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An upper limit to the interstellar C_5 abundance in translucent clouds*

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Abstract. We have analyzed high resolution spectra of several slightly to moderately reddened stars collected at two observatories: ESO (La Silla) and Terskol (Northern Caucasia), to estimate the abundance of the C_5 molecule in the interstellar medium. We confirm the presence of a feature near 4975 Å which appears to be a weak DIB rather than the predicted C_5 band since the origin band near 5109 Å remains invisible even in spectra of high signal–to–noise ratio (~2500) and spectral resolution ($R \sim 220\,000$). This confirms that the C_5 abundance in translucent interstellar clouds is very low. We estimate its limit as low as 10^{11} cm^{-2} in the scale $E(B-V) = 0.35$ for "zeta" type objects that is two times lower than that of Maier et al. (2002).

Key words. ISM: clouds – molecules

1. Introduction

A vast majority of the identified interstellar molecules contain carbon atoms, i.e. they are organic species, many of them are based on linear carbon skeleton – up to 11 atoms long. This fact suggests the presence of bare carbon chain molecules in interstellar clouds. Such chains, being homonuclear species, do not create rotational transitions observable at radio wavelengths and thus they can only be detected by means of observing their electronic and/or vibrational spectral features in visible and UV spectral ranges. It seems natural that the simplest carbon molecules, observed in interstellar clouds, very likely can be building blocks for many observed (due to radio rotational transitions) polar interstellar molecules which are often based on carbon skeletons. Douglas (1977) proposed linear carbon molecules as possible carriers of diffuse interstellar bands (DIBs) – the spectral features which remain unidentified since their discovery in 1922.

The first pure carbon molecule, the two–atom homonuclear C_2 species, 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. However, only Hobbs & Campbell (1982) and later Danks & Lambert (1983) succeeded to discover the Phillips (2–0) band (near 8760 Å) of C_2 in the spectrum of ζOph (HD 149757). A bit later another C_2 band – the Phillips (3–0) band was discovered by van Dishoeck & Black (1986). Also the Mulliken system at 2313 Å was observed (Lambert et al. 1995), but only in spectra of two stars: HD 149757 and HD 24912. It seems not less important that the latter band was not detected in HST spectra of HD's: 144217, 143018 and 144470 despite a substantial reddening and the presence of reasonably strong diffuse interstellar bands in their spectra (Westerlund & Krełowski 1988).

The next member of the family of carbon chains, the linear C_3 molecule was discovered only very recently. First seen in the infrared spectrum of the circum-stellar shell of the star IRC +10216 (Hinkle et al. 1988) it was mentioned in the spectrum of one heavily reddened star, HD 147889, by Haffner & Meyer (1995). The latter described the blue band of C_3 of $A^1\Pi_u - X^1\Sigma_g^+$ transition, near 4052 Å. The characteristic structure of this rich band was observed almost simultaneously by two research teams and described in two papers by Maier et al. (2001) and by Roueff et al. (2002). The very recent observations made at ESO revealed that C_3, more or less as C_2, remains undetectable in "sigma" type objects (like HD 144217,

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* Based on data collected at the ESO 3.6 m telescope operated on La Silla Observatory, Chile and 2-m telescope of the Terskol Observatory, Russia.

see Krełowski & Sneden 1995), but can easily be observed in "zeta" type targets (Galazutdinov et al. 2002). However, the abundance ratio of C_2 and C_3 does not seem to be constant (Galazutdinov et al. 2002) despite similar strength ratios of the major diffuse bands. We consider observed objects as "sigma" if they are characterized by a high strength ratio of 5780/5797 diffuse bands. Also in such objects relative (to E_{B-V})) intensities of atomic and molecular features are relatively low in contrast to "zeta" type objects.

The laboratory 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 spectra of still longer chains are known only from the matrix isolation spectroscopy and are thus difficult to be directly compared to astrophysical spectra. The molecule C_5 was discovered in the infrared spectrum of IRC+10216 (Bernath et al. 1989); this proves that this species is present in the circum-stellar envelope and thus it seems reasonable to search for it in translucent, interstellar clouds as well.

The visual spectrum of C_5 consists of four features, discovered in laboratory gas–phase experiments, but only two of them, situated near 4975 and 5109 Å, should be strong enough to allow observational detection (Motylewski et al. 1999). The features found in laboratory are narrow and thus high resolution spectral observations are highly desirable.

Possible detection of these two spectral features has been described recently by Galazutdinov et al. (2001). They have averaged 13 high resolution (R = 80 000) spectra of several reddened stars to create one, high S/N ratio spectrum. The latter revealed two extremely weak features around the predicted wavelengths of C_5 bands. However, the observed features proved to be broader than the laboratory ones which may create doubts on whether the molecule was really discovered. Perhaps the broadening was caused by the insufficient resolution of the applied spectra.

The very recent paper by Maier et al. (2002) reported the lack of the 5109 Å feature in the spectrum of HD 149757 (R = 120 000 and $S/N \sim 2500$ per pixel). The spectrum is, however, known to be populated with numerous relatively (to E_{B-V}) weak diffuse interstellar bands and this weakness may be an explanation for the latter, negative result. It is thus necessary, to make a decisive test of the presence of the C_5 carbon chain in interstellar, translucent clouds, collecting several spectra of very high resolution and S/N ratio of reddened stars. The chosen objects should not be too heavily reddened as such stars are usually shining through several clouds of different radial velocities which makes observed profiles of interstellar spectral features broadened or even splitted by the Doppler effect and thus, incomparable to laboratory spectra. To avoid the latter the selected targets have to be characterized by atomic interstellar lines possibly free of any Doppler splitting.

2. The observational data

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. We have collected both the targets in which the 5797/5780 strength ratio is high ("zeta" type objects) as the already observed molecular features are strong towards such objects and the opposite "sigma" type clouds where usually broad DIBs are strong while the narrow ones – rather weak (5797/5780 – low). We have acquired spectra of the selected targets using the high resolution (R = 120 000) echelle spectrometer fed with the 2 m telescope of the Terskol Observatory (Northern Caucasia); they cover the range between 3500 and 10 100 Å. The chosen targets are listed in Table 1 where HD numbers, spectral types, luminosity classes, colour excesses and rotational velocities are given. The brightness of all our targets was crucial to allow the achievement of high S/N ratio.

Very high resolution spectra of several reddened stars have been collected at ESO with the aid of the CES (Coude Echelle Spectrograph) fed by the fiber 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,

Table 1. The observed stars. Upper part – spectra form Terskol (R = 120 000). Lower part – spectra from ESO (R = 220 000). First column – HD number; second – spectral and luminosity class; third – reddening; fourth – rotational velocity; fifth – number of spectra used to produce average spectrum in region of 4975 Å; sixth – number of spectra used to produce average spectrum in region of 5109 Å. Average E_{B-V} represent average reddening of stars with spectrum in 4975 and 5109 Å region.

HD	SpL	E_{B-V}	$v \sin i$	4975	5109
23180	B1III	0.29	120	6	6
24398	B1Ib	0.34	59	4	4
24760	B0.5V	0.04	150	0	2
24912	O7.5III	0.26	216	3	5
30614	O9.5Iae	0.34	-	0	2
34078	O9.5V	0.49	5	0	2
41117	B2Iae	0.47	80	3	2
143275	B0.5IV	0.15	200	1	0
144217	B0.5V	0.17	130	1	0
144218	B2V	0.18	84	1	0
148184	B2IVpe	0.44	134	2	0
149757	O9.5V	0.30	379	3	2
164284	B2Ve	0.19	220	4	3
164353	B5Ib	0.13	15	3	0
179406	B3V	0.31	150	1	0
193237	B2pe	0.65	75	3	0
200120	B1ne	0.20	374	2	0
206165	B2Ib	0.42	36	1	1
207198	O9IIe	0.60	76	5	0
210839	O6If	0.50	285	6	3
average E_{B-V}				0.36	0.32
143275	B0.5IV	0.15	200	0	1
144217	B0.5V	0.17	130	1	1
144470	B1V	0.19	142	0	1
147165	B1III	0.32	53	1	1
147933	B2IV	0.45	300	0	1
148184	B2IVpe	0.44	134	1	1
149757	O9.5V	0.30	379	1	1
179406	B3V	0.31	150	1	0

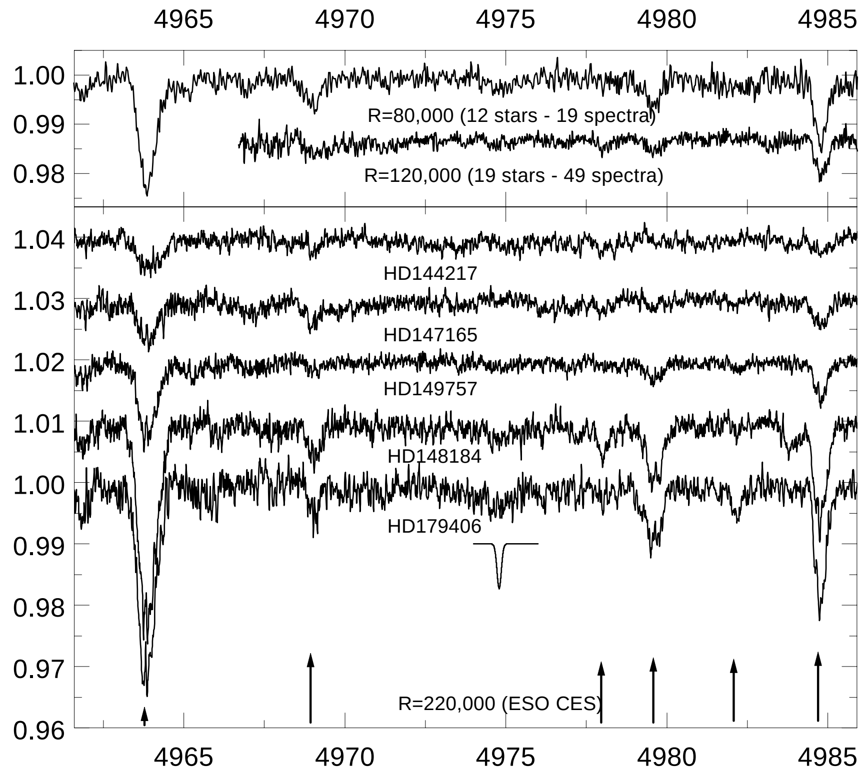

Fig. 1. Upper panel: the already published (Galazutdinov et al. 2001) (R = 80 000) average spectrum compared to a similar average of R = 120 000 Terskol spectra. Lower panel: individual ESO spectra and the Gaussian representing the 4975 C_5 line. Arrows indicate known and possible diffuse interstellar bands.

R = 220 000, using the Very Long Camera in the spectral range from 4958 to 4993 Å and from 5091 to 5127 Å. 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 first selected spectral range contain two well-known diffuse bands: 4964 and 4985 as well as two additional features already mentioned by Galazutdinov et al. (2001). The presence of these interstellar features of well known rest wavelength (Galazutdinov et al. 2000) allowed to measure precisely radial velocities of the intervening clouds and to shift the whole spectra to the rest wavelength frame. New, higher S/N and resolution data reveal a number of new features, most likely of interstellar origin. The second range (around 5109 Å) does not contain any known interstellar lines which the fact created some difficulties while determining precise scale for the interstellar rest–wavelength frame. The task has been performed on the basis of calculated heliocentric correction velocity and published radial velocities (Welty & Hobbs 2001) of the clouds situated along the lines of sight towards the observed stars. To check possible instrumental shifts we have used very weak (but well seen in our high S/N spectra) telluric lines.

3. Results

Figure 1 presents the wavelength range around the 4975 Å C_5 spectral feature. We have plotted together the already published average spectrum of 12 stars for which we observed 19 spectra with the resolution R = 80 000. This spectrum has already been presented by Galazutdinov et al. (2001). Below we added another average spectrum; this time it is combined spectrum of 49 spectra of 19 stars observed with the spectral resolution R = 120 000. The growing length of single orders of echelle spectra made the part around the 4964 DIB out of the CCD chip and thus – invisible. However, all other spectral features which can be traced in the R = 80 000 spectrum can be traced in this one as well.

Very high resolution (R = 220 000) spectra, recorded at ESO with the S/N ratio ~1500 (per pixel) are shown in the lower panel. All the spectral features detectable in the above spectra can be traced in these ones also. However, all the spectral features are seemingly stronger in the "zeta" type targets (HD 149757, 148184, 179406) than in "sigma" type ones (HD 144217, 147165). The vertical arrows indicate all possible spectral features of interstellar origin. It is to be emphasized that they must be originated in the interstellar space; otherwise they would disappear in the combined spectra because all individual stars are characterized by different radial velocities as well as rotational speeds which makes stellar features either invisible or very broad and shallow in combined spectra (Galazutdinov et al. 2000).

The Gaussian curve below represents the laboratory feature of the C_5 chain. Its wavelength coincides with some interstellar band clearly visible in "zeta" type objects and invisible in "sigma" type ones. The behaviour of this feature mimics thus that of shorter carbon chains (C_2 and C_3; Galazutdinov et al. 2002) as well as of many weak diffuse interstellar bands.

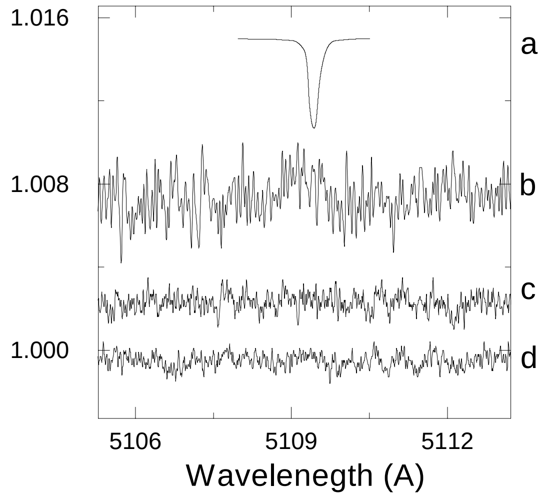

Fig. 2. The wavelength region of the C_5 5109 feature represented by the Gaussian **a**). **b)** the average of 32 (R = 120 000) spectra from Terskol. **c)** the average of 3 ζ-type ESO spectra (HD 148184, 149757, 179406) **d)** the average of 4 σ-type ESO spectra (HD 143275, 144217, 144470, 147165). Note the lack of the feature in the astrophysical spectra.

All of them are much stronger towards "zeta" than "sigma" type objects. We can thus consider the extremely weak feature near 4975 Å as an interstellar beyond a doubt. Is it a spectral signature of the C_5 chain molecule?

If yes, we should observe in the same spectra another spectral feature, situated around 5109 Å (Motylewski et al. 1999) being of the same equivalent width but a bit broader. To check this we have first averaged 32 of the $R = 120\,000$ spectra acquired at Terskol Observatory. They belong to 19 stars. The spectral range is around the maximum sensitivity of our CCD chip which allowed to get a very high S/N ratio (~2000 per pixel). The echelle spectra contain some other interstellar features which allowed to shift all the individual spectra to the rest wavelength velocity frame.

We have combined the ESO $R = 220\,000$ spectra of "zeta" and "sigma" type objects separately. Figure 2 shows the laboratory C_5 band (Gaussian), the Terskol average (32 spectra), the "zeta" average ESO spectrum (combined of those of HD 149757, HD 148184 and HD 147933) and the "sigma" average ESO spectrum (combined of HD 147165, HD 144470, HD 144217 and HD 143275). These combined spectra are of $S/N \sim 4000$ per pixel. We estimated S/N ratio using very simple but vivid method: by estimating a deviation of intensity from mean value, measured in some fragment of spectrum which is free of any spectral features. Of course, the method depends on "where is the chosen fragment", but fortunately the region of interest is absolutely free from any spectral features (5109 Å). The very close vicinity (exactly corresponding to the width of the 5109 feature) is really free of noise. Despite the very high resolution and S/N ratio the band remains below the level of detection. This result coincides with that of Maier et al. (2002) which, however, was based on a single target only. Our "zeta" spectrum has higher S/N than that of HD 149757 acquired by Maier et al. (2002) and the resolution is almost twice as large. Thus the C_5 upper limit estimate appears to be less than 10^{11} cm^{-2} as estimated by Maier et al. (2002).

The lack of the 5109 C_5 band proves that the observed 4975 Å feature is rather one of the very numerous weak diffuse interstellar bands which coincides with the expected C_5 narrow band only by chance. The result shows also that abundances of longer carbon chains decrease quickly with the growing length of the chain. But it should be emphasized that models predicts that much longer carbon chains, containing more than 10 carbon atoms, become considerably resistant to photodissociation (Taylor & Duley 1997). Observations of C_2 and C_3 molecules showed already that abundance of short carbon chains seems to be very sensitive to the strength of UV radiation (Galazutdinov et al. 2002). Now upper limit of C_5 abundance leads to the conclusion that formation of chains containing less than six carbon atoms cannot effectively compete with photodissociation rate. The length of carbon chains from which their abundance could alternatively start to grow should thus be bigger than that of C_5 molecule. Yet in a case of "step by step" (from shorter to longer) formation of carbon chains growing abundance of longer ones (containing 6–10 carbon atoms) seems to be unlikely.

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