DIFFUSE INTERSTELLAR BANDS: PHYSICAL CONDITIONS THAT FACILITATE THE FORMATION OR PRESERVATION OF THEIR CARRIERS

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ABSTRACT

This paper suggests that the formation and/or preservation of the carriers of at least some of the diffuse interstellar bands (DIBs) depends on the level of ionization of certain interstellar atoms, such as potassium and calcium inside H I clouds. The spectral lines of these elements are apparently well correlated with the narrow diffuse bands, such as 5797 or 6379 Å. Thus, the physical conditions that facilitate the growing abundance of neutral alkali atoms also facilitate the formation or preservation of the carriers of the narrow diffuse bands. The broad features, such as 5780 or 6284 Å, apparently originate in different ionization conditions.

Subject headings: dust, extinction — ISM: abundances — ISM: general

1. INTRODUCTION

Diffuse interstellar bands (DIBs) were originally discovered by Heger (1922). The interstellar nature of several strong DIBs has been established by, e.g., Merrill (1934, 1936), Beals & Blanchet (1937), York (1971), and Herbig (1975). But for more than 60 yr, DIBs were not observed in individual ISM clouds, in spite of the fact that multiple Doppler components were identified in the atomic Na I D and Ca II K lines of many reddened stars as early as the 1930s, raising the question of whether all these individual clouds might be characterized by identical spectra and physical parameters.

To the present, no reliable identification of the carrier(s) of DIBs has been made. Almost all conceivable forms of matter have been proposed as possible carriers, ranging from dust grains to free molecules of very different sizes and structures, even to the hydrogen negative ion. It is now commonly believed that DIBs originate in something "in-between" the identified molecules and dust grains. Such molecular clusters can share some quantum as well as classical spectral properties; i.e., they could be responsible for both DIBs and some segments of the interstellar extinction curve. Their internal structures can be very complicated, and the possible presence of many species makes the task of identification very difficult.

Before the advent of low-noise solid-state detectors in stellar spectroscopy, DIBs (being usually rather shallow features) had been observed only in spectra of heavily reddened stars. Such targets are very likely to be obscured by several clouds. Thus, the resulting ISM spectrum will only be an ill-defined average over all the clouds along any specific sight line. Until the early 1980s, no one had observed any differences in the DIB spectra of different interstellar clouds. However, the first survey of ISM extinction curves in the vacuum UV (Bless & Savage 1972) showed large differences between extinction curves derived from spectra of bright nearby stars—objects likely to be obscured by only single clouds. Then Krełowski & Westerlund (1988) and Krełowski & Walker (1987) (see also

Josafatsson & Snow 1987) combined high-resolution spectra of the Na I D lines and the major 5780 and 5797 Å DIBs to show that the DIB ratios were quite different in the spectra of σ Sco, ζ Oph, ζ Per, and HD 40111. Clearly, DIBs are not all of the same origin, and individual clouds may differ both in DIB intensity ratio and in the shape of ISM extinction curves.

DIBs seem to be related to other spectral features originating in the interstellar clouds, such as atomic or molecular lines (of simple molecules) and the continuous extinction curve (Krełowski et al. 1992). The problem of the possible relationship between the abundances of DIB carriers and those of known elements, as well as the influence of the observed elemental depletions on DIB strengths, was addressed by Herbig (1993). He found possible relationships between abundances of DIB carriers and gas atoms of elements such as H, Na, K, and C. No relationship to H_2 has been found. DIBs are usually quite well correlated to $E(B-V)$, but not to any far-UV extinction measure. The latter condition may, however, be due to possible mismatch effects between standards and stars under consideration while determining extinction curves for $\lambda < 1800$ Å, a region densely populated with strong stellar lines.

DIBs can now be easily detected in spectra of very lightly reddened stars, shining through fairly homogeneous interstellar media. It is important to analyze the DIB strengths toward these stars together with the much sharper ISM atomic lines in order to reveal the structure of the ISM along chosen lines of sight and possible relationships of DIB spectra to elemental depletion patterns or to the ionization state of interstellar atoms. Correlations of DIBs with other ISM parameters are essential to the identification of the DIB carriers.

2. THE OBSERVATIONAL RESULTS

The present paper considers possible relationships between the abundances of DIB carriers and interstellar gas atoms. The abundances of certain ions depend on physical

conditions that facilitate the formation of the DIB carriers or their preservation in the space. Such information is of basic importance for future identification of the diffuse interstellar bands. DIB intensity ratios evidently vary from cloud to cloud, which phenomenon must be related to the varying physical conditions inside the clouds. The atomic lines can help determine these conditions. Considerations of the features originating in simple, two-atom molecules are left to another paper.

2.1. *The Spectral Features Observed*

The spectra in the optical wavelength range available from ground-based observatories (i.e., ~ 3500–10000 Å) contain only a few spectral lines originating in atomic interstellar gas. These are the lines of Fe I (3719.9, 3859.9 Å), Ca II (H and K), Ca I (4226.7 Å), Na I (D1, D2), Li I (6707.9 Å), and K I (4044.1, 7699.0 Å). Other features, also originating in neutral interstellar atoms, are observable only in the extraterrestrial ultraviolet.

The atomic lines, originating in the very low density medium of interstellar clouds, are only resonant lines, as almost all interstellar atoms inside an H I cloud rest at the ground electronic state. This is why only elements with very low ionization potential, such as the above-mentioned metals, can create some features observable from ground-based observatories.

The most popularly observed Na I (D1, D2) and Ca II (H and K) interstellar lines are typically very strong. Saturation effects make interpretation of their measurements difficult. However, Herbig (1993) found a fairly tight linear correlation between the column density of the 5780 Å DIB carrier and that of Na I atoms. In H and K profiles, we often observe Doppler splitting—an effect that proves that many early-type, young stars are observed through more than one cloud.

The Ca I (4226.73 Å) line is usually quite weak and thus difficult to detect and measure. However, it is visible in several high S/N spectra of early-type stars, and it can be useful. However, it may be difficult to calculate the ionization balance of calcium, as most of its atoms are ionized and observed only in saturated H and K lines.

The lithium doublet at 6707.91 and 6707.96 Å is barely seen and only in certain spectra. It has never been observed as resolved into two lines. The feature is so weak that no more than the conclusion that it is present or absent is possible.

The potassium (K I) 7664.91 and 7698.96 Å doublet is also very interesting. These lines are much stronger than those of Ca I or Li I, but are still not saturated. However, the first of these features is usually inextricably intertwined with telluric oxygen lines and thus is difficult to resolve and measure. Only the second member of the doublet, the 7698.96 Å line, is easy to measure and can be a useful source of information concerning the physical conditions inside interstellar clouds.

2.2. *The Material*

The material presented in this paper is based on spectra from the Russian Special Astrophysical Observatory (SAO). They have been acquired with the aid of the new echelle spectrometer installed at the coude focus of the SAO 1 m telescope (Musaev 1993). The Wright Instruments CCD camera, equipped with a matrix of 1242×1152 pixels (pixel size 22.5 μm $\times$ 22.5 μm) allows coverage in a single expo-

sure of the range ~ 3500–10100 Å with resolution $R = 40,000$. The spectrum is originally formed on the CCD matrix in the form of 95 partially overlapping (to ~ 8500 Å) orders. The observed set of objects contains 45 stars.

Our reduction of the CCD images and echelle spectra was made using the DECH code (Galazutdinov 1992). All standard procedures were performed: bias subtraction, removing of traces of cosmic particles, flat-fielding, and so forth. As a comparison spectrum, we used either the solar spectrum or the spectrum of Procyon, which allowed us to mark at least 15–20 points in each spectral order. The laboratory wavelengths are taken from the tables of solar spectra of Pierce & Breckinridge (1973). In the task of removing the telluric lines (for example, for measuring DIB 6284 Å), we have used the spectra of fast-rotating nonreddened B stars.

Our observations involve mostly bright stars; such objects can be considered as nearby and seen through single, individual clouds. The broad spectral range available using the above apparatus allows simultaneous observations of the atomic interstellar lines as well as of many unidentified diffuse interstellar bands (Jenniskens & Désert 1994; Krelowski, Sneden, & Hiltgen 1995).

The stars observed are listed in Table 1.

2.3. *Intensities of the Atomic and Diffuse Spectral Features*

Below, we demonstrate example profiles of different interstellar features derived from three of our spectra. The spectra allow detection of Ca I and K I lines; the Li I lines, which are hardly seen, are not analyzed. The three stars have been selected because the strength of the strong and broad diffuse band near 5780 Å is identical in their spectra (Fig. 1).

As we see in Figure 1, while the intensities of the broader and stronger feature are identical in all targets, those of the
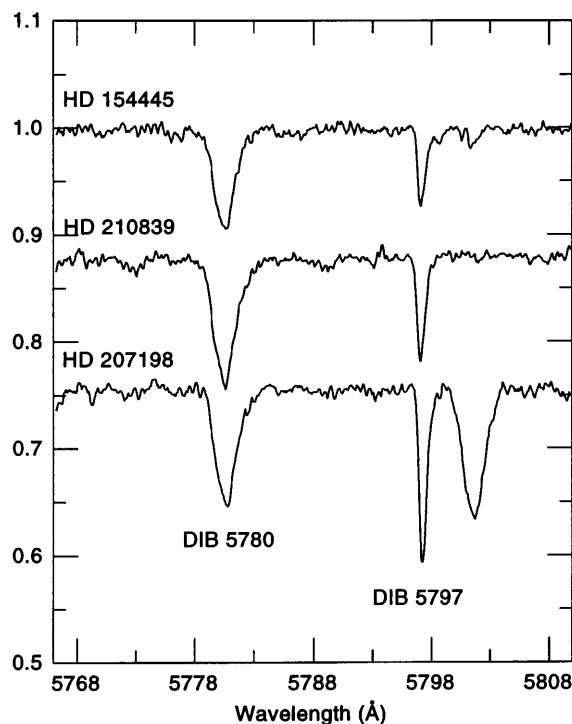

FIG. 1.—Profiles of the diffuse interstellar bands 5780 Å and 5797 Å seen in the spectra of three stars. The 5780 Å DIB intensity is identical in all cases.

TABLE 1

BASIC STELLAR DATA

HD No.	Spectral Type and Luminosity	V	$B-V$	$E(B-V)$
10516.......	B2 Vpe	4.09	−0.09	0.12
20336.......	B2.5 Ve	4.80	−0.11	0.08
21389.......	A0 Iab	4.54	+0.56	0.56
21428.......	B3 V	4.58	−0.09	0.07
22928.......	B5 III	2.99	−0.11	0.04
22951.......	B0.5 V	4.95	0.00	0.24
23180.......	B1 III	3.82	+0.05	0.26
24398.......	B1 Ib	2.85	+0.12	0.31
24760.......	B0.5 V	2.88	−0.17	0.07
24912.......	O7 III	4.04	+0.01	0.29
25940.......	B3 Ve	4.04	−0.03	0.15
29763.......	B3 V	4.29	−0.14	0.04
30614.......	O9.5 Iae	4.29	0.03	0.29
37022.......	O6 pe	5.13	+0.02	0.31
37023.......	B0.5 Vp	6.71	+0.08	0.34
38771.......	B0 Iab	2.06	−0.17	0.05
41753.......	B3 V	4.42	−0.17	0.01
47839.......	O7 Ve	4.66	−0.25	0.04
78316.......	B8 III	5.25	−0.12	0.00
87737.......	A0 Ib	3.49	−0.03	0.00
91316.......	B1 Ib	3.85	−0.14	0.05
108767......	B9.5 V	2.95	−0.05	0.00
109387......	B6 IIIpe	3.87	−0.13	0.02
116658......	B1 III-IV	0.98	−0.23	0.00
120315......	B3 V	1.86	−0.19	−0.01
138485......	B3 V	5.50	−0.14	0.04
143275......	B0.2 IV	2.30	−0.10	0.15
144217......	B0.5 V	2.62	−0.07	0.17
149757......	O9 V	2.60	−0.02	0.26
154445......	B1 V	5.64	0.16	0.39
163472......	B2 IV-V	5.82	0.09	0.30
164284......	B2 Ve	4.64	−0.03	0.18
164353......	B5 Ib	3.97	−0.02	0.06
164852......	B3 IV	5.27	−0.12	0.06
166182......	B2 IV	4.35	−0.15	0.06
174638......	B7 Ve	3.45	0.00	0.13
187811......	B2.5 Ve	4.94	−0.13	0.06
190603......	B1.5 Iae	5.64	0.56	0.73
193237......	B2pe	4.81	0.42	0.62
200120......	B1 ne	4.74	−0.05	0.17
202850......	B9 Iab	4.23	+0.12	0.13
202904......	B2 Ve	4.43	−0.11	0.10
207198......	O9 IIe	5.95	+0.31	0.54
210839......	O6 Iab	5.06	+0.23	0.52
224572......	B1 V	4.88	−0.06	0.17

narrower 5797 Å DIB increase from top to bottom. The uppermost object resembles a σ-type cloud (Krełowski & Sneden 1995), the third one is of the ζ type, and the second is of an intermediate type. The σ-type cloud is characterized by a 5780 Å DIB much deeper than the neighbor 5797 Å band; in the ζ-type cloud, the narrower 5797 Å DIB is deeper than the 5780 Å. The spectra show this difference beyond a doubt.

The same conclusion can be drawn from a comparison of the Ca I profiles in the same three targets (Fig. 2). The line barely seen in the σ-type object is quite strong in the ζ-type, and is evidently also visible in the intermediate one. We can also expect that calcium is ionized in the σ-type clouds, which phenomenon may be related to the abundance of photons at $\lambda < 2030$ Å in this environment. The spectra are aligned using the neighbor CH$^+$ line.

The spectral range of the K I 7698.96 Å line is shown in Figure 3 for the same targets as in the above figures. This line is the strongest atomic feature in our sample (except for the saturated Ca II and Na I lines), and thus is clearly visible
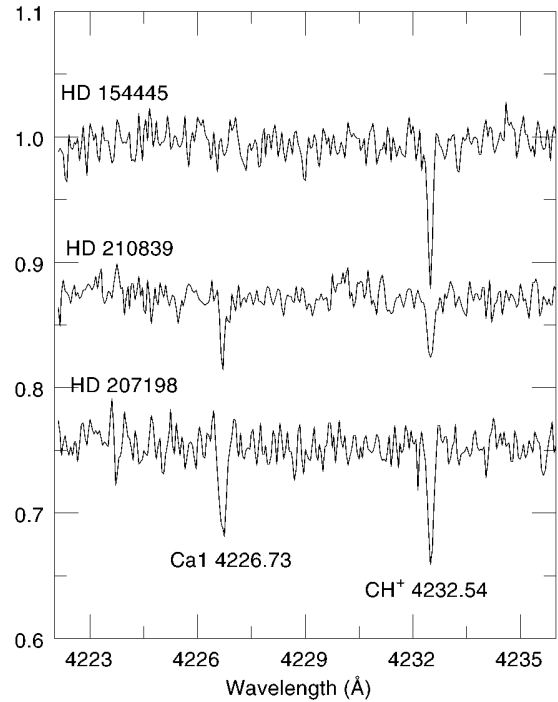

FIG. 2.—Profiles of the interstellar Ca I line seen in the spectra of the same targets as in Fig. 1.

in all spectra. However, as before, it is very weak in the σ-type object. This phenomenon should be related to the abundance of photons at $\lambda < 2858$ Å owing to the ionization potential, which is 4.34 eV for K I atoms.

3. DISCUSSION

The sample of stars in which K I and Ca I lines have been observed (Table 1) allows a more statistical approach. We
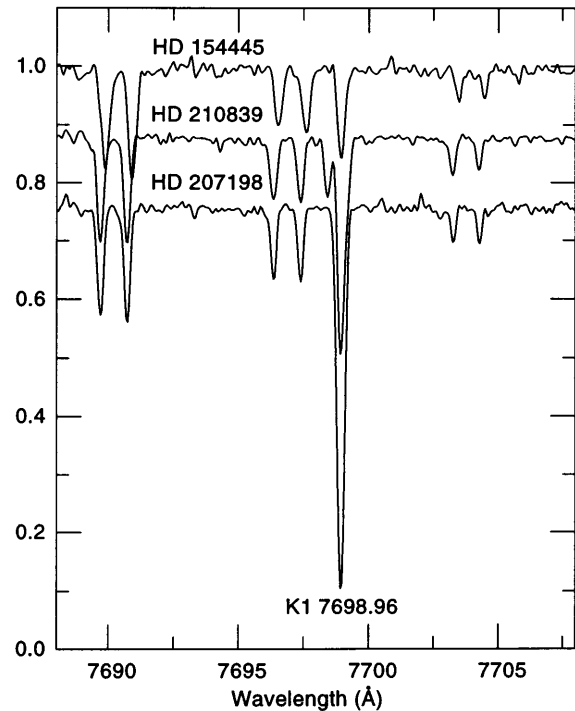

FIG. 3.—Profiles of the interstellar K I lines seen in the spectra of the same targets as in Fig. 1.

have measured the central depths of the atomic lines and of the well-known DIBs. The sample contains some narrow as well as some broad DIBs. It is obvious that the 5780/5797 Å ratio is heavily variable in our sample, i.e., that the latter contains both σ- and ζ-type objects. We have used the measurements of central depths, since relatively shallow features all stick to the linear segment of the curve of growth.

Figure 4 presents a correlation plot between the depth of the K I line (observed in all our targets) and the major diffuse bands at 5780 and 5797 Å; Figure 5 presents the correlation between 6284 and 6379 Å. The abundances of K I atoms are proportional to those of the narrow DIB carriers; however, we clearly demonstrate the absence of any correlation between K I and the 5780 or 6284 Å bands. We emphasize that the same effects exist for Ca I features, but the precision of measurements is lower in those cases owing to the weakness of the considered lines.

It is important to mention that the results presented above are fully supported by measurements of the K I line already supplied by other authors (Chaffee & White 1982; Hobbs 1974, 1976). In all these cases, the intensities of the K I line correlates with the narrow 5797 and 6379 Å DIBs. Note particularly the exclusively strong K I line observed by Hobbs (1974, 1976) in spectra of ζ Oph, ζ Per, and o Per.

It is an important question whether the growing fraction of neutral alkali atoms signalizes the physical conditions in which the carriers of some narrow DIBs, such as 5797 or 6379 Å, are likely to be formed or preserved. In extremely rarefied interstellar clouds, the attenuation of some spectral feature signals that the relevant ionization degree is scarcely populated. In the case of potassium, one cannot expect grain depletion, as this element is not involved in interstellar dust particles.

Another question concerns the carriers of the broad DIBs. Are they getting only *relatively* stronger in the environments in which alkali atoms are ionized and the

FIG. 5.—The same as in Fig. 4, but for 6379 Å and 6284 Å DIBs. The first behaves as 5797 Å; the second, as 5780 Å.

carriers of narrow DIBs are ionized or photodissociated as well? Or does such a situation (high ionization of some metals) facilitate the formation of broad DIB carriers? In the spectrum of HD 154445 (seen in Fig. 1), the 5780 Å band is of the same strength as in two other objects despite its lower reddening. This may suggest that the abundance of the ionizing photons, signalized by a high degree of ionization of the alkali elements, facilitates the formation of the broad DIB carriers.

We conclude that the carriers of narrow diffuse interstellar bands are relatively abundant in the media in which the energetic, vacuum UV photons are scarce. They must be either easily photodissociated by such photons or ionized, which changes their optical properties. The carriers of broad DIBs seem to be resistant to vacuum UV photons; it might be suggested that the presence of such irradiation facilitates the formation of these carriers. It seems possible that the carriers of the narrow DIBs are created in a gas-phase chemistry and follow the behavior of the interstellar atomic gas. On the other hand, the carriers of the broad unidentified features are more likely to be created on the surfaces of dust grains. We emphasize that the shapes of the interstellar extinction curves observed in σ- and ζ-type clouds are quite different. The former suggest the relative lack of small dust particles, which may result from an accretion of gas-phase atoms and molecules onto grain surfaces.

The simultaneous observation of different interstellar absorption features seems to be the right method to solve the intriguing puzzle of the DIB origin. It has been well known for more than a decade (see Krełowski & Walker 1987) that DIBs do not form a spectrum of one carrier. The present paper suggests a possibility for specifying the physical conditions that facilitate the formation of different "families" of diffuse interstellar bands. We do not intend to discuss possible hypotheses of DIB origin; it is only a signalization of the interesting phenomenon observed in interstellar space.
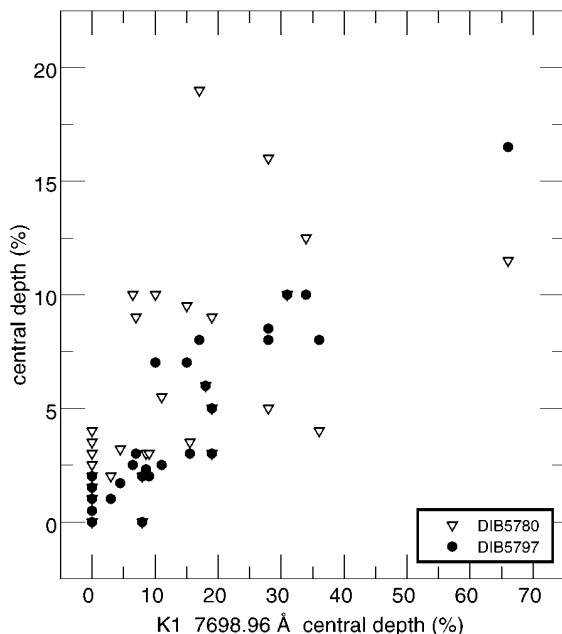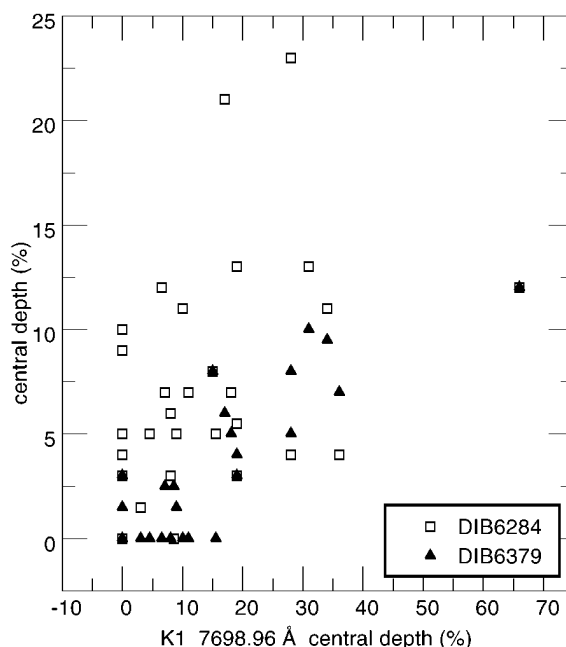

FIG. 4.—Correlation between the interstellar K I line strength and the depths of the 5797 Å and 5780 Å DIBs measured in the spectra of the targets listed in Table 1. Note the fairly tight correlation in the case of 5797 Å and the lack of correlation in the much broader 5780 Å.

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