Extracting diffuse interstellar bands from cool star spectra: tracing Galactic ISM structures, kinematics, and properties

L Puspitarini¹, R Lallement², H-C Chen³, A Monreal-Ibero²
¹Bosscha Observatory and FMIPA Institut Teknologi Bandung Indonesia
²GEPI, Observatoire de Paris, CNRS UMR8111, Universit Paris Diderot, Place Jules Janssen, 92190 Meudon, France
³Institute of Astronomy, National Central University, Chungli, Taiwan
E-mail: lucky.puspitarini@gmail.com

Abstract. Diffuse interstellar bands (DIBs) are broad and weak absorption features that appear in spectra recorded towards stars that lie behind interstellar (IS) clouds. They are known as a long-standing challenge in astronomical spectroscopy because of their unknown carriers. However, they are also a potential IS tracers, in particular to probe distant clouds because they are not easily saturated. We devised automated DIB-fitting methods appropriate for cool star spectra and multiple IS components. The data were fitted with a combination of a synthetic stellar spectrum, a synthetic telluric transmission, and empirical DIB profiles. The initial number of DIB components and their radial velocity were guided by HI 21 cm emission spectrum, or, when available in the spectral range, IS neutral sodium (NaI) absorption lines. For NaI, radial velocities of IS NaI lines and DIBs were maintained linked during a global simultaneous fit. Using the tools, we have analyzed Gaia-ESO Survey (GES) spectra of stars that probe between 2-10 kpc long line-of-sight (LOS) in few different regions of the Milky Way (fields). For all fields, the DIB strength and target extinction are well correlated. We show that, toward distance-distributed target stars, DIBs can be used to locate dense clouds in the Galaxy (i.e., Galactic arm) and probe a LOS kinematical structure. In addition, we have devised the DIB-DIB global fit to study the relation between DIBs and can be a potential tool to trace interstellar environmental conditions.

1. Introduction
A longstanding challenge in astronomical spectroscopy is to uncover the carriers of the diffuse interstellar bands (DIBs). They are broad absorption features observed in stellar spectra. The first observational record of DIBs was made by [6] and systematic studies began with the work of [10] who detected several DIBs in stellar spectra. Today, around 500 DIBs have been identified in the UV, visible, and infrared part of the electromagnetic spectrum (see [13, 9] and references therein). These DIBs behave like interstellar (IS) lines with regard to occurrence, strength, and Doppler shift. Instead of being narrow and sharp, they are somewhat widened and irregular. They are described as being diffuse as their widths are greater than the absorption features of well-known atoms or molecules. Using a high resolution spectrograph, there is an evidence that the widths are due to unresolved blending of individual rotational/vibrational lines as could arise
in the electronic spectrum of gas phase molecules or molecular ions [13, 4]. Therefore, candidate carriers might be sought among a large number of possible carbon-based organic molecules.

Although we do not know yet the carriers of DIBs, they can still be a promising tool to trace and to study interstellar medium (ISM) in the Galaxy, and also in nearby galaxies (e.g., see [3]). First of all, DIBs are numerous. Moreover, they are not easily saturated even for stars located at great distance or behind dense clouds, which is a strong advantage for Galactic-scale ISM mapping [8]. Furthermore, they may indicate the physical conditions in the ISM owing to their differential behaviors, i.e., some DIBs are sensitive to the stellar radiation field, and some are not. DIBs are correlated with extinction with a considerable dispersion and differences for each band.

In this article, we will show methods on extracting DIBs from cool (late-type) star spectra. We will also show that DIBs can be used to locate dense clouds in the Galaxy (i.e., Galactic arm), to probe a line-of-sight (LOS) kinematical structure and to trace IS environmental conditions.

2. Data

Data from Gaia-ESO Spectroscopic Survey (GES; [5]) and some analysis have been presented in [11]. In this article, we only review 2 GES fields, namely CoRoT anti-center and CoRoT center (see table 1), due to their interesting kinematical structures. The fields are almost diametrically opposite on the sky (see figure 1). All target stars were observed with the FLAMES multi-object spectrograph (GIRAFFE, $R \approx 17000$ and UVES, $R \approx 47000$) with different observation settings.

| Field   | GIR. | UVES | $l_c$ (°) | $b_c$ (°) | $D_{\text{min}}$ (kpc) | $D_{\text{max}}$ (kpc) | $A_{\text{min}}$ min mag | $A_{\text{max}}$ max mag | $\text{Ang. size}$ (°) | Setting(s) | Studied DIBs |
|---------|------|------|-----------|-----------|------------------------|------------------------|---------------------------|---------------------------|----------------------|-------------|--------------|
| COROT-AC| 57   | 7    | 212.9     | -2.0      | 0.1                    | 8.6                    | 0.0                       | 2.5                       | 0.4                  | UVES5800, HR15N, HR21 | 6283, 6614, 8620 |
| COROT C | 105  | 5    | 37.5      | -7.0      | 0.1                    | 16.1                   | 0.0                       | 2.1                       | 0.3                  | UVES5800, HR15N, HR21 | 6283, 6614   |

**Figure 1.** CoRoT fields (black line) and the target stars (black marks) in a slice of the 3D ISM map [8]. Color-excess is shown in rainbow color. Purple shows higher reddening region. Red shows lower reddening region. The CoRoT anti-center direction (left) encounters gradually denser clouds, whereas the CoRoT center field (right) encounters nearby dense region (probably associated with Aquila rift).
3. Method

We have devised several fitting methods to extract DIBs from cool star spectra. The principle of the fitting methods is essentially the same as in [2]. The spectrum is fitted with a combination of a synthetic stellar spectrum, a synthetic telluric transmission, and empirical DIB profile(s). The main difference compared to [2] is that we allow for multicomponent DIBs and subsequently we extract kinematic information. See [11] for the complete description.

For multicomponent DIB fitting, it is necessary to start with initial parameters that are close to the actual solution to avoid secondary minima and to converge more rapidly toward the final solution. In the absence of any IS absorption line (as for GIRAFFE spectra), the initial guesses for the number of required velocity components and DIB radial velocities come from a simplified decomposition of the HI emission spectrum [7] taken from the spectral HI cube in the direction of the target star. Whereas for UVES spectra, the initial guesses come from IS NaI lines.

![Figure 2](image1.png)

**Figure 2.** Illustration of the multi-component DIB fitting. The radial velocities of the NaI and DIBs are kept linked (see the black vertical line). Figure is taken from [11].

![Figure 3](image2.png)

**Figure 3.** Illustration of the NaI doublet-6614 Å DIB global multi-component analysis. The radial velocities of the NaI and DIBs are kept linked. Figure is taken from [11].

### 3.1. Hierarchical DIB fitting

When no IS lines are available in the spectral range, independent HI emission spectrum can be used. Since the HI emission spectrum represents the totality of the IS clouds, both in front of and
beyond the target star, it should be used carefully. The HI emission spectrum was therefore used to construct a table of velocity guesses (v_{HI}) and provide upper and lower limits to the velocity range. Then, the DIBs were fitted using the hierarchical sequence of the velocity prior values. Figure 2 shows an illustration of the multi-component 6614 Å DIB fitting. The red line shows the stellar spectrum. The dotted lines are the models: stellar (orange), telluric (green), empirical DIBs (grey). The thick blue line is the optimal model adjustment. The initial guesses for the DIB velocity centroids are 24, 40, 50 km/s and based on the HI spectrum in the same direction (see top plot). The middle panel is an example of a preliminary adjustment with a unique DIB component. The DIB velocity is found to be \( \sim 33 \) km/s. The large difference from the initial guess (24 km/s) demonstrates the need for the introduction of a second cloud component. The lower panel is an example of a subsequent adjustment with two DIB components. The two fitted velocities are now close to the first two HI emission peaks.

3.2. Global analysis of lines and DIBs
IS NaI lines are not only used as sources of the first guesses of the cloud parameters, but also enter in the global analysis of lines and DIBs, which means that they are simultaneously measured together with the DIB components. Their radial velocities are linked so that they remain identical throughout the adjustment, component by component. Figure 3 shows an illustration of the NaI doublet-6614 Å DIB global multi-component analysis. The NaI region is shown at top panel and the DIB region at lower panel. The red line shows the stellar spectrum (lower plot) and the fitting residuals (upper plot). The dotted lines are the models: stellar (orange), telluric (green), and interstellar components (blue) respectively. The thick blue line is the fitting result.

3.3. Global analysis of DIBs
In addition to the methods that have been presented in [11], we have devised DIB-DIB global analysis. The global analysis is applied between two different diffuse bands in which their radial velocities are linked. This method can be used to derive the ratio variability between two DIBs. It can be a strong advantage in the detection itself too: as an example, it helps constraining the radial velocity interval for a very wide DIB from its association with a much narrower one, or it helps detecting a weak DIB from the constraint on its radial velocity deduced from a stronger one. See an example of the fitting in figure 4.

Figure 4. Illustration of the Global analysis: the 6614 Å DIB and 6283 Å DIB for star 06432980-0050546 in CoRoT anti-center field. Vertical black lines show the radial velocity.
Figure 5. Distribution of target stars projected in Galactic plane and superimposed with Galaxy sketch by Robert Hurt of the Spitzer Science Center. Colors show 6614 DIB strength (mA). Unit in pc.

Figure 6. DIBs can be used to locate Galactic arm. Abrupt increases corresponds to the crossings of dense clouds and plateaus to interclouds or interarms. Shown in the plots are results for target stars in CoRoT anti-center field. Figure is taken from [11].

Figure 7. DIBs can be used to trace LOS kinematical structure. The figure shows comparison between the DIB radial velocities and the HI 21 cm emission spectra. Black (red) markers and lines are DIB fitting results and HI spectra from CoRoT anti-center field (CoRoT center field). For CoRoT anti-center field, a significant number of spectra requires two velocity components, which very likely correspond to the Local and Perseus arms. Figure is taken from [11].

4. Results and perspectives
Figure 5 shows the two directions of the selected fields in the Galactic Plane and measurement results of 6614 Å DIB.

For the CoRoT anti-center field, the target stars are located about the Galactic plane and...
are widely distributed in distances (from 0 to 7 kpc from the Sun). This allows us to probe not only the local arm, but also external Galactic arm (i.e., Perseus arm). As the distance of the target star increases, the LOS intersects a greater part of the ISM and therefore the EW of the DIB is expected to increase, with abrupt increases corresponding to crossings of dense clouds and plateaus to interclouds or interarms (see figure 6). From upper to lower panels are EW 6614 Å DIB vs. estimated distance from Bayesian method [1], EW 8620 Å DIB vs. distance, and $A_0$ vs. distance. Circles show GIRAFFE observations. Triangles show UVES observations. Colors correspond to the number of IS components used to fit the IS line or band. All nearby targets ($D \leq 1$kpc) have only single IS component. Distant targets have more than one velocity component, in agreement with the crossing of at least one external arm. Comparison with IPHAS data [12] is also shown in the figure. Here is a demonstration that DIBs can be used to locate dense clouds in the Galaxy (i.e., Galactic arm).

DIBs can also be used to trace LOS kinematical structure (see figure 7). Here, we compare the fitted DIB radial velocities and the HI 21 cm emission spectra. In addition, we have UVES data in which DIBs are linked to IS NaI lines. Thus, DIBs, HI emission spectrum, and IS NaI lines radial velocities are actually in agreement.

In addition, we have applied the 6614 and 6283 Å DIBs global analysis to the GES/UVES targets in the two CoRoT fields. There were 12 target stars that are tested: 7 targets in the anti-center direction and 5 in the center direction. Interestingly, we found that the two directions differ in terms of equivalent width (EW) ratios. With $\frac{EW_{6614}}{EW_{6283}} \simeq 0.1 - 0.2$ for the CoRoT anti-center and $\frac{EW_{6614}}{EW_{6283}} \simeq 0.3$ for the CoRoT center. These differences may be explained by the specific behavior found in several studies. Environmental conditions (especially radiation field) may destroy or favor the DIB carrier(s). The 6283 Å DIB in particular has been shown to be one of the DIBs sensitive to the stellar radiation field. This a preliminary test that DIBs can be used to trace interstellar environmental conditions.

Altogether, these results show how DIBs can be used to reconstruct the large-scale distribution of the ISM in the Galaxy, and can be especially useful for distant clouds because in this case they are strong enough, but not saturated. These results pave the way to three-dimensional mapping of the Galactic ISM based on DIB absorption measurements from current or future stellar spectroscopic surveys. Like all three-dimensional maps, future DIB-based maps are expected to gain in accuracy in a considerable way when Gaia parallax measurements will be available soon in the next data release.

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