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On the Relation between Diffuse Bands and Other Interstellar Features*

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Abstract

We discuss possible relations between different constituents of interstellar clouds, such as gas atoms (Fe I), simple molecular species (CH, CN), and the carriers of the puzzling diffuse interstellar bands (DIBs 5780, 5797, 5850 Å) as well as dust grains. We exemplify that abundances of carriers of these spectral features, revealed by the Doppler components, may be astonishingly poorly related to each other. Spectra of interstellar clouds seem to be sensitive to the changes of the environmental parameters such as density, temperature, and irradiation from nearby stars. The diffuse bands' carriers likely do not occupy the same volumes with CH, CN, or Fe I and/or are much less sensitive to the processes related to the formation/destruction of these species.

Unified Astronomy Thesaurus concepts: Interstellar clouds (834); Interstellar dust (836); Interstellar atomic gas (833); Interstellar medium (847)

1. Introduction

The first observations of interstellar absorptions of atomic lines (of ionized calcium) were obtained at the beginning of the 20th century (Hartmann 1904). Later, more atomic lines and those of simple interstellar radicals (Merrill 1937; Beals & Blanchet 1938; McKellar 1940) were discovered, leading to the obvious question: do all interstellar lines, seen along a sight line, originate in the same environment? Also, are the interstellar spectra along all individual sight lines identical, i.e., are the strength ratios of all interstellar features the same everywhere? High-resolution profiles of interstellar lines (Merrill 1937) proved that the interstellar medium is not a continuous and homogeneous environment but is composed of many separate clouds. The observed Doppler split of interstellar spectral lines proves that some of the lines are formed in separate volumes either closer or farther away from an observer. However, even if no split of spectral lines is observed, it is still not certain whether the source of interstellar lines (bands) is an isolated volume of matter or is a set of sparse interstellar clouds having a similar projection of the peculiar velocities along the line of sight.

Federman (1982) demonstrated, using a large sample of high-resolution spectra, that CH abundance (i.e., the first interstellar molecular species discovered) is correlated with that of H_2 (the most abundant one) while CH^+ is not. Also, radial velocities of the features of CH and CH^+ were found to be different in many cases. This led to the conclusion that the interstellar medium is filled with clouds differing in physical parameters like density, temperature, external irradiation, etc. This fact is proven by essential differences in spectra of individual clouds. It was confirmed for the southern sky by Danks et al. (1984). Apparently some environments are either "friendly" or "hostile" to simple molecular species.

Diffuse interstellar bands (DIBs) are absorption features of a large variety of intensity and profile shapes, seen in the spectra of astronomical objects observed in the Milky Way and other galaxies. DIBs likely are caused by the absorption of light in semitransparent interstellar clouds. There are ~500 diffuse bands that have now been detected in the ultraviolet, visible, and near-infrared wavelengths ranges (Galazutdinov et al. 2000, 2017a, 2020; Fan et al. 2019). The origin of DIBs has been disputed since the original discovery 100 years ago. The supposed candidates for the carriers of DIBs are carbon-bearing molecules including carbon chain molecules, polycyclic aromatic hydrocarbons (PAHs), and fullerenes. The only almost confirmed carrier of a few near-infrared diffuse bands is fullerene C_{60}^+ (Campbell et al. 2015), but the variability of the intensity ratio of the features, assigned to this molecule, still needs to be explained (Galazutdinov & Krełowski 2017; Galazutdinov et al. 2017b). In any case, the interstellar origin of the carriers of diffuse bands is accepted beyond any doubt. A variability of all interstellar medium (ISM) components is observed, including carriers of diffuse interstellar bands. Krełowski & Westerlund (1988) and Krełowski & Walker (1987) demonstrated that interstellar clouds may be separated into two classes having either flat (σ type) or steep (ζ types) rising far-UV extinction, i.e., similar either to HD147165 (σ Sco) or to HD149757 (ζ Oph), respectively (Krełowski et al. 2019a).

Different strength ratios of DIBs must reflect different physical parameters of the intervening clouds. The separation of clouds into σ and ζ types demonstrates that the different strength ratios of the major DIBs at 5780 and 5797 Å are related to intensities of spectral features of simple interstellar radicals (Krełowski et al. 1992). Along a vast majority of sight lines toward reddened stars one can trace several clouds, revealed by Doppler-split profiles of narrow interstellar lines Ca II, Na I, and K I or molecular features CH and CN. Spectra of high resolving power ($R \equiv \lambda/\Delta\lambda \geqslant 75{,}000$) can resolve many Doppler components in profiles of interstellar lines.

It is obvious to observe several Doppler components of naturally narrow lines (FWHM 1–2 km s^{-1} in spectra of very high resolving power $\gtrsim$140,000) of interstellar atoms and diatomic radicals like CH or CN, while it is very difficult in the case of relatively broad DIBs (FWHM $\geqslant$ 25 km s^{-1}) and is impossible in the case of continuous extinction. Thus it is

* This Letter includes data gathered with the UT2 telescope—a part of the VLT ESO telescope (Chile).

important to analyze profiles of identified, narrow interstellar lines. The lack of Doppler splitting may serve as a criterion for the selection of the most important objects, those where the interstellar spectra depend only on physical parameters of single intervening clouds, not being ill-defined averages of many environments. In this Letter we analyze spectra of reddened objects demonstrating peculiar behavior of interstellar lines.

The latter is really important for an analysis of physical and chemical processes in interstellar clouds. It is emphasized that the study of individual clouds showing "peculiar" spectra is in many cases more enlightening than a global analysis of correlations between ISM features that is based on a huge sample. Almost every pair of interstellar features exhibit a reasonably tight correlation of intensities. However, even if a correlation is very tight (Krełowski et al. 2016) still the two features may be of different origin. Thus a final conclusion of the common origin of two features may be inferred only while analyzing carefully selected individual, single clouds.

2. Observations

We used observations toward 136 stars (ESO program 0102. C-0040(B)) carried out with the Ultraviolet and Visual Echelle Spectrograph (UVES), fed by the 8 m Kueyen VLT mirror. There are only 4 objects out of 136 demonstrating a peculiar pattern of the interstellar lines, and thus were selected for the present analysis. The UVES observations were performed using the standard "390+760" setup with a wavelength range of approximately 3270–4450 Å in the blue arm, 5700–7520 Å in the lower red arm, and 7660–9460 Å in the red upper arm with some gaps between the spectral orders.

We processed UVES raw data and measured line profiles in the reduced spectra with our interactive analysis software DECH.[5] For the DECH data reduction, we averaged bias images for subsequent correction of flat-field, wavelength calibration, and stellar spectra images. The extracted spectra of the same object observed in the same night were averaged to increase the signal-to-noise ratio. Fiducial continuum normalization was based on a cubic spline interpolation over interactively selected anchor points.

3. Results

The well-known interstellar molecules, CH and CN, can be formed in different physical conditions as well as the DIB carriers, which are believed to be much more complex species (e.g., Huang & Oka 2015). CH is believed to originate in cold environments (~50 K), while CH^+ likely represents hot media (~4000 K)—perhaps shock-driven environments, as evidenced in their different profiles and sometimes different heliocentric radial velocities (Federman et al. 1997; Pan et al. 2005). In this study we discuss a comparison of strengths and profiles of simple radicals in relation to DIBs. For the analysis we have selected four objects with relatively complex profiles of Ca II lines with evident Doppler split, situated at different distances (HD47107, HD50562, HD91969, and HD99890), and one so-called single-cloud object that shows no Doppler split and has sharp Ca II profiles and strong molecular lines, HD147701 (Figures 1 and 2). The molecular spectra of these targets are clearly peculiar.

Ionization potentials of Fe I and Fe II are 7.87 eV and 16.18 eV, respectively. Therefore, the dominant form of gas-phase interstellar iron found in H I regions should be Fe II (Jensen & Snow 2007). Nevertheless, Fe I line is very strong in the nearby object of the program and is completely absent in the distant ones.

Apparently, the ISM environments along the sight lines to the four upper targets in Figure 1 are different than that toward HD147701. All of these four objects are situated quite far away (Table 1). We remind that intensities of interstellar Ca II lines observed in spectra toward hot OB stars are related to distances (Megier et al. 2005); thus, Ca II profiles are more complex in more distant objects. Generally, distant sight lines are occupied by several separate clouds. However, reddening, which is carried by dust particles, is not directly related to distance, as Trumpler (1930) has already postulated and as we recently suggested (Siebenmorgen et al. 2020). Indeed, the most heavily reddened target, HD147701, is the most nearby one in the sample. Apparently, it is obscured by a relatively small and dense cloud. The cloud is small because otherwise it would been observed as a large dark spot on the sky, which is not the case, and dense because it causes the essential reddening that cannot be caused by a small, low-density cloud. Such small, dense ISM clumps are apparently a very good environment for the formation of simple molecular species. We inspected the WISE 3–22 μm emission morphology of our stars. HD47107 and HD91969 appear stellar while for the three other stars some enhanced diffuse background is observed, but dust emission associated with the star is not detected (see Table A.3 in Siebenmorgen et al. 2020). Also, our spectra do not exhibit weak H_α emissions. Consequently, there are no evident signs of the presence of a circumstellar shell around studied stars.

As shown in Table 1, our targets differ essentially in distances and reddening. $E(B-V)$ values are calculated using photometric data from the Simbad database (Wenger et al. 2000), and color indices are adopted from Papaj et al. (1993). Spectral and luminosity classes of the stars were estimated following the procedure described in detail by Krełowski et al. (2018). At first, we measured ratios of the H I, He I, and Mg II line strengths as suggested by Walborn & Fitzpatrick (1990) and by the Stony Brook catalog.[6] Then we confirmed/corrected the spectral class estimation through careful inspection of the observed spectra. Contrary to expectations the star that shows the highest reddening in our sample has the closest distance. It is interesting that in the spectra of four of our targets the molecular lines (features of simple radicals) are hardly visible (Figure 2). In contrast, the nearby star exhibits strong molecular features. Let us emphasize that the complete lack of molecular lines in the reddened and distant stars is a quite rare phenomenon (Danks et al. 1984). Indeed, we found only these four CH, CN, and Fe I free objects by digging in our recently acquired sample of 136 reddened stars (Siebenmorgen et al. 2020).

Now there is the question whether DIBs, believed to be carried by complex molecules, also remain below the level of detection. Figure 3 shows that this is not the case. Major DIBs at 5780 and 5797 Å are strong in all of our targets. Again, contrary to expectations, their intensities are not simply related to $E(B-V)$, which is, generally speaking, the quantity of dust particles. Indeed, diffuse bands in HD91969 are stronger/comparable to those in

[5] Available upon request.

[6] http://www.astro.sunysb.edu/fwalter/SMARTS/spstds_f2.html

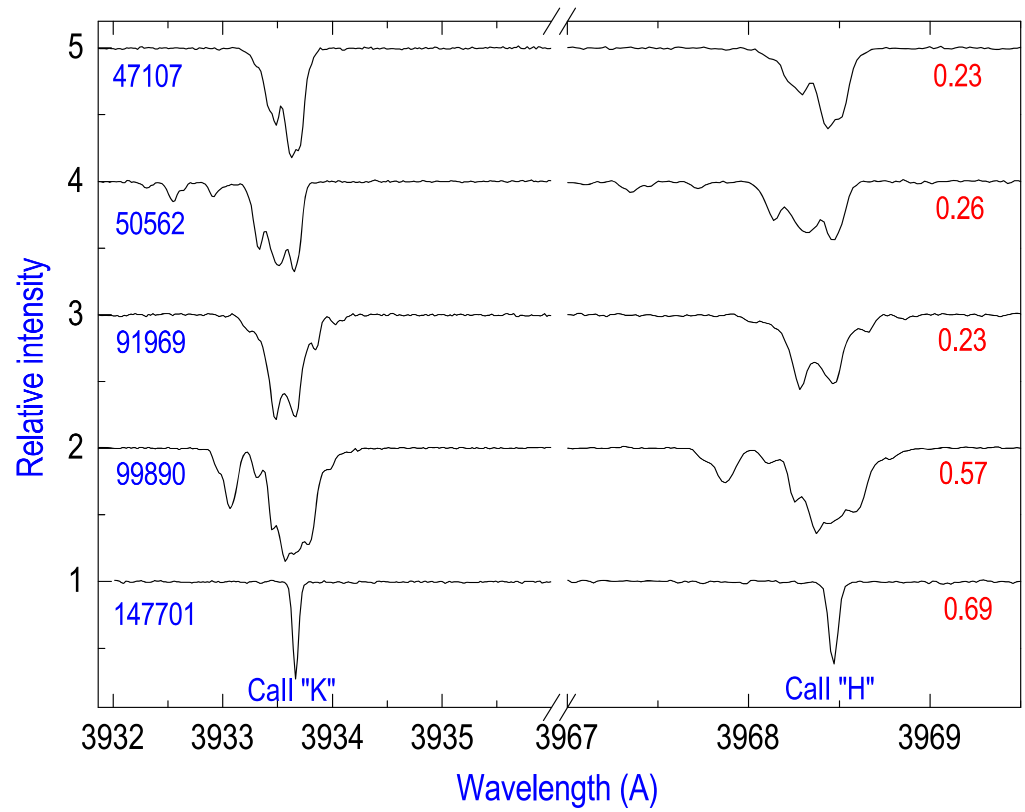

Figure 1. Ca II lines observed in the spectra of reddened stars. The reddening magnitudes $E(B - V)$ are given on the right, and HD numbers of the observed stars are on the left.

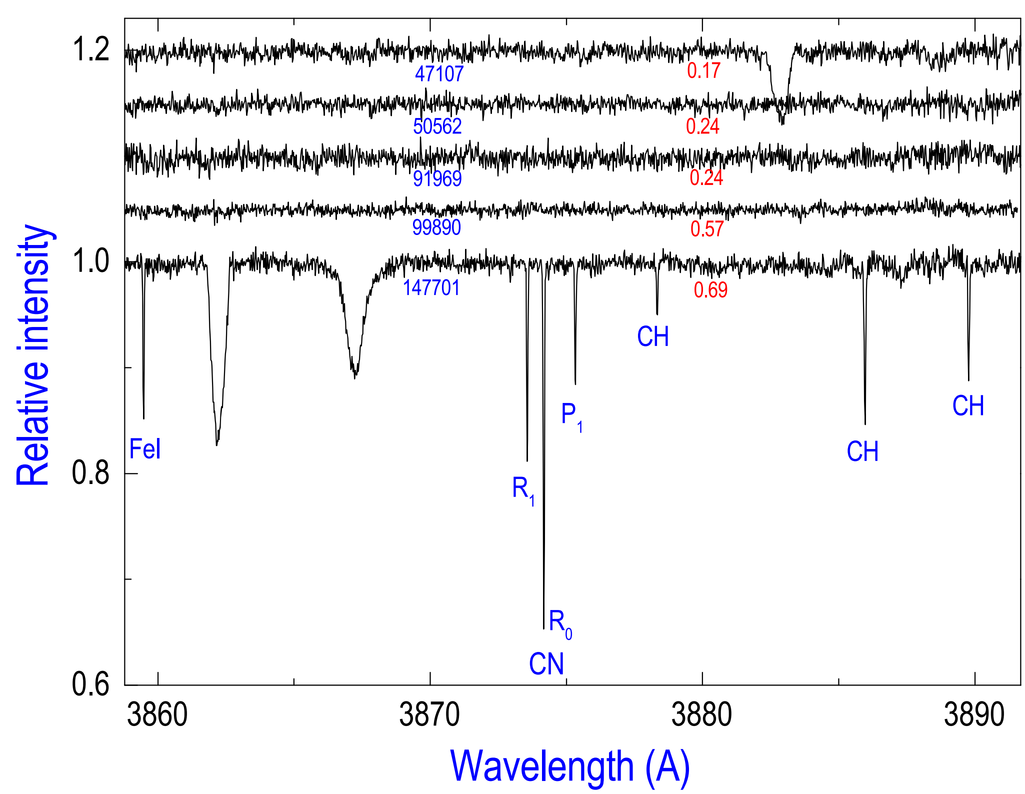

Figure 2. Molecular and atomic interstellar lines of our targets as labeled. The lines are strong for the nearby star HD 147701, while they remain undetected for other, distant stars. Reddening magnitudes $E(B - V)$ are given on the right, and digits on the left refer to the HD numbers of the observed stars.

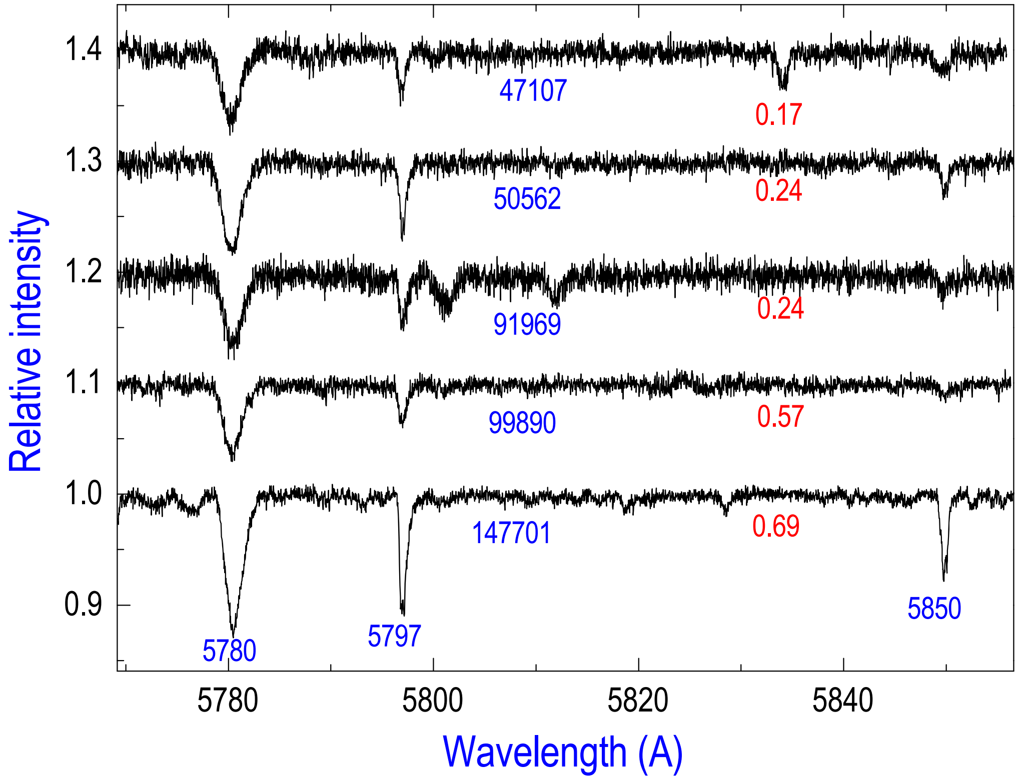

Figure 3. Major diffuse bands at 5780 and 5797 Å in the spectra of our targets. Note that both DIBs are strong in the spectra where the features of simple radicals are hardly visible. Reddening magnitudes $E(B-V)$ are given on the right.

Table 1
Basic Physical Parameters of the Observed Objects

Star	V	$B-V$	Sp/L	D(Gaia)	$E(B-V)$
47107	8.00	−0.05	B1.5V	800	0.17
50562	9.41	0.08	B3III	3400	0.24
91969	6.43	−0.02	B0Iab	2570	0.24
99890	9.26	0.36	B1III	1860	0.57
147701	9.20	0.54	B5.5V	140	0.69

Note. The V magnitude, color index $B-V$, spectral and luminosity class Sp/L, distance (in parsecs) from Gaia (Bailer-Jones et al. 2018), and reddening $E(B-V)$ are given.

HD99890, while the latter exhibits almost three times larger reddening $E(B-V)$. Also, the diffuse band 5850 Å is weak in HD99890 despite the essential reddening magnitude toward this object (Figure 3). Let us remind that any pair of ISM spectral features is reasonably well correlated in a large sample. Clearly, the chemistry of interstellar clouds is very complex, and different components of the interstellar medium are not "well mixed" and do require different physical conditions to be formed and maintained. Figure 1 and Table 1 confirm that at longer distances along each sight line we observe more components in the Ca II line profiles. The Ca II absorption lines are related to the distance but neither to $E(B-V)$ nor to intensities of spectral features carried by simple radicals (Megier et al. 2005).

4. Conclusions

Intensities of major diffuse bands in all objects of our sample are similar, while the $E(B-V)$ varies in a wide range of magnitudes (Figure 3), i.e., the reddening (or amount of dust) is not a key factor for the carriers' formation of diffuse bands despite good general correlation between them (Friedman et al. 2011; Krełowski et al. 2019b).

The narrow spectral features carried by simple radicals (CH, CN, etc.) can be very weak in reddened spectra of certain rare targets (Figure 2). On the other hand, these species are evidently strong in the spectrum of a nearby object HD147701, where lines of Ca II are weak, narrow, and free of Doppler splitting. Apparently, the CH and CN are not building blocks of the DIB's carriers, or the DIB's carriers are much less sensitive to the processes of formation/destruction of these species. This is surprising while a relatively strong correlation between CH bands and intensities of diffuse bands is well known (e.g., Weselak et al. 2008). The dissociation energy of DIB's carriers likely is higher than the first ionization energy of iron (7.9 eV). This exceeds the bond dissociation energy of the carbon chains (e.g., 3.9 eV for ethane C_2H_6; Pedley et al. 1986), but is lower than the energy needed to remove a single carbon atom from the C_{60} cage (24.1 eV) estimated by Stockett et al. (2018).

Although we do not know how far from the hot UV-flux emitters the studied clouds are, it seems natural that molecular species like CH cannot survive in low-density diluted clouds due to the strong irradiation from the nearby stars (if any). Thus, we can suppose the lack of sufficiently dense clouds toward our well-reddened but distant targets. On the other hand, the lack of both interstellar iron and molecular lines is also in the agreement with the supposed presence of strong UV-flux emitters close to the clouds observed toward four distant stars of the program. The puzzling carriers of the DIBs, which are believed to be some complex molecules, likely may be abundant in environments, which are hostile for simple radicals, i.e., the DIB carriers are fairly resistant against the diffuse UV radiation. Further support for our hypothesis is given for example by diffuse bands observed in the slightly reddened Pleiades cluster (Krełowski et al. 2019b). In addition, there is evidence of short timescale fluctuations of DIBs that are probably caused by a variable stellar wind (Galazutdinov et al. 1999). The DIB carriers seem to be sensitive to changes of the environmental parameters such as density, temperature of the cloud, and irradiation from *nearby* stars.

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