

## A SURVEY OF INTERSTELLAR LINES: RADIAL VELOCITY PROFILES AND EQUIVALENT WIDTHS

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### ABSTRACT

An atlas of high resolution ( $\lambda/\Delta\lambda=45,000$ ) profiles of interstellar atomic lines of K I (7665, 7699 Å), Na I (D1, D2), Ca II (H, K), Ca I (4227 Å), molecular structures of CH, CH<sup>+</sup>, CN and the major diffuse interstellar bands at 5780 and 5797 Å based on ~300 echelle spectra of ~200 OB stars is presented. Relationships between the reddenings, distances and equivalent widths of Na I, Ca II, K I, CH, CH<sup>+</sup>, CN and diffuse bands are discussed. The equivalent width of K I (7699 Å) as well as of CH4300 Å' correlate very tightly with E(B-V) in contrast to the features of neutral sodium, ionized calcium and the molecular ion CH<sup>+</sup>. The equivalent widths of the H and K lines of Ca II grow with distance at a rate ~250mÅ per 1 kpc. A similar relation for Na I is much less tight. The strengths of neutral potassium lines, molecular features and diffuse interstellar bands do not correlate practically with distance. These facts suggest that ionized calcium fills the interstellar space quite homogeneously while the other carriers mentioned above, especially K I, CH and these of diffuse bands occupy more and more compact volumes, also filled with dust grains. Apparently the carriers of narrow diffuse bands are spatially correlated with simple molecules and dust grains - all abundant in the so-called "zeta" type clouds. The same environment seems to be hostile to the carriers of broad diffuse interstellar bands (DIBs) (like 5780 or 6284) and - to a certain extent - also to Ca II, Na I and CH<sup>+</sup>.

*Key words* : ISM: dust, extinction, ISM: clouds, ISM: atoms, ISM: molecules, ISM: lines and bands

### I. INTRODUCTION

According to the present knowledge, the composition of interstellar absorbing matter is very complex: it involves atomic gas (revealing its presence through resonant lines, observable mostly in the extra-atmospheric UV), 137 molecules already identified (mostly polar species, some of them composed of up to 13 atoms), some larger species (e.g. polycyclic aromatic hydrocarbons - PAHs), and dust grains of various sizes and shapes. Diffuse interstellar bands (DIBs) were discovered long ago (Heger 1921) but their carriers remain unknown despite considerable efforts of astronomers and the unprecedented progress in observational astronomy during the last 10-15 years. The identification of DIB carriers is the longest standing unsolved problem in all of spectroscopy. The list of these spectral lines or bands continues to grow, including more and more weak DIBs (Galazutdinov et al. 2000a). For recent reviews of the properties of DIBs, see Snow (1997), and Herbig (1995).

More than a decade ago (Krelowski & Walker 1987), (Josafatsson & Snow 1987) and (Krelowski & Westerlund 1988) demonstrated that in individual clouds DIB strength ratios may vary from cloud to cloud, revealing different physical conditions leading to different abun-

dances of the DIB carriers. One of the striking examples of this phenomenon is that of the two neighboring diffuse bands, centered around 5780 and 5797 Å. Lines of sight, referred to as "sigma" clouds (because the line of sight toward  $\sigma$  Scorpii is the archetype), are characterized by a low strength ratio of 5797/5780 DIBs. Conversely, in "zeta" clouds (after  $\zeta$  Ophiuchi), one can expect a high ratio of these DIBs (Krelowski & Westerlund, 1988). Moreover, "zeta" type clouds show usually strong absorption lines of interstellar molecules such as CH, CH<sup>+</sup>, CN, C<sub>2</sub>, C<sub>3</sub>, etc., whereas the latter are weak in "sigma" type clouds (in many cases - below the level of detection). However, the lines of sight where DIBs are observed always display lines of atoms and ions such as Na I (D1 and D2), Ca II (H and K), K I at 7699 Å (the line at 7665Å is typically blended with strong telluric lines and thus usually escapes detection). Unfortunately, pure "sigma" and "zeta" type spectra are not numerous - most of the observed stars, especially heavily reddened ones, shine through several clouds of different optical properties and thus the resultant spectra are ill-defined averages along these sight-lines. It remains unknown whether both kinds of clouds are evenly distributed in our Galaxy and what physical parameters cause the observed spectral differences.

Doppler splitting of atomic spectral features reveals different radial velocities of individual clouds along many sight-lines (see, e.g., Adams 1943; Beals 1938;

Galazutdinov et al. 2000b). However, DIBs are relatively broad and hard to be resolved except the narrowest ones, like 6196 Å, where the Doppler splitting was convincingly demonstrated (Herbig & Soderblom 1982). This fact makes building relations between individual components of atomic and/or molecular features and those of DIBs very difficult in most of cases. The examples of single clouds along the sightlines towards reddened stars are very scarce.

In spite of the above mentioned difficulties, we succeeded to detect a correlation between the intensities of “narrow” (like 5797 Å) DIBs, and the K I 7700 Å line (Krelowski et al. 1998). Apparently the formation and/or preservation of the carriers of at least some of the diffuse interstellar bands is related to the level of ionization of certain interstellar atoms which depends on irradiation by hot, neighboring stars. It is to be emphasized that an interstellar cloud is very likely to be influenced by its neighborhood in a sharp contrast to stars. In most of cases interstellar clouds are not gravitationally bonded and their limited optical depth allows penetration of stellar radiation even into their cores. High energy photons leaving hot stars are very likely to ionize most of the atoms characterized by the ionization potential lower than that of hydrogen.

Investigations of the features originating in simple molecules and atoms/ions are tempting as they can lead to a determination of physical conditions which apparently influence the formation of DIB carriers (Krelowski et al. 1999). It seems also important to construct a new picture of the gas motions relative to the Sun. The already accepted model (Genova et al, 1997) is only a crude approximation due to scarcity of the samples used as well as the lack of precise distance determinations of the objects observed. In this survey, we attempt to depict the distribution of interstellar matter: ionized/neutral atoms, simple molecules and mysterious carriers of DIBs in the Solar neighborhood (most of objects are nearer than  $\sim 2$  kpc) basing on a statistically meaningful sample of OB stars.

Only very recently, the amount of observational data necessary to conduct such a research started to grow reasonably quickly mostly due to the broad application of echelle spectrometers installed at many observatories during the 1990s. Allowing to cover a very broad wavelength range in a single exposure, these instruments permitted the simultaneous registration of many stellar and interstellar features. This opened the possibility to analyze mutual relations between the latter, as well as their dependence on the color excess ( $E(B - V)$ ), commonly used measure of the amount of interstellar matter along any sightline). The goal of this paper is to create a statistically meaningful sample of measurements of radial velocities and equivalent width measurements for a choice of absorption spectral features (Table 1). Radial velocities may allow to measure the motion of gas clouds in relation to our Sun. The proposed analysis of the relations between EW's of different interstellar features should reveal to what

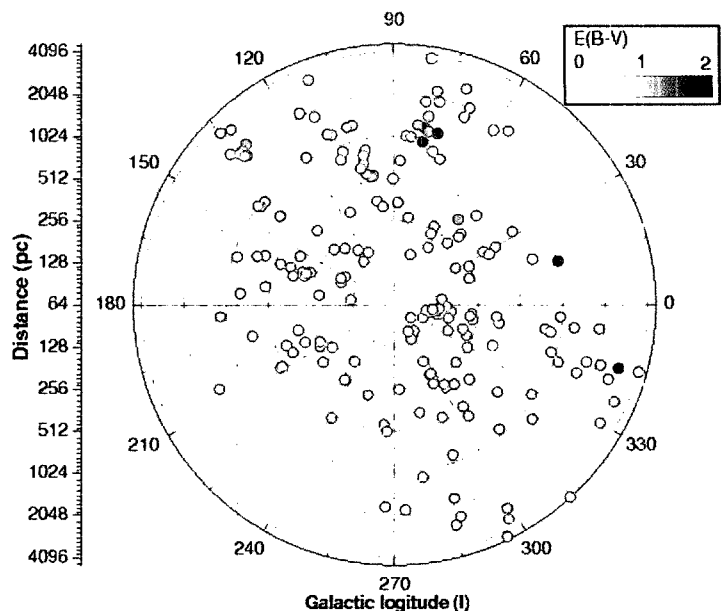


Fig. 1.— Positions of the program stars in projection on the Galactic plane. The Sun is in the center. Distance scale is logarithmic and begins at 64 pc, for clarity. Brightness of filling depends on the reddening  $E(B - V)$ . Note the lack of clear dependence of reddening level on the distance from the Sun.

an extent are interstellar molecules (and especially the carriers of DIBs) spatially correlated with atomic lines of different origin. Relating the DIB strengths to the features of some well-identified species can shed some light at the nature of their carriers being, most probably, complex molecules.

## II. SUMMARY

The main results and conclusions of this paper may be listed as follows:

- We demonstrate profiles of interstellar features derived from spectra of  $\sim 200$  reddened, mostly hot stars; radial velocities of the intervening clouds are measured and published;
- Our statistically meaningful sample of early type, reddened stars permits to propose the following picture: the vast interstellar space is filled with ionized gas, revealed by Ca II H and K lines, their strength being directly proportional to the distance. Equivalent widths of H and K interstellar lines can be thus used to estimate roughly distances to absorbing clouds. Denser clouds may produce also Na I D1 and D2 lines; the latter are usually strong because of the very high oscillator strengths of the relevant transitions. The densest and compact clouds, producing most of the reddening, are populated with dust, neutral potassium atoms, molecules (like CH) and DIB carriers. Apparently molecular(?) carriers of DIBs can be formed and preserved under conditions similar

to those required for well known simple interstellar molecules. Most likely, the presence of grains plays also an important role;

- The carrier of DIB5780 seems to be more resistant to the photo-ionization than that of 5797 (and probably – those of other narrow DIBs). On the other hand, DIB5780 as well as Na I, Ca II, and probably, CH<sup>+</sup>, is relatively weak while formed in environments rich in molecular species and narrow DIB carriers (“zeta” type clouds);
- Our sample of objects demonstrates a good coincidence with the HI distribution map (Huthoff & Kaper 2002). The sightlines between  $l \sim 90 \pm 20^\circ$  are rich in interstellar matter and demonstrate a wide diversity of the profiles of interstellar lines;
- An independence of the reddening ( $E(B - V)$ ) on distance (Fig.1) (at least within the range  $< 4$  kpc) is demonstrated. This behavior may be due to the Local Bubble “wall” – the possible main source of continuous extinction, molecular features, and DIBs;
- We report for the first time the Doppler splitting of the DIB5797 in spectra of HD 13256; it clearly reflects the doppler splitting seen in the KI line, supporting a close spatial relation between the neutral potassium and the DIB carrier; in several other cases very similar Doppler splitting, seen in Na I or Ca II lines is not observable in any DIB profile
- The profiles of interstellar features observed towards heavily reddened stars show spectacular Doppler-splitting. But the radial velocities of disparate components, as well as the number of such components vary from species to species in the same spectrum. Current work does expand the study already demonstrated by Galazutdinov et al. (2000b);
- The plot presenting the distribution of radial velocities of interstellar clouds versus Galactic longitude is a promising tool for selecting objects with an unusual (rather circumstellar than interstellar) origin of the surrounding matter. An additional profit that may follow a complete survey of radial velocities derived from interstellar lines seen in spectra of stars in *the Galactic plane* vs. galactic longitude would be a reliable method of determining the Solar apex related to interstellar gas. Preliminary result revealed that the direction is close to the one postulated for the Solar apex versus interstellar gas, namely  $l = 6^\circ$ ;
- The variation of DIB5780 profile with its growing intensity is demonstrated. This leads to a possible red-shift of the radial velocity value. This effect is likely to be found in many other diffuse interstellar bands;
- The small and dense clouds seem to be distributed mostly in the Galactic plane. Their opacity must

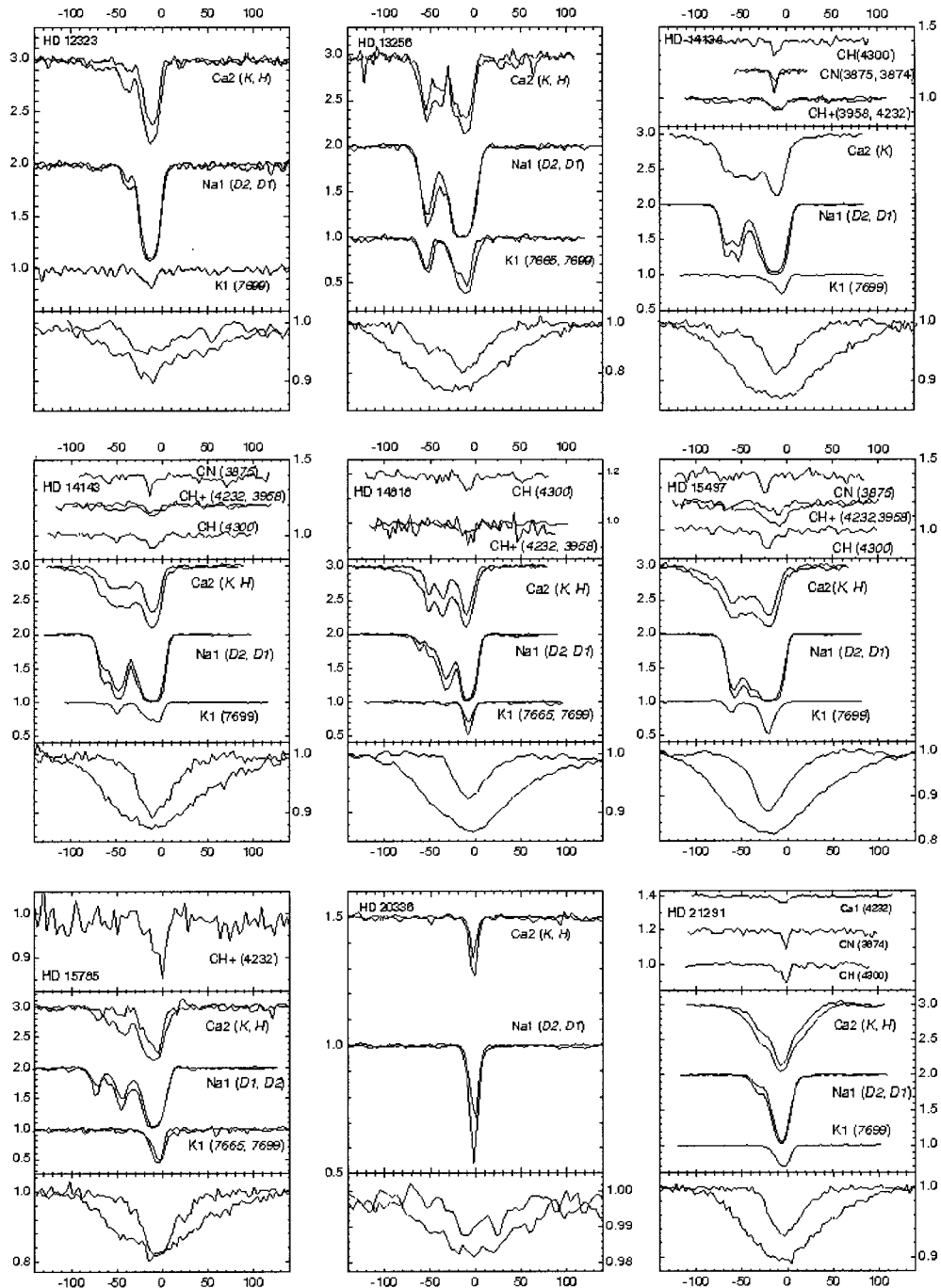
be relatively high, and thus interstellar extinction does not grow in unison with distance. It depends strongly on how many such opaque clouds are situated along any specific sightline. As a technical remark, we can advice the measurements of either KI line or CH features to estimate the radial velocities needed to derive rest wavelengths of unidentified interstellar features. This is justified, since diffuse bands, potassium, CH radical, and DIB carriers seem to be spatially correlated.

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**Fig. 2.**— Profiles of interstellar features seen in spectra of program stars. There are 9 stars on a page. Each star profile is divided into three subpanels: top - molecular and Ca I lines, middle - K I, Na I, Ca II lines and bottom one – diffuse interstellar bands at 5797 and 5780 Å. If only single profile in the bottom subpanel presented – it is DIB5780. In a case of absence (“below the level of detection”) of some feature, another panel occupies a liberated space.