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The interstellar C_3 chain molecule in different interstellar environments⋆

G. Galazutdinov[1,4,5], A. Pętlewski[4], F. Musaev[1,4,5], C. Moutou[2], G. Lo Curto[3], and J. Krełowski[4]

[1] Special Astrophysical Observatory, Nizhnij Arkhyz 369167, Russia
e-mail: gala@sao.ru;faig@sao.ru
[2] Laboratorie d'Astrophysique de Marseille, Traverse du Siphon, Les trois Lucs, BP 8, 13376 Marseille Cedex 12, France
e-mail: Claire.Moutou@oamp.fr
[3] European Southern Observatory, Alonso De Cordova 3107, Vitacura, Santiago, Chile
e-mail: glocurto@eso.org
[4] Center for Astronomy, Nicholas Copernicus University, Gagarina 11, 87-100 Toruń, Poland
[5] Isaac Newton Institute of Chile, SAO Branch, Russia

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Abstract. We present an analysis of spectra of six stars taken with high resolution ($R = 220\,000$). The stars are reddened by molecular clouds that differ by the relative strength of the 5797 and 5780 diffuse interstellar bands (DIBs). The high signal-to-noise ratio of the spectra ($S/N \approx 700$–1000) shows that the abundance of the linear molecule C_3 with respect to E_{B-V} varies considerably from one star to an other. There is no correlation with E_{B-V}. The strong variations in the abundance of C_3 must therefore be caused by another circumstance. We point out that this may be the case: from an analysis of the interstellar potassium lines in the same spectra we conclude large differences in the state of ionization produced by interstellar photons with energies below the ionization potential of hydrogen. The ratio of the abundances of C_3 and C_2 varies considerably in different directions, even when the ratio between the strengths of various DIBs remains approximately constant.

Key words. ISM: clouds – molecules

1. Introduction

It seems of importance to check possible relations between identified atomic and molecular features and diffuse interstellar bands (DIBs) which remain unidentified since 1922. It has already been suggested that all possible interstellar absorptions (extinction, atomic and molecular lines, diffuse bands) change in unison i.e. their strengths vary together from cloud to cloud (Krełowski et al. 1992). This fact may be important as the observations of well–identified spectral features can help us to determine physical conditions in individual clouds and thus relate the observed variations of DIB strengths to physical parameters such as temperature or density. This may be very helpful for the task of identifying DIBs – the longest standing unsolved problem in all of spectroscopy.

Douglas (1977) proposed linear carbon molecules as possible carriers of DIBs. Bare carbon chains, being homonuclear species, do not create rotational transitions observable at radio wavelengths and thus only their electronic and/or vibrational spectral features can be compared with those observed. The latter may cover the spectral range from vacuum UV until far infrared. It seems thus of importance to estimate the abundances of simplest carbon molecules in interstellar clouds. They can be building blocks for many observed (due to radio rotational transitions) interstellar molecules which are often based on carbon skeletons (chains up to 11 atoms long).

The gas-phase optical spectra of linear carbon chains are known for C_2, C_3, C_4 and C_5 (e.g. Motylewski et al. 1999). The first pure carbon molecule, the two–atom homonuclear C_2, was discovered by means of near infrared spectroscopy in 1977 by Souza & Lutz in the spectrum of the opaque cloud obscuring the star Cyg OB2 No. 12. The same authors failed to find the Phillips band (2–0) near 8760 Å in the spectrum of HD 149757 because of the weakness of the features, seemingly correlated with the reddening.

The latter, Phillips (2–0) band of C_2 was found in the spectrum of HD 149757 by Hobbs & Campbell (1982) and confirmed in higher S/N spectra by Danks & Lambert (1983). Both teams estimated the C_2 column densities to be of the order 10^{13} cm^{-2} in the case of this, well known object characterized by E_{B-V} close to 0.3. The estimate of van Dishoeck & Black (1986) based on (3–0) Philips band around 7720 Å gave a very similar result. The estimates given for another targets by Danks & Lambert (1983) proved that the ratio of the C_2

Send offprint requests to: J. Krełowski,
e-mail: jacek@astri.uni.torun.pl

⋆ Based on data collected at the ESO 3.6 m telescope operated on La Silla Observatory, Chile.

Table 1. The list of targets with the $A^1\,\Pi_u - X^1\,\Sigma_g^+$ band of C_3 molecule observed (upper part – published data, lower part –our data). Column headings: HD – HD number; SpL – spectral and luminosity class; V – visual apparent magnitude; E_{B-V} – reddening; $v{\cdot}\sin i$ – rotational velocity; K I – equivalent width of K I 4044.14 line; 5780 and 5797 – equivalent widths of 5780 and 5797 DIBs respectively; C_2 – column density of C_2 molecule, based on the average of $Q(2)$ and $Q(4)$ lines of the (2,0) Philips system, oscillator strengths from Federman et al. (1994); C_3 – column density based on the average of $Q(4)$, $Q(6)$, $Q(8)$, $Q(10)$, $Q(12)$ lines of $A^1\,\Pi_u - X^1\,\Sigma_g^+$ transition; all of the same oscillator strength $f = 0.0073$ (Roueff et al. 2002); C_2/C_3 – the ratio of average column densities. All EW measurements are in mÅ.

HD	SpL	V	E_{B-V}	$v{\cdot}\sin i$	K I (4044.14 Å)	5780	5797	C_2	C_3	C_2/C_3
24398	B1I	2.96	0.34	59	-	98 ± 4	57 ± 1	3.95(12) ± .45[a]	1.74(11) ± .6[e]	22.7 ± 10.4
149757	O9V	2.60	0.29	379	-	70 ± 2	29 ± 2	4.25(12) ± .85[b]	1.96(11) ± .6[e]	21.7 ± 11
179406	B3V	5.36	0.30	170	-	143 ± 2	79 ± 2	1.92(13) ± .22[c]	2.02(11) ± .3[e]	95 ± 25
210121	B3V[j]	7.83	0.40	<20	-	57	-	1.6(13)[d]	6.8(11) ± 2.6[f]	23.5 ± 12
143275	B0.3V	2.30	0.19	200	-	79 ± 4	14 ± 1.0	-	≤0.30(11)	-
144217	B0.5V	2.62	0.17	130	0.19 ± 0.03	161 ± 4	15.3 ± 0.5	≤1.7(12)[g]	≤0.42(11)	-
147165	B1III	2.89	0.32	53	0.22 ± 0.03	243 ± 2	26.0 ± 3.0	-	≤0.29(11)	-
148184	B2V	4.40	0.44	118	1.23 ± 0.10	104 ± 3	48 ± 1.8	7.15(12) ± .15[h]	3.4(11) ± 0.5	21 ± 3.5
149757	O9V	2.60	0.30	379	0.8 ± 0.04	70 ± 2	29 ± 1.5	4.25(12) ± .85[b]	2.2(11) ± 0.2	19.3 ± 5.6
152236	B1I	4.80	0.65	60	0.5 ± 0.04	-	-	3.06(12) ± .45[i]	2.6(11) ± 0.2	11.8 ± 2.6

[a] Chaffee et al. (1980); [b] Danks & Lambert (1983); [c] Federman et al. (1994); [d] Gredel et al. (1992); [e] Maier et al. (2001); [f] Roueff et al. (2001); [g] Lambert et al. (1995); [h] van Discoeck & de Zeeuw (1984); [i] van Dishoeck & Black (1989).

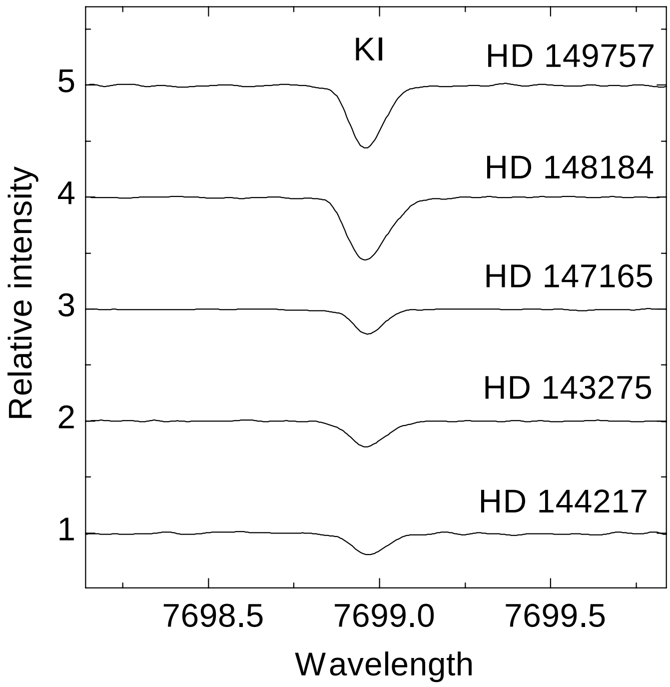

Fig. 1. Figure demonstrates the lack of Doppler splitting in atomic potassium interstellar lines in the spectra of the programme stars (excluding HD152236). The spectra are from Terskol observatory (R = 120 000 coudé-echelle spectrometer, Musaev et al. 1999). Note that the set of targets splits into the subsets of objects in which the line is either strong or weak. Very recent paper (Welty & Hobbs 2001) based on the spectra from Ultra High Resolution Facility confirms this result.

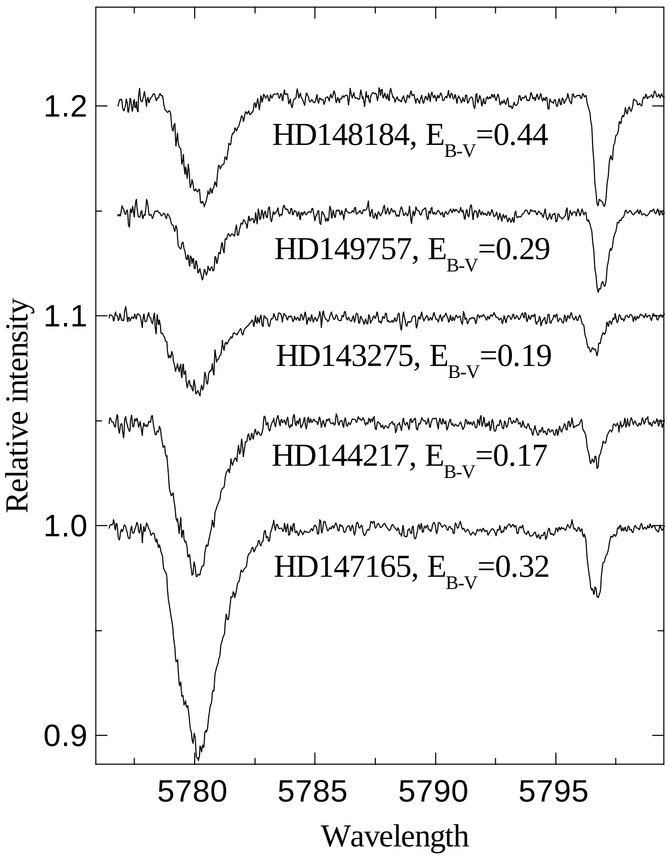

Fig. 2. The major diffuse interstellar bands observed in the spectra of our five selected targets using the McDonald Observatory echelle spectrometer. HD 152236 was not observed, but we consider it as "zeta"–type object (see text).

column density and E_{B-V} is rather similar in cases of other reddened stars. Also Crawford (1990) found similar (relative to E_{B-V}) C_2 column densities towards Sco OB1 stars. The largest existing survey by van Dishoeck & Black (1989) supports also the above mentioned results. The estimates based on the HST spectra which contain the Mulliken system at 2313 Å are below those based on the infrared spectra by a factor of 1.5–2 (Lambert et al. 1995). The extensive survey of C_2 abundances,

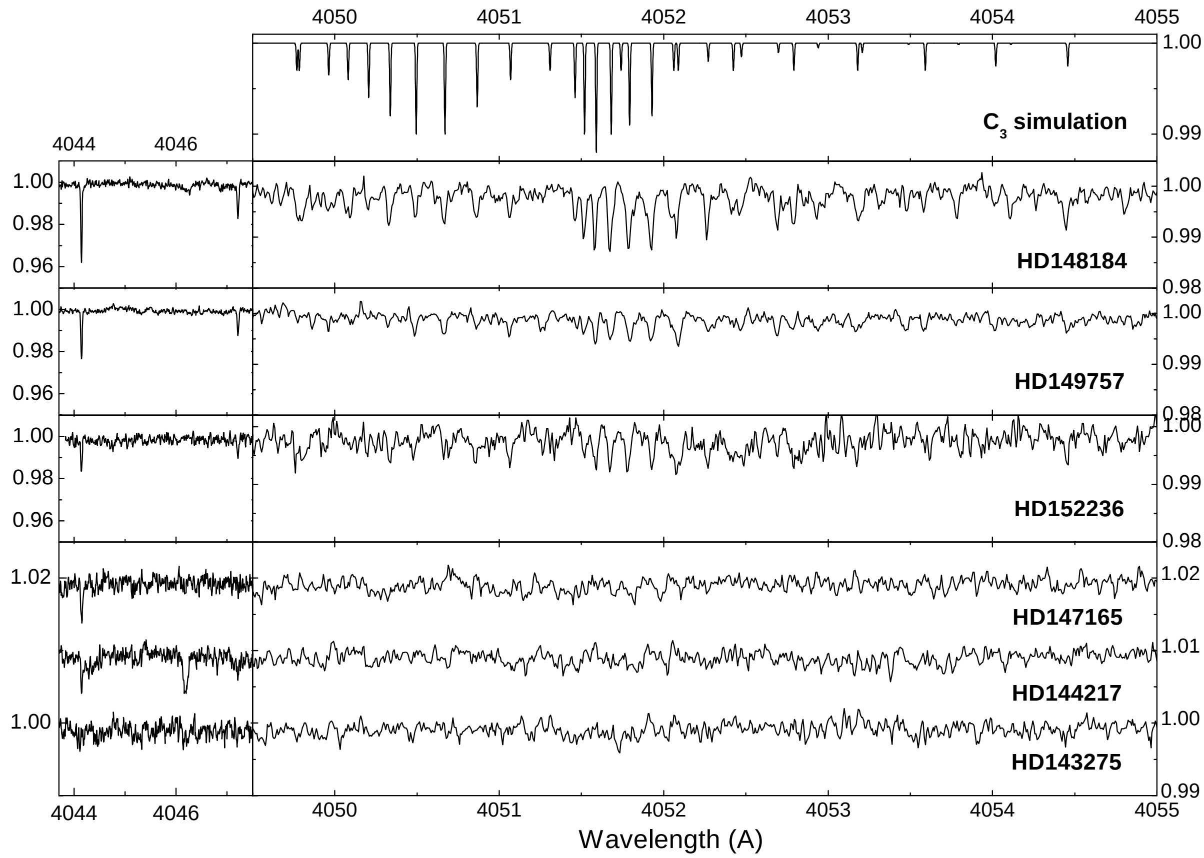

Fig. 3. C_3 band observed in the spectra of our six targets: relatively strong towards "zeta" objects and below the level of detection in "sigma" ones (bottom panel). The neighbour KI interstellar lines are also presented but in another scale as they are deeper than C_3 features. The "synthetic" spectrum of C_3 shows only the wavelengths of the subsequent transitions. It does not carry any physical information.

based on the Phillips 2–0 band (published by van Dishoeck & Black 1989) contains 18 objects. The most recent compilation of Federman et al. (1994) was able to give estimates of the C_2 column densities towards 32 reddened stars plus a couple of upper limits. Not less important seems the fact that vacuum–UV Mulliken band of C_2 has not been detected in the HST spectra of HD's: 144217, 143018 and 144470 despite a substantial reddening and the presence of reasonably strong diffuse interstellar bands observed towards them (Westerlund & Krełowski 1988).

The next member of the possible family of carbon molecules, C_3, is much more difficult to be observed. It was discovered by Hinkle et al. (1988) in the infrared spectrum of the circumstellar shell of the star IRC +10216. This spectral range is, however, not covered with observations of interstellar, translucent clouds due to relatively low opacity. The possible discovery of this molecule (its absorption band $A^1\ \Pi_u - X^1\ \Sigma_g{}^+$ near 4052 Å) was described by Haffner & Meyer (1995). It was based on several spectra of the heavily reddened star HD 147889 in which the possible C_3 feature appeared as a very weak one. The detailed structure of this band was found towards four nearby reddened stars in July 2000 (Maier et al. 2001; Roueff et al. 2002). The summary of already existing observations gives Table 1. The data in which DIBs have been measured are McDonald $R = 60\,000$ spectra (Krełowski & Sneden 1993), except the case of HD 210121. The table contains also C_2 column densities, calculated as averages of published equivalent widths of two strong transitions $Q(2)$ and $Q(4)$ with the oscillator strengths given by Federman et al. (1994). The column densities of the C_3 species were calculated in a similar way using $Q(4)$, $Q(6)$, $Q(8)$, $Q(10)$, $Q(12)$ lines of $A^1\ \Pi_u - X^1\ \Sigma_g{}^+$ transition; all of the same oscillator strength $f = 0.0073$ (Roueff et al. 2002).

However, the existing data on C_3 do not allow to compare the abundances of this species in different environments. All the existing observations concern "zeta" type clouds i.e. the objects in which the narrow DIBs and the spectral features of simple molecules are relatively strong. The lack of C_2 in certain ("sigma" type, where molecular and narrow DIBs are typically very weak) objects may suggest that one should expect C_3 to be very weak as well. However, if the Douglas hypothesis is correct, the abundances of longer carbon chains may start growing starting from a certain length. Our observations were made in order to make the simplest test of this possibility i.e. to estimate the abundances of the C_3 bare carbon chain in "sigma" and "zeta" environments as defined by Krełowski & Sneden (1995).

2. The observational data

The observational material has been collected at ESO with the aid of the CES (Coude Echelle Spectrograph) fed by the fiber

Table 2. Equivalent widths (mÅ) of C_3 lines measured in program stars spectra. Wavelengths are adapted from Gausset et al. (1965).

λ(air)	Line	HD 149757	HD 148184	HD 152236
4049.963	$R(16)$	0.07 ± 0.03	0.26 ± 0.08	–
4050.081	$R(14)$	0.12 ± 0.04	0.31 ± 0.07	0.13 ± 0.05
4050.206	$R(12)$	0.13 ± 0.05	0.12 ± 0.06	0.11 ± 0.02
4050.337	$R(10)$	0.12 ± 0.04	0.16 ± 0.04	0.22 ± 0.04
4050.495	$R(8)$	0.13 ± 0.03	0.19 ± 0.06	–
4050.67	$R(6)$	0.173 ± 0.04	0.26 ± 0.06	0.23 ± 0.03
4050.866	$R(4)$	0.102 ± 0.05	0.31 ± 0.07	0.21 ± 0.04
4051.069	$R(2)$	0.16 ± 0.04	0.32 ± 0.05	0.23 ± 0.04
4051.519	$Q(4)$	0.25 ± 0.03	0.28 ± 0.04	0.26 ± 0.04
4051.59	$Q(6)$	0.27 ± 0.04	0.35 ± 0.05	0.28 ± 0.04
4051.681	$Q(8)$	0.23 ± 0.04	0.41 ± 0.06	0.29 ± 0.02
4051.793	$Q(10)$	0.21 ± 0.04	0.39 ± 0.04	0.31 ± 0.05
4051.929	$Q(12)$	0.23 ± 0.04	0.40 ± 0.04	0.27 ± 0.05
4052.473	$Q(18)$	0.128 ± 0.05	–	–
4052.698	$Q(20)$	0.16 ± 0.03	0.28 ± 0.05	0.14 ± 0.04
4052.792	$P(8)$	0.13 ± 0.04	0.28 ± 0.05	0.24 ± 0.04
4053.591	$P(12)$	0.13 ± 0.03	–	–
4053.794	$Q(28)$	0.08 ± 0.03	0.19 ± 0.05	–

link with the Cassegrain focus of the 3.6 m telescope of the La Silla Observatory. All the stars have been observed with the highest resolving power, using the Very Long Camera in the spectral range from 4040 to 4066 Å. Centering CES at a wavelength of 4053 Å we determined $R \sim 220\,000$ by the full width at half maximum of ~2.7 pixel for a narrow line in the spectrum. The instrument is equipped with an image slicer which splits the starlight into a dozen of well–illuminated slices. The detector is an EEV 2K×4K CCD (pixel size 15×15 μm) with 80% quantum efficiency in the domain of interest.

The objects for this project were chosen using the existing sample of McDonald spectra (Krełowski & Sneden 1993) which includes the NaI D_1 and D_2 lines as well as the major 5780 and 5797 DIBs. Spectra of some objects have been acquired also using the high resolution ($R = 120\,000$) echelle spectrometer fed with the 2 m. telescope of the Terskol Observatory (Northern Caucasia) – in this case the KI line at ~7700 Å was observed. The chosen targets are listed in Table 1 where HD numbers, spectral types, luminosity classes, colour excesses and rotational velocities are given. We also added some other interstellar data such as intensities of the 5780 and 5797 Å major DIBs (measured in the McDonald spectra) and the column densities of the C_2 molecule (found in publications). The targets were selected using the profiles of atomic interstellar lines i.e. they do not show Doppler splitting (Fig. 1). Such a choice of targets is necessary to see the closely packed rotational features of the C_3 band resolved. We have added HD 152236, a relatively bright, reddened southern star. This star is known to have relatively strong CH, CN and C_2 interstellar lines (Crawford 1990; Crawford 1995), what leads, together with the enormous strength of the 5850 Å diffuse band, usually well correlated with the 5797 Å DIB (Jenniskens et al. 1996), to the conclusion that it is the "zeta" type object, although the behaviour of major DIBs is not known directly. The brightness

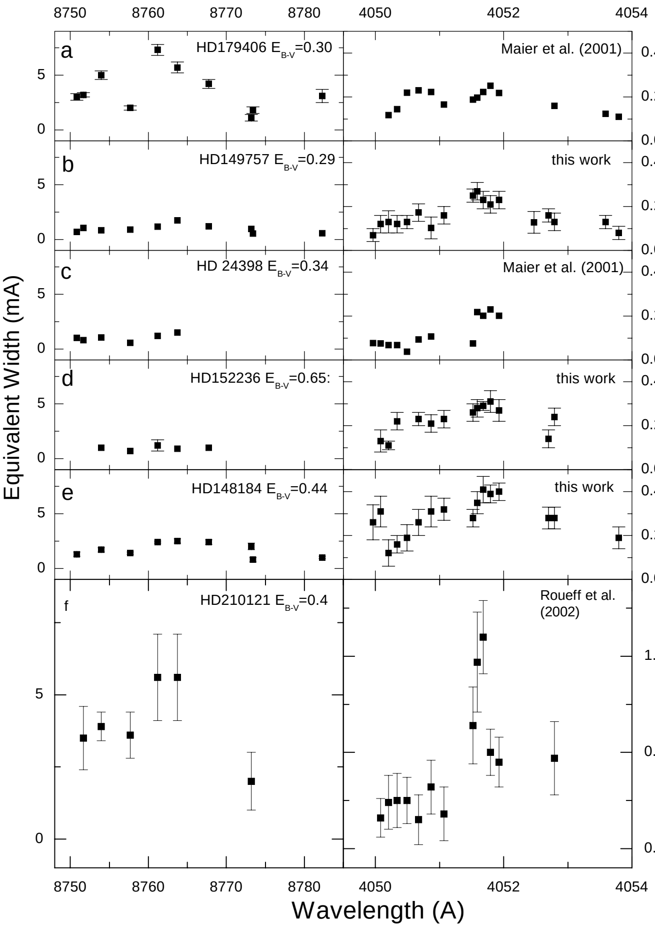

Fig. 4. Equivalent widths of the subsequent transitions inside the C_2 (left panels) and C_3 (right panels) bands for individual targets. Panels of each molecule are shown in the same wavelength and intensity scale for better clearness. Note the different relative abundances of the considered species. The measurements of C_3 features in the spectrum of HD 210121 are less certain because of the relatively low resolution of the spectra applied. *EW* data are taken from: [a] Federman et al. (1994); [b] Danks & Lambert (1983); [c] Chaffee et al. (1980); [d] van Dishoeck & Black (1989); [e] van Discoeck & de Zeeuw (1984); [f] Gredel et al. (1992).

of all our targets was crucial to allow the achievement of high S/N ratio.

Figure 1 clearly demonstrates that some of the targets, selected for the project and listed in Table 1, show very strong KI lines while the others – very weak. The same division can be made using the intensity ratio of the major DIBs: 5780 and 5797 as a criterion – see Fig. 2. Apparently the 5797/5780 ratio grows together with that of KI/$E(B-V)$ i.e the band 5797 seems to be correlated with interstellar atomic lines as suggested by Krełowski et al. (1997). Narrow DIBs generally look stronger in "zeta" type interstellar clouds than in "sigma" ones as already suggested by Krełowski & Sneden (1995). Our sample deliberately contains both "sigma" and "zeta" type objects to make a comparison of the behaviour of the C_3 chain in both environments possible.

Every target, listed in the lower part of Table 1, was observed at least twice to make a successful removal of cosmic ray spikes possible. The exposure times were selected to achieve the S/N ratio higher than 500 as the expected depths of the C_3 features are of the order of 1% of the continua. Our target list contains HD 149757, observed also by Maier et al. (2001) to allow a direct comparison between the existing and new measurements.

3. Results

Our reduction of the spectra was made using the DECH code (Galazutdinov 1992). This program allows a flat-field division, bias/background subtraction, one–dimensional spectrum extraction from the 2–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.

Figure 3 presents the six reduced spectra. Our very high resolution and S/N ratio makes the very narrow C_3 features detectable. The C_3 band is evidently seen in three of spectra – they are all "zeta" type objects in which the bands of C_2 are also quite strong. The C_3 bands are below the level of detection towards the remaining three "sigma" type objects. Only the upper limits can be estimated which makes a measurement of C_2 to C_3 abundance ratio impossible in these environments.

It seems of importance to compare the intensities of C_3 transitions, measured in our spectra with those from the publication of Maier et al. (2001). The comparison is given in Fig. 5. It is evident that the observed features are usually of the same equivalent width, especially the strongest ones. The weaker features differ sometimes between the two sets of data. Thus it seems well-advised to use only the strongest C_3 features to estimate the abundance of this species towards some chosen targets. It may be also concluded that the resolution of $R = 120\,000$ is high enough to allow precise measurements of the narrow C_3 features.

To compare C_3 and C_2 abundance ratios we preferred to use direct results of observations (equivalent widths) instead of published column density values, calculated using various oscillator strengths. Ratio of equivalent widths of C_3 and C_2 absorption bands may be a very sensitive parameter, characterizing individual interstellar clouds. Figure 4 demonstrates a comparison between the intensities of single transitions inside C_2 and C_3 bands. In the case of C_3 it is quite evident that the column density of this species can be estimated using the four strongest transitions ($Q6$ till $Q12$). Their equivalent widths (listed in Table 2) are similar and thus the level, based on the intensities of these features is a good measurement of the C_3 column density towards a chosen target. In the case of C_2 we used $Q(2)$ and $Q(4)$ transitions as they have been measured in all targets of Table 1. One can see from the Fig. 4 that the abundance ratio of the two bare carbon species: C_2 and C_3 is variable; it is very high towards the HD 179406 star which is known to be shining through a very special cloud. The latter produces very narrow but also very strong DIBs (Walker et al. 2001). We would like to emphasize that a C_3 abundance estimate should be rather uncertain in the case of HD 210121 (Roueff et al. 2002) due to relatively low spectral resolution

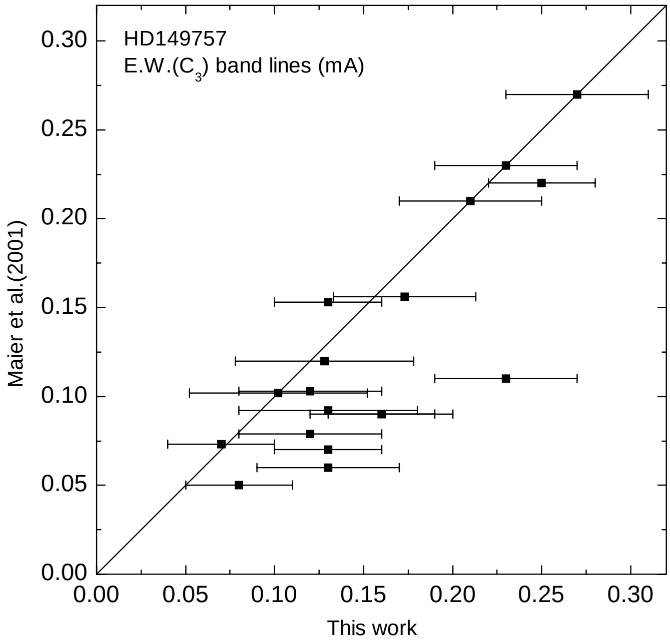

Fig. 5. A comparison of the equivalent widths of subsequent features of the C_3 band in the spectrum of HD 149757 observed by Maier et al. (2001) with those from the present work.

evidently not enough to make reliable measurements of equivalent widths.

The plotted spectra suggest that C_3 molecule, as well as C_2, is hardly detectable in the observed "sigma" type clouds. It generally behaves in a way very similar to that of the neighbour KI (4044.136 and 4047.206 Å) lines (see also Fig. 1). This observation confirms that the C_2 and C_3 abundances depend on the ionization level of elements characterized by the ionization potential lower than that of hydrogen. Apparently the molecular abundances depend on the density of high frequency photons originating in neighbour, hot stars.

The proximity of KI lines allows an additional test of the presence of C_3 features in "sigma" type objects. While the wavelengths of potassium lines are shifted to the rest wavelength frame, C_3 transitions coincide with those, published by Roueff et al. (2002) up to the third decimal point! In this case the identification of the molecular band leaves no doubt. The high precision of the wavelengths of different transitions inside the C_3 band allows us to add the same spectrum up to ~40 times in the scale of radial velocities. The spectrum is being shifted to zero radial velocity of subsequent transitions and then all spectra prepared in this way are combined. This creates just one strong feature at the zero radial velocity which may represent the total strength of the band. The S/N ratio of the spectrum prepared in this way is 5–6 times higher than the original one (Fig. 6). However, even this procedure has not allowed to measure directly the band intensity towards "sigma" type objects; we can only make a better estimate of their upper limits. Table 1 gives the observed column densities of C_3 molecule and 3σ upper limits for "sigma" type stars derived from

$$W_{3\sigma} = 3 \times (wd)^{1/2}(S/N)^{-1},$$

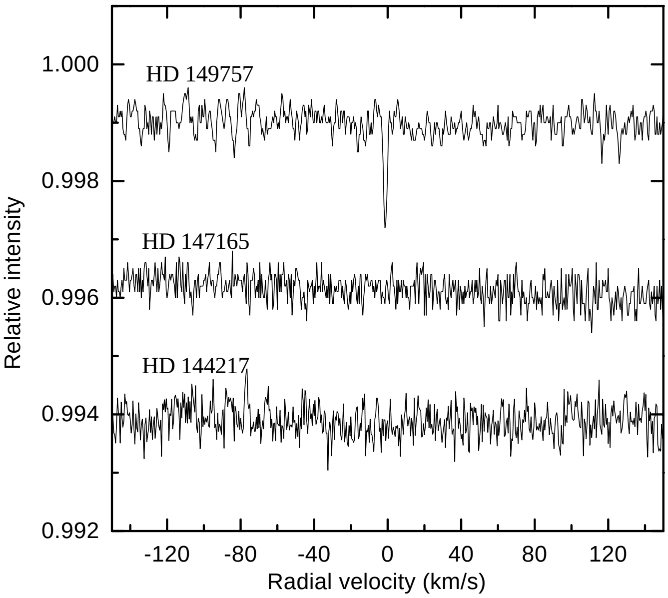

Fig. 6. Illustration of differences in C_3 abundance in "zeta" (HD 149757) and "sigma" (HD 147165 and HD 144217) objects. Demonstrated spectra were achieved by shifting all rotational lines to point zero at radial velocity scale and combining them to get as a result one narrow structure that represents average absorption of all rotational levels.

where $W_{3\sigma}$ is 3σ limiting equivalent width, w is $FWHM$ of the feature presented in Fig. 6, estimated as 0.03 Å, d is the spectrograph dispersion, in Å/pixel, and S/N is signal–to–noise level of spectra presented in Fig. 6.

C_3 molecule was thus proved to be below the level of detection towards "sigma" type targets as well as the shorter C_2 molecule (Lambert et al. 1995). Apparently the environments, characterized by relatively strong broad diffuse bands and weak polar molecules do not contain short, bare carbon chain species.

C_2 and C_3 molecules are much more likely observed towards targets characterized by strong narrow DIBs and the features of simplest polar molecules as well as high far-UV extinction ("zeta" type objects). In these cases both carbon species are usually observable but their mutual abundance ratio may be variable.

As it is clearly seen in Fig. 4 the C_2 and C_3 abundances are not simply related to E_{B-V}; they must depend on other parameters of intervening clouds as well.

Neither C_2 nor C_3 can be considered as carriers of any of the diffuse interstellar bands. However, they are likely precursors of the species in which narrow DIBs (such as 5797) are originated.

An extension of the sample of C_3 observations towards reddened stars seems highly desirable as the above conclusions are inferred from extremely scarce samples of reddened stars.

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