 (estimated by FWHM of narrow Fe+Ar hollow cathode lamp lines). However, any single exposure covers only a very small fraction of the above mentioned range: 5–10 Å in each spectral order, depending on wavelength. This requires a precise setting for every DIB; in one case only, two of the considered features could have been observed in the same exposure. We have chosen only one reddened star, free of the Doppler splitting along the line of sight towards it, which, in fact, follows very narrow atomic lines without the detectable Doppler splitting observed by Welty & Hobbs (2000) in ultra-high-resolution spectra. The object is the well-known star ζ Per (HD 24398), a bright B1 supergiant, characterized by a reasonable reddening (E_B−V = 0.31). The apparent magnitude (2.5 mag) makes the task of recording ultra-high-resolution spectra possible. Our reduction of the echelle spectra was made using the DECH code (Galazutdinov 1992). This program allows flat-field division, bias/background subtraction, one-dimensional spectrum extraction from the two-dimensional images, correction for the diffuse light, spectrum addition, excision of cosmic ray features, etc. The DECH code also allows location of a fiducial continuum, measurements of the line equivalent widths, line positions and shifts, etc.

3 RESULTS

The extracted DIB profiles are shown in Figs 1–4. Each spectrum of HD24398 was divided by a telluric line divisor (HD218045) to make sure that the resultant profiles are free of contamination originating in the terrestrial atmosphere. Fig. 1 compares our profile of the well-known 5797-Å DIB with that already obtained by Kerr et al. (1998). We emphasize that the DIB has been observed in two different

Figure 1. The ultra-high-resolution profile of the 5797-Å DIB (courtesy of P. Sarre) observed toward HD 149757 by Kerr et al. (1998), compared to our profile seen in the spectrum of HD 24398 in two different resolutions.

Figure 2. Evident substructures in the ultra-high-resolution profile of the 5850-Å DIB observed using the MAESTRO spectrograph of the Terskol Observatory. The slightly inclined line is a fragment of the synthetic spectrum, calculated with physical parameters, corresponding to ζ Per (T_eff = 24 000, lgg = 3.0, vsin(i) = 120 km s⁻¹). This demonstrates well that the DIB profile shape is not affected by stellar lines. Note the importance of the observations being at ultra-high resolution.
objects and thus its profile may be a bit different (see Galazutdinov et al. 2002a). However, the general features of this diffuse band remain the same in both spectra. This result leaves no doubt that the considered DIB shows a complex structure, possibly revealing its molecular origin. The most narrow feature avoids detection at \( R = 120,000 \); however, this sharp feature may play a very important role when a similar profile is found in laboratory gas-phase experiments. We have also analysed possible stellar contaminations which are perhaps present in the DIB profiles. Each of our figures contains a line corresponding to the \( \xi \) Per (\( T_{\text{eff}} = 2400 \), \( \text{logg} = 3.0 \), \( \text{vsin}(i) = 120 \text{ km s}^{-1} \)) synthetic spectrum in order to identify possible stellar features. The above comparison shows how reliable our ultra-high-resolution spectra are. The same precision characterizes the profiles of some other DIBs which have not yet been observed with such high resolution. Fig. 2 demonstrates a rather complicated profile of the fairly narrow 5850-Å DIB. It is known to be well correlated (by intensity) with the stronger 5797-Å feature and thus the presence of a substructure pattern is not unexpected. How far the pattern of these substructures may vary from object to object remains unknown until other objects are observed. The 6196-Å profile observed towards \( \xi \) Per (Fig. 3) shows no substructure pattern. The DIB is quite wide and thus the S/N ratio inside the profile is not very high. However, it clearly resembles some of the \( R = 220,000 \) profiles observed recently by Galazutdinov et al. (2002a). However, the profile extracted from this paper (concerning HD 149757) shows some substructures. Apparently, a similarity of two profiles of one DIB (Fig. 1) does not imply the same in a case of another DIB. The 6196-Å feature is the narrowest diffuse band of this kind, which makes it very sensitive to the Doppler splitting. The 6379-Å DIB, presented in Fig. 4, has never been observed with such a high resolution. Evidently, its profile resembles that of the 5797-Å DIB (their strengths correlate quite well) but is a bit narrower. One can trace in the profile two evident strong substructures (also easily seen in the \( R = 120,000 \) profile acquired with the Gecko spectrograph) and, possibly, a very sharp, central one which resembles that found by Kerr et al. (1998) in the 5797-Å profile.

4 DISCUSSION

The high-resolution and high S/N spectra acquired with the International Centre for Astronomical, Medical and Ecological Researches (IC AMER) instruments leave no doubt that the profiles of the four diffuse interstellar bands are complex, showing a substructure pattern. The profiles obtained with the new apparatus resemble those obtained by Kerr et al. (1998) or by Galazutdinov et al. (2002a). At the moment, we cannot identify any of the observed DIBs. Nevertheless, some linear species, based on a carbon skeleton, remain to be the most likely carriers of narrow DIBs which show typically a substructure pattern. The above demonstrated profiles may be directly compared to laboratory gas-phase ones of complex species. It must, however, be emphasized that no clear interpretation of the profiles is possible at the moment. DIB carriers are very likely to be molecular species, but their structure remains a puzzle until at least one of them is evidently identified. The recent gas-phase laboratory spectra of other proposed DIB carriers – polycyclic aromatic hydrocarbons (PAHs) (Bréchignac & Pino 1999; Romanini et al. 1999) proved that their spectral features are broad (FWHM of up to 20 Å) and thus they are not likely to produce the great majority of known DIBs, which are an order of magnitude narrower. Theoretically narrow PAH features are also possible, but no such bands have been discovered yet in laboratory gas-phase experiments. Also, fullerenes are not very likely to be carriers of many DIBs – most probably, they can carry only a few interstellar features (Galazutdinov et al. 2000b). It seems now more likely that DIBs may be identified by means of analysing fine details of their profiles rather than by relating their strengths and obtaining ‘families’ of possibly the same origin. Spectra of single molecular species are most likely to contain one strong and several weak features each. As strengths of weak DIBs are measured necessarily with a much lower precision, it is difficult to state that they correlate perfectly with any other one. However, the profiles of single features may also vary from object to object (Galazutdinov et al. 2002a), which makes their comparison with laboratory counterparts difficult. One may need a set of laboratory profiles obtained under different physical conditions as well as a set of high-resolution spectra of several reddened stars.
5 CONCLUSIONS

Fine structure has been revealed in three DIBs, which confirms some previous observations (especially those of Kerr et al. 1998). Substructure pattern, similar to that in the 5797-Å DIB, was also found in the 6379-Å DIB. The 5850-Å DIB profile shows a complicated shape; this feature is well correlated by strength with the two DIBs mentioned above. The presence of these structures provides more evidence for the gas-phase molecular nature of the DIB carriers.

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