Diffuse Interstellar Bands in the High-Resolution GAOES Data

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Abstract. Diffuse interstellar bands (DIBs) are an enigmatic set of interstellar absorption features, observed at optical and near infrared wavelengths in the spectra of reddened stars in our Galaxy also in other galaxies. Identifying the carriers of DIBs has been a longstanding challenge and is still very much a work in progress. In recent years, surveys of DIBs have been conducted, but mostly focus on strong bands. In this work, we extracted and measured DIBs recorded in the high-resolution stellar spectra of \( \varepsilon \) Auriga (\( \varepsilon \) Aur) and IQ Per observed by using Gunma Astronomical Observatory Echelle Spectrograph (GAOES) (spectral resolution R~65000). Observations were aimed at obtaining high resolution spectra of double-lined detached eclipsing binaries. For each selected DIB, we performed spectral fitting of a combination of a smooth stellar continuum (polynomial function), an empirical DIB model, and a synthetic telluric transmission. The high-quality data allow us to measure not only strong and well-known DIBs, but also weaker DIBs.

Keywords: Diffuse Interstellar Bands and GAOES Data

1. Introduction

Interstellar matter (ISM) is a “rich laboratory”. Interstellar gas and dust are found in a wide range of temperatures and densities providing numerous different interstellar species (atoms or molecules). Many of them are still unidentified. Diffuse interstellar bands (DIBs) are an enigmatic set of absorption features, they behave like interstellar lines with regard to occurrence, strength, and Doppler shift. Instead of being narrow like the well-known interstellar lines, their profiles are widened and irregular. The first observational record of DIBs was made in 1922, whereas systematic study has started since 1934 [17], however to date the carrier(s) of the DIBs are still unclear, except for the two infrared DIBs [3]. Identifying DIBs carriers is a subject of active research for many years (see [7],[12], [22] and references therein). Despite the unclear carrier(s), DIBs can be a promising ISM tracer since (1) DIBs are ubiquitous, around 500 DIBs are identified in optical and IR domain (see [15], [13], [16]), (2) DIBs are not easily saturated thus they can be used to trace distant Galactic IS structures [19], (3) DIBs are correlated with interstellar extinction but with some dispersion (see [18], [19] and references therein). The relationships can be used to estimate interstellar extinction and/or to provide information about interstellar physical conditions for the reason that some DIBs are sensitive to the stellar radiation field. Massive measurements of DIBs can be used to study the nature of DIBs (i.e. identifying DIB families [2]), but also to build spectroscopic database for ISM mapping.
2. Data
We used high resolution stellar spectra observed by using Gunma Astronomical Observatory Echelle Spectrograph (GAOES) (see [9], [10], [11]). GAOES was designed and built for the GAO 150-cm telescope. Our data are spectra of two stars i.e., ε Aur (RA= 05 01 58.13, Dec= 43 49 23.87) and IQ Per (RA= 03 59 44.68, Dec=48 09 04.49) (see Fig. 1 and Table 1). Our data consists of one spectrum of ε Aur and two spectra of IQ Per with spectral resolution R or Δλ/λ ~65000 and spectral range of 4779.54 Å to 6691.74 Å. Observations were primarily aimed at obtaining high resolution spectra of double-lined detached eclipsing binaries. But since the two stars are located behind interstellar clouds, this allows us to study DIBs. Stellar parallaxes were obtained from Gaia DR2 (see [5] and [6]). Interstellar extinction data were obtained by using a computerized model by [8] and from Gaia DR2 when available. We have selected 10 DIBs which consists of not only strong type of DIBs, but also weaker ones, i.e., 6283.84, 5780.48, 5797.06, 6613.62, 5849.81, 6204.49, 6203.05, 5705.08, 6195.98, 6445.28, and 6089.85 Å. The criteria of the selection are their equivalent width and FWHM, also the selected DIBs should be able to be distinguished from stellar features.

![Figure 1. Distribution of the target stars (ε Auriga and IQ Per) as seen in the HI map.](image1)

![Figure 2. Vertical slices of the 3D IS dust map along the longitude of the target stars [14]. Interstellar clouds are seen at a distance of ~100-400 pc.](image2)

| Name | Stype | Lon (°) | Lat (°) | p +/- Δp (mas) | d (pc) | dmin (pc) | dmax (pc) | Av DR2 | Av Model |
|------|-------|---------|---------|---------------|-------|-----------|-----------|-------|---------|
| ε Aur | A9Ia  | 162.79  | 1.18    | 2.41 +/- 0.51 | 414.18| 341.73    | 525.62    | -     | 0.77 +/- 0.32 |
| IQ Per | B9    | 152.24  | -3.71   | 3.26 +/- 0.05 | 306.80| 302.03    | 311.71    | 0.52 +/- 0.26 | 0.91 +/- 0.39 |

3. Method
We aim at extracting and measuring DIB equivalent width (W). The equivalent width is defined as the area between the line profile and the continuum, proportional to the measure of the strength of spectral features. We applied automated DIB fitting to a narrow region of spectrum which contains of DIB. We fitted the spectrum with a combination of smooth continuum (polynomial function), an individual DIB model, and a telluric transmission model simultaneously. The fitting used Levenberg-Marquardt algorithm in IGOR Pro 8 software (WaveMetrics, Inc.). The DIBs models are empirical models/profiles from series of observations of nearby stars previously determined (see [18]). To determine the model, spectra of few reddened stars were selected. Then, we normalized, scaled, and...
averaged the spectra. For a specific DIB, we took the new averaged-profile as the individual DIB model. The synthetic telluric transmission was computed by using the line-by-line radiative transfer model (LBLRTM) code and the HIghResolution-TRANsmission molecular absorption (HITRAN) spectroscopic database (see [4] and [21]) and is available online in the Transmissions of the Atmosphere for Astronomical data (TAPAS) web-based service [1].

4. Results
Some examples of DIB fitting can be found in Fig. 3 to 8. Table 2 shows result of DIB measurements. Since we have two independent spectra for the IQ Per, we compared DIB measurements from the first and the second spectrum (Fig. 9), it shows consistent results within the uncertainties. In addition, with the high-resolution spectra, we possibly detect sub-structure variability in the DIB feature (see Fig. 10). However, we caution that the target stars are binary type and variable star. Thus, further careful investigation needs to be done.

**Figure 3.** An example of automated fitting for 6283Å DIB in the IQ Per (1) spectrum. The 6283Å DIB is one of the strongest DIBs. The black line is the spectrum of target star and the blue line is the fitting result. Dashed lines show three models (DIB model + synthetic telluric transmission model + continuum).

**Figure 4.** An example of automated DIB fitting. Similar to Fig. 3, but for 5780Å DIB.
**Figure 5.** An example of automated DIB fitting. Similar to Fig. 3, but for weaker DIB, i.e., 5849.81Å DIB. Stellar line is masked when present.

**Figure 6.** An example of automated DIB fitting. Similar to Fig. 3, but for weaker DIB, i.e., 6203.05 Å DIB. Stellar line is masked when present.

**Figure 7.** An example of automated DIB fitting. Similar to Fig. 3, but for weaker DIB, i.e., 6445Å DIB. Stellar line is masked when present.
Figure 8. An example of automated DIB fitting. Similar to Fig. 3, but for weaker DIB, i.e., 6090Å DIB.

Table 2. DIB measurements from spectra of ε Aur and IQ Per.

| DIB λcen (Å) | ε Aur | IQ Per (1) | IQ Per (2) |
|--------------|-------|------------|------------|
|              | $W_\lambda$ & $\Delta W_\lambda$ & $W_\lambda$ & $\Delta W_\lambda$ & $W_\lambda$ & $\Delta W_\lambda$ |
| 6283.84      | 422.94 & 26.49   | 187.59 & 8.83  | 224.60* & 28.68 |
| 5780.48      | 193.35 & 9.72   | 117.26 & 2.59  | 117.88 & 10.05 |
| 5797.06      | 63.76  & 5.17    | 36.65  & 1.93  | 30.94  & 5.59  |
| 6613.62      | 117.78 & 5.12    | 63.25  & 1.87  | 67.29  & 5.66  |
| 5849.81      | 15.83  & 4.14    | 16.88  & 1.47  | 20.12  & 4.59  |
| 6203.05      | 45.89  & 8.69    | 11.91  & 2.34  | 6.65   & 8.96  |
| 5705.08      | 42.33  & 13.36   | 17.11  & 3.08  | 15.55  & 13.50 |
| 6195.98      | 30.91  & 2.48    | 14.39  & 1.17  | 17.73  & 2.89  |
| 6445.28      | 14.17  & 4.60    | 13.93  & 1.49  | 11.15  & 5.02  |
| 6089.85      | 10.68  & 2.25    | 4.18   & 1.13  | 4.84   & 2.65  |

Figure 9. Comparison of DIB measurements from the IQ Per (1) spectrum and the IQ Per (2).

Figure 10. Potentially sub-structure variability in the DIB profile by comparing the spectrum of IQ Per (1) and IQ Per (2) (see the right wing of the profile).
5. Conclusions
From this study, DIBs have been correctly extracted from our spectroscopic data. We have performed spectral fitting of a combination of a smooth stellar continuum, empirical DIB model, and telluric lines model which is proper for the spectral type of the target stars, i.e., early-type star spectra. Comparing with 3D ISM map [14], the target stars (ε Aur and IQ Per) are located behind the interstellar clouds that have a distance of 100-300 pc, i.e. Perseus region. The high-resolution GAOES spectra allow us to study not only strong DIBs, but also weak and barely studied DIBs. In addition, it may allow us to detect sub-structure variability in DIB profile. For future prospect, massive spectroscopy data from the past and ongoing survey are now or will be available in archive facility. They may help us to improve our understanding about DIBs and to map the distribution of the ISM.

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