Gaia Data Release 3: Exploring and mapping the diffuse interstellar band at 862 nm

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Aims. Here, we demonstrate the capacity of the Gaia-Radial Velocity Spectrometer (RVS) in the rest-frame wavelength with unprecedented precision (compare spatial distributions of the DIB carrier with interstellar reddening and find evidence that DIB carriers are present in a local bubble around 1. Introduction

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ABSTRACT

Context. Diffuse interstellar bands (DIBs) are common interstellar absorption features in spectroscopic observations but their origins remain unclear. DIBs play an important role in the life cycle of the interstellar medium (ISM) and can also be used to trace Galactic structure.  

Aims. Here, we demonstrate the capacity of the Gaia-Radial Velocity Spectrometer (RVS) in Gaia DR3 to reveal the spatial distribution of the unknown molecular species responsible for the most prominent DIB at 862 nm in the RVS passband, exploring the Galactic ISM within a few kiloparsecs from the Sun.  

Methods. The DIBs are measured within the GSP-Spec module using a Gaussian profile fit for cool stars and a Gaussian process for hot stars. In addition to the equivalent widths and their uncertainties, Gaia DR3 provides their characteristic central wavelength, width, and quality flags.  

Results. We present an extensive sample of 476,117 individual DIB measurements obtained in a homogeneous way covering the entire sky. We compare spatial distributions of the DIB carrier with interstellar reddening and find evidence that DIB carriers are present in a local bubble around the Sun which contains nearly no dust. We characterised the DIB equivalent width with a local density of 0.19 ± 0.04 Å/kpc and a scale height of 98.60±11.10 pc. The latter is smaller than the dust scale height, indicating that DIBs are more concentrated towards the Galactic plane. We determine the rest-frame wavelength with unprecedented precision (λ0 = 8620.86 ± 0.019 Å in air) and reveal a remarkable correspondence between the DIB velocities and the CO gas velocities, suggesting that the 862 nm DIB carrier is related to macro-molecules.  

Conclusions. We demonstrate the unique capacity of Gaia to trace the spatial structure of the Galactic ISM using the 862 nm DIB.

Key words. ISM: lines and bands. ISM: kinematics and dynamics. dust, extinction

1. Introduction

Diffuse interstellar bands (DIBs) are interstellar absorption features that primarily exist in the optical and near-infrared (NIR) wavelength range, the physical origin of which is still debated. The name was formally given by Merrill [1930], where ‘diffuse’ refers to the fact that their profiles are broader than those of interstellar atomic lines (e.g. NaI lines). DIBs presumably originate from molecular absorption, which is supported by the fact that their central wavelength does not match any known atomic transition lines. The fine structure observed in some DIBs also suggests that the molecular carriers are probably in the gas phase. For reviews on DIBs, see Leger & Puget [1984], Herbig [1995], Sarre [2006], and Snow & McCall [2006].

Nowadays, molecules are strongly suggested to be associated with the DIB carrier, because DIB profiles are usually much broader than atomic lines and contain substructures even through single-cloud sight lines (e.g. Sarre et al. 1995, Cami et al. 1997, Kerr et al. 1998, Galazutdinov et al. 2008). Carbon-bearing molecules are the most favoured species in this respect as carbon can form many stable compounds and is relatively abundant in the Universe (Puget & Leger 1989).  

The DIB at 862 nm (hereafter referred to as DIBJ862) is a strong band, but was not identified until 1975 (Geary 1975).
more than 50 years after the discovery of the first DIBs, because the wavelength range beyond 8600 Å was not covered by earlier work. The DIB \( \lambda 862 \) was confirmed by Sanner et al. (1978), who further reported \( \lambda 8620.7 \pm 0.3 \) Å and a tight linear correlation between the DIB equivalent width (EW862) and the colour excess, that is \( E(\lambda - V) = 2.85 \pm 0.11 \times EW_{862} \) (coefficient calculated by Kos et al. 2013), Munari (1999) and Munari (2000) made preliminary studies of the relation between the EW862 of DIB and interstellar extinction. This author found a surprisingly tight correlation with \( E(\lambda - V)/EW_{862} = 2.63 \) (Munari 1999) and 2.69 ± 0.03 (Munari 2000), respectively. Therefore, the DIB \( \lambda 862 \) was suggested to be a tracer of Galactic extinction in the context of the Gaia mission, while Krewolski (2018) and Krewolski et al. (2019) argued that \( E(\lambda - V)/EW_{862} \) can vary depending on the line of sight. Munari et al. (2008) measured the DIB \( \lambda 862 \) in the spectra of 68 early-type stars observed by the RAdial Velocity Experiment (RAVE; Steinmetz et al. 2006) and derived a very good correlation between \( EW_{862} \) and \( E(\lambda - V)/EW_{862} = 2.72 \pm 0.03 \). These results, as well as those of Munari (1999) and Munari (2000), were all consistent with each other, but none agreed with those of Wallerstein et al. (2007), who derived a much higher ratio of \( E(\lambda - V)/EW_{862} \).

Munari et al. (2008) determined the rest-frame wavelength of DIB \( \lambda 862 \) as \( \lambda 8620 \pm 0.1 \) Å based on the assumption that the average velocity of their carriers towards the Galactic center is approximately zero, as derived from the interstellar-medium (ISM) radial-velocity map of Brand & Blitz (1993).

To make use of the vast number of cool-star (5000 ≤ \( T_{\text{eff}} \) ≤ 7000 K) spectra in RAVE, Kos et al. (2013) implemented a data-driven method to derive the EW862 of interstellar spectra using real spectra at high Galactic latitudes (\( b < -65^\circ \)) and furthermore stacked spectra in small spatial volumes to increase the signal-to-noise ratio (S/N) and measure EW862 with high precision. In this way, they confirmed the linear EW862−\( E(\lambda - V) \) correlation in a statistical way.

Based on measurements with a large number of RAVE spectra, Kos et al. (2014) built the first projected DIB \( \lambda 862 \) intensity map, mainly within 3 kpc from the Sun, where for the first time the large-scale structure of the distribution of the DIB \( \lambda 862 \) carrier was shown. The findings of these authors further suggested an exponential distribution of EW862 in the direction perpendicular to the Galactic plane with a scale height of 209 ± 11.99 pc, larger than the scale height of 117.7 ± 4.7 pc for the dust derived by their \( \Delta V \) map. Puspitarini et al. (2015) measured the DIB \( \lambda 862 \) in the spectra of 64 late-type stars from the Gaia–ESO (GES) survey (Gilmore et al. 2012) towards a Galactic anticentre region at \((t, b) = (212.9^\circ, -2.0^\circ)\). Puspitarini et al. (2015) fitted the observed spectra with synthetic spectra containing stellar components, telluric transmissions, and a DIB empirical profile. For DIB \( \lambda 862 \), they obtained the empirical model by averaging the profiles detected in several spectra based on the data analysis reported by Chen et al. (2013).

Similar to Puspitarini et al. (2015), Krewolski et al. (2019) also argued that a simple Gaussian fit was not enough to describe the irregular profile of the DIB \( \lambda 862 \). They therefore used the observation towards BD + 40 4220, a heavily reddened and rapidly rotating star, as a template for the profile of \( \lambda 862 \). Measurements of other targets were obtained by rescaling the depth of the template to match the observed band profiles.

Using this method, Krewolski et al. (2019) measured 56 high-resolution spectra \((R > 30000)\) and derived a ratio of \( E(\lambda - V)/EW_{862} = 2.03 ± 0.15 \) with an offset of 0.22, which was close to the result of Puspitarini et al. (2015), Maíz Apellániz (2015) showed a linear relation between EW862 and the colour excess \( E(4405 - 5495) \) up to \( T_{\text{eff}} \sim 6 \text{ mag} \) with a Pearson coefficient of \( r_p = 0.878 \). All previous studies suggested a linear relation between EW862 and extinction except Damineli et al. (2016), who reported a quadratic relation based on the observations of 12 bright field stars and 11 members of Westerlund 1 cluster. Their relation is in good agreement with those found by Wallerstein et al. (2007) and Munari et al. (2008) for EW862 < 0.8 Å.

In this paper, we discuss the DIB \( \lambda 862 \) measurements of nearly half a million DIBs measured by the RVS spectrometer. This is, by one order of magnitude, the largest sample of individual DIB measurements with full sky-coverage to be obtained so far.

In Sect. 2, we discuss the DIB \( \lambda 862 \) sample. In Sect. 3, we define our high-quality sample and in Sect. 4, we validate the DIB \( \lambda 862 \) measurements in the HR diagram. In Sect. 5, we show the correlation with the dust extinction and in Sect. 6, we present our analysis of the spatial distribution of the DIBs \( \lambda 862 \). In Sect. 7, we describe how we determined the rest-frame wavelength of DIB \( \lambda 862 \), and in Sect. 8, we look briefly at an application to kinematic studies. We conclude in Sect. 9.

### 2. Description of the sample of diffuse interstellar bands

This work makes use of the DIB \( \lambda 862 \) parameterisation derived from the Gaia RVS spectra using the General Stellar Parameteriser spectroscopy (GSP-Spec, Recio-Blanco et al. 2022) module and made available through the astrophysical parameters table of the Gaia third data release (DR3). We note that the RVS wavelength range is \([845, 870] \text{ nm}\) (Sartoretti et al. 2018), and its medium resolving power is \( R = \lambda/\Delta \lambda \sim 11500 \) (Cropper et al. 2018). In addition to the DIB \( \lambda 862 \) parameterisation, GSP-Spec estimates the main atmospheric parameters and the individual abundances of 12 different chemical elements from Gaia RVS spectra of single stars. When necessary (e.g. stars with \( T_{\text{eff}} < 7000 \text{ K} \)), the DIB \( \lambda 862 \) spectral parameterisation is based on the MatisseGauin GSP-Spec workflow. More details on the DIB \( \lambda 862 \) measurement algorithms can be found in Zhao et al. (2021a). A GSP-Spec catalogue flag was implemented (Recio-Blanco et al. 2022) during the post-processing with a chain of 41 digits including all the adopted failure criteria and uncertainty sources considered during the post-processing. In this chain, value ‘0’ is the best, and ‘9’ is the worst, generally implying the parameter masking. For our purposes, we use only the first 13 characters (see Sect. 3 Table 2).

We performed a local renormalisation of the spectrum around the DIB \( \lambda 862 \) feature (35 Å wide around its central wavelength) for each Gaia-RVS spectrum. We carried out a preliminary fit using a preliminary detection of the DIB \( \lambda 862 \) profile and sources where noise is at the level of or exceeds the depth of the DIB \( \lambda 862 \) feature were eliminated. Only detections above the 3σ-level are considered as true detections. In order to perform the main fitting process of the DIB \( \lambda 862 \), our sample is separated into cool \((3500 < T_{\text{eff}} \leq 7000 \text{ K})\) and hot \((T_{\text{eff}} > 7000 \text{ K})\) stars. For cool stars, we divided the observed spectrum by the best matching synthetic spectrum from GSP-Spec (corresponding to the derived atmospheric parameters), and fitted the DIB \( \lambda 862 \)
The measured central wavelength, mean function (Eq. 1) with the strategy of Kos (2017) and used exponential-squared kernel models for the stellar absorption lines:

\[ f_0(\lambda, p_0, p_1, p_2) = p_0 \times \exp \left( -\frac{(\lambda - p_1)^2}{2p_2^2} \right) + C, \]  

where \( p_0 \) and \( p_2 \) are the depth and width of the DIB profile, \( p_1 \) is the measured central wavelength, \( C \) is the constant continuum, and \( \lambda \) is the spectral wavelength.

For hot stars, we applied a Gaussian process similar to [Kos (2017)] in which the DIB .862 profile is fitted by a Gaussian process regression [Gerschman & Blei (2012)]. In order to extract the information of the DIB feature, we applied a Gaussian mean function (Eq. [1]) with \( C = 1 \). For the kernels, we followed the strategy of [Kos (2017)] and used exponential-squared kernel models for the stellar absorption lines:

\[ k_{\mu}(x, x') = \alpha \exp \left( -\frac{|x - x'|^2}{2\nu^2} \right), \]  

and a Matérn 3/2 kernel model for the correlated noise:

\[ k_{m3/2}(x, x') = \alpha \left( 1 + \frac{\sqrt{3}|x - x'|}{l} \right) \exp \left( -\frac{\sqrt{3}|x - x'|}{l} \right), \]  

where \( \alpha \) scales the kernels, and \( l \) is the characteristic width of each kernel. We refer to Zhao et al. (2021a) for a more detailed description of this process.

For each of the sources, the EW .862, depth (\( p_0 \)), central wavelength (\( p_1 \)), and width (\( p_2 \)) together with their uncertainties are determined with \( \text{EW}_{862} = \sqrt{2\pi} \times |p_0| \times |p_2| \times C \) where \( C \) is the continuum level and \( p_2 = \text{FWHM}/(2 \sqrt{2\ln(2)}) \), where FWHM is the full width at half maximum of the DIB .862 profile.

We consider two main uncertainties on the derived EW: the random noise error (\( \sigma_{\text{noise}}^2 \)), which is related to the signal-to-noise ratio (S/N) of the spectrum, and the mismatch between the observed spectrum and the synthetic one (\( \sigma_{\text{spec}}^2 \)). \( \sigma_{\text{noise}}^2 \) was estimated for different DIB profiles using a random-noise simulation (see Sect. 2.6 in Zhao et al. [2021a] for more details). The total uncertainty of the EW is considered to be \( \sigma_{\text{EW}}^2 = \sigma_{\text{noise}}^2 + \sigma_{\text{spec}}^2 \). We refer to Zhao et al. (2021a) for a more detailed description of the derived uncertainties.

Quality flags (QFs) ranging from QF = 0 (highest quality) to QF = 5 (lowest quality) are generated. The defined values of the QF depend on the parameters \( p_0 \), \( p_1 \), and \( p_2 \), but also on the global noise level \( R_\lambda \) defined by the standard deviation of the data–model residuals between 8605 and 8640 Å as well as the local noise level \( R_\lambda \) within the DIB .862 profile. Table [I] shows the definition of the QF values. For a more detailed description of QF, we refer to Zhao et al. (2021a) and Recio-Blanco et al. (2022). In this paper, we concentrate on a high-quality sample (QF ≤ 2, see Sect. 3) but we stress that the full DIB .862 sample should be scientifically exploited; for example, weak DIBs .862 in low extinction areas.

The full GSP-Spec sample contains 5,591,594 sources. Of these, 476,117 have a valid DIB .862 measurement (5.8%). The number of sources for each QF is specified in Tab. [I].

Figure [I] shows the distribution on the sky of the DIB .862 measurements at a resolution of 1.8° (HEALPix map with level 5). As expected, the DIBs .862 are concentrated towards the Galactic plane which is even more pronounced for the high-quality DIBs .862 (right panel).
case for the high quality (HQ) DIB $\lambda 862$ measurements ($QF \leq 2$, see Sect. 4).

3. Definition of the high-quality sample

Figure 3 displays the GSP-Spec Kiel diagram of a subsample with $QF < 5$ as a function of the fractional uncertainty of the $EW_{862}$. The vast majority of our sources show typical uncertainties below 20%. However, on the red giant branch (RGB) sequence, the cooler stars (which are in general metal-richer) show larger uncertainties compared to the hotter ones. This can be explained by the fact that for cooler metal-rich stars, in general, we see a poorer agreement between the observed and the synthetic spectra due to the presence of molecular bands. This is also revealed by the larger log $\chi^2$ values from GSP-spec.

We also notice higher uncertainties for hot dwarf stars in the range $7000 < T_{\text{eff}} < 8000$ K. The majority of those stars are classified as very metal-poor with $[M/H] < -3$ dex by GSP-Spec. They further exhibit very large vsini values from ESP-HS (Extended Stellar Parametrizer for Hot Stars; see Sect. 5.3). In addition to the parameter degeneracy between $T_{\text{eff}}$ and $[M/H]$ for high-temperature stars, these objects present large vsini values, which are not taken into account in the present GSP-Spec parameterisation, inducing parameter biases (c.f. Recio-Blanco et al. 2020). Applying the specifically defined GSP-Spec flags (see Tab. 2) removes the majority of these stars.

Figure 4 shows the distribution of the fractional uncertainties ($err(EW_{862})/EW_{862}$) with $QF < 5$. A clear bimodal distribution is apparent that is related to cool stars ($T_{\text{eff}} < 4500$ K) with relatively weak DIBs $\lambda 862$ ($< 0.2$ Å) and a mismatch between the observed and the synthetic spectrum. We decided to reject sources with uncertainties larger than 35%. In addition, we decided to neglect DIB $\lambda 862$ measurements outside the wavelength interval $8620 < C_{\text{obs}} < 8626$ Å — where $C_{\text{obs}}$ is the measured central wavelength in the heliocentric frame with $C_{\text{obs}} = p_1 + v_{\text{rad}}/c$ where $v_{\text{rad}}$ is the stellar radial velocity and $c$ the velocity of light— because the majority of those are weak DIBs $\lambda 862$, where the determination of the $p_1$ parameter could be corrupted and lead to high, unrealistic velocities. We stress that $p_1$ and $C_{\text{obs}}$ are reported in the vacuum.

Our HQ sample is defined based on the criteria specified in Tab. 2 which comprises 141 103 objects. For a detailed explanation of the GSP-spec flag we refer here to Recio-Blanco et al. (2022).

4. The Kiel diagram

Figure 5 shows the Kiel diagram colour-coded as a function of the $EW_{862}$ (left panel), the corresponding Gaia distances from Gaia EDR3 (middle panel, Bailer-Jones et al. 2021), and the DIB $\lambda 862$ width ($p_2$). The very similar trend in these diagrams is striking, and indicates a clear relation between the $EW_{862}$ of the DIB $\lambda 862$ carrier and its distance, that is stars with larger distances show larger $EW_{862}$. This is to be expected: As an interstellar feature, the DIB $\lambda 862$ profile measured in the spectrum of a background star is the result of an integration of the DIB $\lambda 862$ carrier between the observer and the star. DIB $\lambda 862$ strength and dust extinction increase along the line of sight, and so both of them correlate with the distance and therefore also with each other. Also, we note that the distance of the background star is only an upper limit to the true distance of the DIB $\lambda 862$ carrier clouds along the line of sight (Zasowski et al. 2015). As shown by Zhao et al. (2021b), direct measurements of the DIB $\lambda 862$
carrier clouds can be obtained using kinematic distances. This method will be further investigated in another paper.

The right panel of Fig. 5 shows how the measured width of the DIB $\lambda 862$ increases with decreasing surface gravity; that is, we see that widths in giants are generally larger than in dwarfs. One may also conclude that the widths of DIB $\lambda 862$ absorptions increase with distance, and explain this as a consequence of a superposition of an increasing number of clouds at slightly different radial velocities which accumulate along the line of sight. However, we also see DIB $\lambda 862$ with large widths for close-by stars with $T_{\text{eff}} < 5000$ K and log $g > 3$. This could be a consequence of spectral mismatches between observed spectra and the templates we use. These systematic trends will be investigated in a future work, but for now we stress that the measured widths of the DIB $\lambda 862$ should be interpreted with caution.

From Fig. 5 we see that stars with $5000 < T_{\text{eff}} < 7000$ K and log $g < 2.5$ have strong DIBs $\lambda 862$. These massive stars lie at distances of between 2 and 4 kpc and most of them are located in the closest spiral arms (e.g. Sagittarius/Carina, Local and Perseus arms). This is in perfect agreement with the findings of Recio-Blanco et al. (2022), who clearly identified those objects in their GSP-Spec Kiel diagram as massive stars that are tracers of the spiral arm structure, in agreement with the spatial maps derived from Poggio et al. (2021). The DIB $\lambda 862$ measurements can therefore be considered as an excellent tracer of spiral arm structures.

In contrast, our HQ sample lacks hot dwarf stars in the temperature range $7000 < T_{\text{eff}} < 8000$ K and $4.0 < \log g < 4.5$ because their EW$_{862}$ uncertainties are too high due to their high $v_{\text{sin}i}$ and therefore large uncertainties in their stellar parameters (see Sect. 5). A specific treatment of those stars is necessary but is beyond the scope of this work.

### Table 2. Definition of our high-quality sample

| QF                  | $\leq 2$ | $\leq 0.35$ |
|---------------------|---------|-------------|
| $\text{err(EW}_{862}/\text{EW}_{862}$ | 8620 – 8626 Å |             |
| GSP-Specflag(vbroadT) | $\leq 1$ |             |
| GSP-Specflag(vbroadG) | $\leq 1$ |             |
| GSP-Specflag(vbroadM) | $\leq 1$ |             |
| GSP-Specflag(vradT)  | $\leq 1$ |             |
| GSP-Specflag(vradG)  | $\leq 1$ |             |
| GSP-Specflag(vradM)  | $\leq 1$ |             |
| GSP-Specflag(fluxNoise) | $\leq 1$ |             |
| GSP-Specflag(extrapol) | $\leq 1$ |             |
| GSP-Specflag(negFlux) | $\leq 1$ |             |
| GSP-Specflag(nanFlux) | $\leq 1$ |             |
| GSP-Specflag(emission) | $\leq 1$ |             |
| GSP-Specflag(nullFluxErr) | $\leq 1$ |             |
| GSP-Specflag(KMgiantPar) | $\leq 1$ |             |

5. Correlation with dust extinction

As mentioned in Sect. 1, the DIB $\lambda 862$ shows a strong correlation with measurements of interstellar reddening such as E(B − V) (e.g. Munari et al. 2008, Wallerstein et al. 2007, Kos et al. 2013). Here, we use the interstellar reddening E(BP − RP) derived from GSP-Phot as our main dust extinction tracer for individual objects. GSP-Phot provides a detailed characterisation of single stars based on their BP/RP spectra, including stellar parameters ($T_{\text{eff}}, \log g, [\text{M/H}]$) and extinction $A_0$. We refer to Andrei (2022) for a detailed description of the GSP-Phot module. Due to the extensive filtering in GSP-Phot, only 66 144 stars in our sample have E(BP − RP) measurements from GSP-Phot. Figure 6 compares the distribution on the sky of the median EW$_{862}$ of the DIB $\lambda 862$ with the median E(BP − RP). Overall, we see similarities between these two maps, with both showing larger values in the Galactic plane. Nevertheless, we also see some differences: (i) The DIBs $\lambda 862$ seem to be generally more concentrated towards the galactic plane compared to the interstellar dust (see also Sect. 6.2). (ii) In the inner Galaxy ($|l| < 30^\circ$),
DIBs $\lambda 862$ show a larger scale height compared to the interstellar dust. (iii) We notice at around $\ell \sim 30^\circ$ a low average EW$_{862}$ of the DIB $\lambda 862$ compared to the high amount of dust. This region covers several highly massive star forming regions which were recently surveyed by the GLOSTAR Galactic plane survey in the frequency range between 4 and 8 GHz (Brunthaler et al. 2021).

**Fig. 6.** Comparison between the median EW$_{862}$ of the DIB $\lambda 862$ (upper panel), the median E(BP − RP) (middle panel), and the ratio EW$_{862}$/E(BP − RP) (lower panel) at HEALPix level 5 in the Mollweide projection.
E(BP − RP) might be related to the reduction of the radiation field in the surface layers (‘skin’) of the clouds and that the carrier depletion depends on cloud opacity. Adamson et al. (1998) observed this effect with the NIR DIB, something that was later confirmed by Elyajouri & Lallement (2019) for the APOGEE DIB in the dense cores of the Taurus, Orion, and Cepheus clouds. We do not see this effect in our sample, which could be due to a selection effect in the sense that the Gaia RVS selection function does not trace the most extinguished regions.

5.2. EW_{862} versus E(B − V)

E(B − V) is the most frequently used reddening indicator to study the correlation with DIB strength, especially in early works. To compare our DIB–extinction relation to literature values, we derived the E(B − V)/EW_{862} coefficients from three dust extinction maps: Planck Collaboration et al. (2016), Schlegel et al. (1998), and Green et al. (2019). We calculated E(B − V) from the three maps using the Python package dustmap (Green 2018).

Planck Collaboration et al. (2016) produced a full-sky two-dimensional extinction map using a generalised wavelet method to separate out Galactic dust emission from cosmic infrared background anisotropies. Such E(B − V) values are asymptotic values and therefore represent overestimations for many of our objects (see Fig. 5(b)). This also applies to Schlegel et al. (1998) (Fig. 8(c)). Nonetheless, E(B − V) derived from both of these maps for our objects present linear relations with EW_{862} with very high Pearson coefficients. For both Planck Collaboration et al. (2019) and Schlegel et al. (1998), we limit their E(B − V) to values smaller than 2.6 mag and get 121 627 and 123 175 individual measurements, respectively. We make use of 55 252 available E(B − V) values from Gaia-DPOT with a temperature difference between GSP-Spec and GSP-Phot of smaller than 5000 K. Limited by the sky coverage, only 93 247 objects have E(B − V) from Green et al. (2019), a three-dimensional dust reddening map inferred from 800 million stars with Pan–STARRS1 and 2MASS photometry. Based on Schlafly & Finkbeiner (2011), we apply a recalibration factor of 0.884 for E(B − V) from Schlegel et al. (1998). We also use this factor to convert the reddening unit of Green et al. (2019) to E(B − V). We note that the three-dimensional nature of the dust reddening maps from GSP-Phot (Fig. 8a) and from Green et al. (2019) (Fig. 8d) negates the problem of overestimated E(B − V) values. Table 3 lists the E(B − V)/EW_{862} coefficients and intercepts derived in this work together with values from the literature.

Figure 8 shows the correlation between EW_{862} and E(B − V) as well as their corresponding linear fits. We notice a large variation in the derived E(B − V)/EW_{862}, which is due to the use of different methods for extinction calculation, with a very high value of 4.128 ± 0.062 from Planck Collaboration et al. (2016) and a low value of 2.198 ± 0.066 from Green et al. (2019). It is not surprising that different works report different values for the ratio of E(B − V)/EW_{862}, depending on the sightlines studied and the techniques applied for DIB and extinction measurements. The high coefficients with E(B − V) from Schlegel et al. (1998) and Planck Collaboration et al. (2016) imply that extinction measured from infrared emission is not only overestimated in some regions but presents systematic differences (larger values) compared to the values calculated using other methods.

5.3. Hot stars

In addition to the results obtained by GSP-Phot and GSP-Spec, the Apsis pipeline also contains the ESP-HS (Extended Stel-
The module, their stellar extinction ($A_{\alpha}$), O-, B-, and A-type stars, including an estimate of the interstellar extinction ($A_{\alpha}$), and reddening $E(B - V)$ derived from different extinction maps: (a) GSP-Phot, (b) Planck Collaboration et al. [2016], (c) Schlegel et al. [1998], and (d) Green et al. [2019]. The colours in each panel show the target number per 0.01 Å×0.02 mag bin. The colour bar is the same as in Fig. 7. The red circles are the median values taken in EW$_{862}$ bins from 0 to 0.5 Å with a step of 0.05 Å. The red lines are linear fits to the red dots in each panel, respectively. The fitting gradients ($\alpha$) and their uncertainties are indicated. They are also listed in Table 3. The orange and violet dashed lines in (b) and (c) are the fit results to GSP-Phot and Green et al. [2019], respectively.

Fig. 8. Correlations between EW$_{862}$ and $E(B - V)$ derived from different extinction maps: (a) GSP-Phot, (b) Planck Collaboration et al. [2016], (c) Schlegel et al. [1998], and (d) Green et al. [2019]. The colours in each panel show the target number per 0.01 Å×0.02 mag bin. The colour bar is the same as in Fig. 7. The red circles are the median values taken in EW$_{862}$ bins from 0 to 0.5 Å with a step of 0.05 Å. The red lines are linear fits to the red dots in each panel, respectively. The fitting gradients ($\alpha$) and their uncertainties are indicated. They are also listed in Table 3. The orange and violet dashed lines in (b) and (c) are the fit results to GSP-Phot and Green et al. [2019], respectively.

The hottest stars (labelled 1-3 in Fig. 9) are targets cooler than 7500 K (according to GSP-Spec), and those that were treated with non-adapted synthetic spectra by ESP-HS. Outlier ‘7’ is known from Simbad (Wenger et al. 2000a) to exhibit emission. On the other hand, the H$\alpha$ pseudo-EW provided by the ESP-ELS module is positive (i.e. no significant emission is found in H$\alpha$ from the BP/RP spectrum), and its RVS spectrum appears normal. It therefore remains unclear as to why the derived APs (which include the extinction) do not provide a correct fit to the data. Outlier ‘6’ has a very peculiar RVS spectrum belonging to an extreme He star (FQ Aqr). Outliers ‘4’, ‘5’, and ‘8’ show good agreement between observed and RVS fitted spectra.

A similar trend is observed in the GSP-Phot vs. GSP-Spec data, and plotted in the lower panels of Fig. 9. In the middle panel, the selection is solely based on the effective temperature provided by GSP-Spec. Targets with a DIB EW$_{862}$ of greater than 0.5 Å are identified and numbered (Table A.1). With the exception of the star labelled ‘6’, which shows an RVS spectrum typical for an early-B or late-O star, all the stars have spectral features usually seen in M or late-K-type stars (which is con-
Table 3. Coefficients and intercepts of the linear relations between DIB \(\lambda 862\) and \(E(B - V)\) derived in the literature and this work.

| Works                  | \(E(B - V)/EW_{862}\) (mag \(\AA^{-1}\)) | Intercept |
|------------------------|-------------------------------------------|-----------|
| This work              | \(3.016 \pm 0.047\)                      | 0.023 \(\pm 0.013\) |
|                        | \(4.128 \pm 0.068\)                      | 0.021 \(\pm 0.019\) |
|                        | \(4.031 \pm 0.069\)                      | \(-0.013 \pm 0.017\) |
|                        | \(2.198 \pm 0.066\)                      | \(-0.004 \pm 0.019\) |
| Sanner et al. (1978)   | 2.85 \(\pm 0.11\)                       | –         |
| Munari et al. (2008)   | 2.72 \(\pm 0.03\)                       | –         |
| Wallerstein et al. (2007)| 4.61 \(\pm 0.56\)           | –         |
| Kos et al. (2013)      | 2.49 \(\pm 0.23\)                       | 0.028 \(\pm 0.002\) |
| Puspitarini et al. (2015)| 2.12                                    | –         |
| Kreichowsky et al. (2019)| 2.03 \(\pm 0.15\)          | 0.22 \(\pm 0.05\) |
| Zhao et al. (2021B)    | 3.460 \(\pm 0.313\)                     | \(-0.015 \pm 0.006\) |

Notes.

\((a)\) \(E(B - V)\) from GSP-Phot
\((b)\) \(E(B - V)\) from Planck Collaboration et al. (2016)
\((c)\) \(E(B - V)\) from Schlegel et al. (1998)
\((d)\) \(E(B - V)\) from Green et al. (2019)
\((e)\) Calculated by Kos et al. (2013)
\((f)\) Estimated by their Fig. 7.

firmed by Simbad in two cases; in the other ones no additional information was found). Therefore, these are confirmed outliers, and to consistently (e.g. between the two GSP modules) remove those points, we performed a second selection based on the \(T_{\text{eff}}\) derived by both modules (\(T_{\text{eff}} > 7000\) K). This last selection is plotted in the lower panel of Fig. 9 and provides a \(\text{PCC} = 0.77\). The first selection attempt (middle panel) provides a median \(E(BP - RP)\) versus \(EW_{862}\) that is slightly lower than the relation obtained for the cooler stars (represented by the broken blue line), while the first and third ones are in fair agreement with this latter. The sample combination of the ESP-HS and GSP-Pot/GSP-Spec (Fig. 9 lower panel) selections provides 1 804 hot stars.

5.4. Comparison with the TGE dust map

The total galactic extinction (TGE) map is a full-sky 2D representation of the foreground extinction from the Milky Way towards extragalactic sources, which is constructed from selected sources at large distances beyond the Galactic disk. To derive this map, distant giants were selected in order to obtain a set of stars situated beyond the dust layer of the disk of the Galaxy. The median of extinctions derived by GSP-Pot was then used to assign an extinction value for each HEALPix at different levels. For further details on the TGE maps, see Delchambre (2022).

In the following, we use the HQ DIB sample as defined in Sect. 3. In order to compare the \(EW_{862}\) of the DIB \(\lambda 862\) to the TGE map, it is first necessary to construct a HEALPix map of the \(EW_{862}\) in the same way as for the TGE map. We selected the DIB \(\lambda 862\) HEALPix measurements based on their Galactic altitude (|\(l| > 300\) pc) and then calculated the median \(EW_{862}\) in each HEALPix. Only HEALPix with more than one DIB \(\lambda 862\) measurement were retained.

The resulting DIB \(EW_{862}\) HEALPix map is shown at level 5 in Fig. 10 (top left panel). We note that, due to our selection of DIB \(\lambda 862\) sources, this figure is not the same as the top panel of Figure 6. Also shown in the top right panel of Fig. 10 is the TGE map at level 5, where the value of a level-5 superpixel is the mean of the four level-6 pixels. Any level-5 HEALPix containing at least one level-6 HEALPix with insufficient tracers (less than three) is flagged as having no data. The lower left panel of Fig. 10 shows the resulting skymap of the \(EW_{862}/A_0\) ratio, and the lower right panel shows a scatter plot of \(EW_{862}\) as a function of TGE \(A_0\). Although the DIB \(\lambda 862\) map does not cover the entire sky (due to a lack of sufficient tracers), the two maps trace the same large-scale structures across the sky. The ratio of the two values is fairly constant from low to mid Galactic latitudes, but large fluctuations are seen at higher latitudes where the number of tracers drops considerably. The scatter plot shows good correlation between the two values up to an \(A_0\) of 1.5 mag, after which the \(EW_{862}\) rises more slowly than the TGE \(A_0\). This is a consequence of the fact that \(A_0\) traces asymptotic values of extinction which (in the highly extinct regions) may occur beyond the distance of stars observed in DIB \(\lambda 862\) measurements. A straight line fit to the scatter plot (broken line) below 1.5 mag results in a slope of 0.07 and an intercept of 0.03.
6. Spatial distribution of the DIB \( \lambda 862 \)

Figure 11 shows a full sky map of the median values of the integrated \( \text{EW}_{862} \) of the DIB \( \lambda 862 \) for the whole HQ sample, taken from 0.1 kpc \times 0.1 kpc bins in XY, XZ, and YZ planes, respectively. Stellar photogeometric distances are those from Bailer-Jones et al. (2021). The overall distribution is similar to the pseudo-3D map (Kos et al. 2014) from RAVE data (Steinmetz et al. 2020), although a larger number of sight lines and coverage over the whole sky with Gaia DR3 allow us to draw more specific conclusions.

First, we note that \( \text{EW}_{862} \) increases with distance. This is expected, but it is a nice validation of our results, as this increase was not assumed when measurements of the DIB \( \lambda 862 \) were made. The two cross-sections perpendicular to the Galactic plane in Fig. 11 show that DIBs \( \lambda 862 \) carriers are largely confined to the Galactic plane, as expected. We note that the regions with strong DIBs \( \lambda 862 \) in two directions away from the plane (seen in the YZ cross-section) start locally and do not increase in intensity with distance. They therefore originate in clouds of DIBs \( \lambda 862 \) carriers which reside close to the Sun and cause DIB \( \lambda 862 \) absorption in spectra of all stars located behind them.

The XY panel of Fig. 11 suggests that stars within spiral arms generally show stronger \( \text{EW}_{862} \) of the DIB \( \lambda 862 \) carriers. This is true for the Scutum–Centaurus arm and for the Perseus arm. Our map lacks the reach needed to claim the same for the Outer arm, though an increase of DIB \( \lambda 862 \) intensity at a distance of \( \sim 4 \) kpc in the Galactic antecentre direction agrees with this conjecture. The situation for the Local arm and the Sagittarius–Carina arm is more complicated: a region with strong DIBs \( \lambda 862 \) at \( \ell \approx 60^\circ \) coincides with the spur between these two arms (indicated by the blue line in Fig. 11). However, there is also an indication of a region of strong DIBs \( \lambda 862 \) in the opposite direction, at \( \ell \approx 270^\circ \). This may indicate that DIBs \( \lambda 862 \) fill in the region between the Sagittarius–Carina and Local arms, with the exception of a large void around the Solar position. However, we note that we do not claim the DIB carrier clouds are seen to reside within the spiral arms, as the presence of the Local Bubble around the Sun amplifies a general rise of \( \text{EW} \) with distance in any direction along the Galactic plane. A detailed investigation of the spatial distribution of DIB carriers is beyond the scope of this paper and will be discussed in Zhao et al. (in preparation).

Figure 12 compares the spatial distribution of DIB \( \lambda 862 \) and dust absorptions. We note that only 40% of the DIB \( \lambda 862 \) sample has valid \( \text{E}(\text{BP} - \text{RP}) \) measurements due to a strong quality filtering in GSP-Phot. The comparison therefore only refers to 55,080 sources in common and not to the whole DIB \( \lambda 862 \) HQ sample shown in Fig. 11. The top panels show the distribution of the colour excess, and the bottom panel is the ratio between \( \text{EW}_{862} \) and \( \text{E}(\text{BP} - \text{RP}) \) with a subtracted linear fit from Fig. 7.

Two important results of Figs. 11 and 12 are that the spatial distribution of DIB \( \lambda 862 \) carriers and dust are qualitatively similar, but their ratio shows a pronounced lack of dust absorption for nearby sight lines. The red regions in the bottom panels of Fig. 12 demonstrate that the local bubble around the Sun which contains very little dust does not have a similar low
density of DIB $\lambda$862 carriers. This is confirmed with a median EW$_{862}$ ~ 0.1 Å within the inner 150 pc from the Sun. To investigate the situation further, Fig. [13] shows a zoom into the $4 \times 4 \times 0.6$ kpc rectangular box centred on the Sun for stars that have valid EW$_{862}$ and E(BP − RP) measurements. In addition, the positions of the nearby molecular clouds from Zucker et al. (2020) are indicated by dots: black for clouds within 100 pc from the plane and red for those at heights between 100 and 300 pc. It is encouraging to see that molecular clouds at low Galactic heights are indeed at the head of strong DIB $\lambda$862 directions and dust absorptions in the XY plane. This suggests that the light from behind stars passes through these clouds of simple molecules, dust, and DIB $\lambda$862 carriers and so their volume-filling factor is large enough for this to happen. Similarly, molecular clouds at larger distances from the Galactic plane (red dots) seem to correspond to directions of enhanced dust absorption and DIB $\lambda$862 presence away from the plane.

We note that Figs. [11] and [12] are based on the assumption of a Gaussian profile for the DIB carrier. The profile of the DIB may be more complicated or may vary in shape; in some cases one may expect a superposition of absorptions originating in multiple clouds along the line of sight, but the EW$_{862}$ values we derive are not affected significantly, as long as the radial velocities of the DIB carriers and profile variations are small compared to the width of the profile in our spectra with a moderate resolving power. The EWs we derive are always small, and so we are in a linear regime where the total value is a simple sum of individual absorptions. In addition, the departures from the Gaussian profile caused by the superposition effect have been shown to be insignificant for DIB $\lambda$862 by comparing the fitted EW with the integrated EW (Kos et al. 2013) and EW calculated from an asymmetric Gaussian function (Zhao et al. 2021a).

Due to the large catalogue of DIB $\lambda$862, and the better sampling for different sightlines, we can trace the spatial variation of EW$_{862}$/E(BP − RP) (bottom in Fig. [12]) which can be used as a tracer to reveal the local physical conditions; as in the work of Vos et al. (2011) for the Scorpius OB2 association. The ultimate goal would be to compare the densities of dust and DIB $\lambda$862 carrier derived by extinction and EW, respectively. A series of works carried out such a comparison for the dust (e.g. Capitanio et al. 2017; Rezaei Kh. et al. 2018; Lallement et al. 2014, 2019; Rezaei Kh. et al. 2020). No attempt has been made so far for DIB $\lambda$862.

A detailed analysis of the spatial co-location of molecular clouds and clouds of DIB $\lambda$862 carriers and interstellar dust, together with a study of their spatial filling factors, is beyond the scope of this paper and will be explored in the future.
Fig. 12. Same as Fig. [11] but for $E(BP - RP)$ from GSP-Phot (upper panel), and the ratio of $EW_{862}/E(BP - RP)$ (lower panel), subtracting 0.22, the inverse of the linear gradient fitted in Fig. [7]. Only 55,080 sources in the HQ sample with $E(BP - RP)$ measurements are used.
Fig. 13. Same as Fig. 11 but for a subsample containing 39 224 cases with $|X| \leq 2 \, \text{kpc}$, $|Y| \leq 2 \, \text{kpc}$, $|Z| \leq 0.3 \, \text{kpc}$, and valid $E(BP - RP)$. Median $EW_{862}$ are taken from $0.05 \, \text{kpc} \times 0.05 \, \text{kpc}$ bins in XY, XZ, and YZ planes, respectively. Overplotted are nearby MCs measured in Zucker et al. (2020). The MCs with $Z \geq 0.1 \, \text{kpc}$ are indicated as red dots.
6.1. The Local Bubble

Farhang et al. (2019) studied the low-density cavity known as the Local Bubble and found the presence of the DIB carriers at λ5797 and λ5780 in the bubble. Other detailed studies of the local ISM were obtained from Vergely et al. (2001, 2010), Welsh et al. (2010). Figure 14 shows the distribution of the DIB 862 carrier in the inner 300 pc volume with respect to the Sun within 100 pc from the Galactic plane. In the left-hand panel, a clear asymmetry can be seen in the distribution of the DIB 862, which is also seen in other DIB maps in the Local Bubble (see e.g. Farhang et al. 2019, Bailey et al. 2016), while in the inner 100 pc we see a homogeneous distribution of weak DIBs (EW < 0.05 Å).

Figure 14 shows the correlation of the DIB 862 of our sample with the dust extinction derived from E(BP–RP). Here, we see a clear linear relation in this extreme low-extinction region even for very small EW (< 0.05 Å). However, a more detailed discussion of the behaviour of the DIB 862 in the Local Bubble is beyond the scope of this paper.

6.2. Scale height

To characterise the vertical distribution of the carrier of the DIB 862, we assume an exponential model and follow the straightforward method used in Kos et al. (2014). Following this approach, the DIB strength EW 862 and the stellar distance (d) in a narrow latitude slab can be derived as

$$EW_{862} = \int_0^d \rho_0 \exp\left(-\frac{s \sin(|b|)}{z_0}\right)ds + B = A \left[1 - \exp(-d/d_0)\right] + B,$$

where $z_0$ is the scale height, $b$ is the galactic latitude, $d$ is the heliocentric distance, $d_0 = z_0/\sin(|b|)$, $A = \rho_0 z_0/\sin(|b|)$, and $B$ is a small offset of our EW 862 values due to the fact that only sufficiently strong DIBs 862 pass the selection criteria for the HQ sample. So that we can compare the data points at different latitudes, we follow Kos et al. (2014) and first normalise the curves in different latitude bins by fitting parameters ((EW 862 – B)/A).

This normalised EW 862 is then fitted again by Eq. [5] in order to get the scale height $z_0$. We refer to Kos et al. (2014) for more details, especially their Fig. 2.

Kos et al. (2014) applied this method for 20 latitude slabs from $b = -20^\circ$ to $b = 20^\circ$ with a bin size of 2° and obtained $z_0 = 209.0 \pm 11.9$ pc. We only use eight slabs with moderate latitudes ($-12^\circ < b < -4^\circ$ and $4^\circ < b < 12^\circ$) which show exponential saturation, and take median EW 862 in each 0.25 kpc bin from 0 to $d = 3$ kpc. To compare with the result of Kos et al. (2014), we first consider measurements with $240^\circ < l < 330^\circ$ (upper panel in Fig. 15). The normalised EW 862 with $z > 0.4$ kpc show an apparent offset due to the low quality of the fitting at large distances from the Galactic plane. Therefore, we only fit the data points with $|l| < 0.4$ kpc by Eq. [5] and get $z_0 = 133.15 \pm 0.21$ pc, which is a smaller value than that derived by Kos et al. (2014). We note that we do not survey the same sample here and that Kos et al. (2014) had to resort to averaging of DIB 862 measurements from different stars, meaning that their sample may be influenced by systematic errors in distance measurements available in the pre-Gaia era.

Gaia makes an all sky survey of DIBs 862 which is not restricted to the Southern hemisphere and equatorial region, as is the case for RAVE. Using all available lines of sight (lower panel in Fig. 15), the fitted $z_0$ decreases to 98.69 \pm 0.85 pc. The uncertainties are small and may indicate a variation of the DIB 862 scale height on the line of sight. This is consistent with the spatial distribution of the DIBs 862 (see Fig. 6) where we notice, for example, a larger $z_0$ for the inner disc ($l < 30^\circ$). Our derived $z_0$ of the DIB 862 carrier towards all available lines of sight with $4^\circ < |b| < 12^\circ$ is close to the scale height of the carrier of the DIB at 1.527 µm derived by Zasowski et al. (2015) with $z_0 = 108 \pm 8$ pc but is slightly smaller than the scale height of the dust grains as measured by various authors, such as 134.4 \pm 8.5 pc by Drimmel & Spiegel (2001), 125 \pm 17 pc by Marshall et al. (2006), 119 \pm 15 pc by Jones et al. (2011). On the other hand, Li et al. (2018) reported a smaller value of 103 pc while Guo et al. (2021) obtained two $z_0$, 72.7 \pm 2.4 pc and 224.6 \pm 0.7 pc, for a two-disk model. For comparison, dense molecular gas such as CO has a smaller scale height of ~50–70 pc (Sanders et al. 1984).

For stars with $4^\circ < |b| < 12^\circ$, we derive $\rho_0 = 0.19 \pm 0.04$ Å/kpc.
interstellar counterpart, \( \lambda_0 \) can also be statistically determined with the empirical assumption that the radial velocity in the Local Standard of Rest (LSR) towards the Galactic centre (GC) or the Galactic anti-centre (GAC) is almost null (e.g. Munari et al. 2008; Zasowski et al. 2013; Zhao et al. 2021b).

We apply this statistical method for both GC and GAC by selecting targets with \( \Delta \ell < 10^\circ, |b| < 2^\circ, d < 4 \text{ kpc}, Q = 0, \text{err}(\lambda_C) < 1.0 \text{ Å}, \) and valid stellar radial velocities. This provides 1405 stars for GC and 1106 cases for GAC. Figure 16 shows their measured central wavelengths in the heliocentric frame \( (C_{\text{obs}}) \) as a function of the angular distance from GC and GAC, respectively. By the linear fit to the median values in each \( \Delta \ell = 1^\circ \) bin, we get \( C_{\text{obs}} = 8623.10 \pm 0.018 \text{ Å} \) at \( \ell = 0^\circ \) and \( C_{\text{obs}} = 8623.54 \pm 0.019 \text{ Å} \) at \( \ell = 180^\circ \). We stress that these are vacuum wavelengths, which means they are appropriate for Gaia observations. For GAC, \( C_{\text{obs}} \) increases with Galactic longitude, having a slope of \( 23 \pm 3.4 \text{ mÅ deg}^{-1} \), while the longitude trend is flatter toward the GC, with a slope of \( 1.2 \pm 3.1 \text{ mÅ deg}^{-1} \). Fitting with a more constrained longitude region, such as \( \Delta \ell < 2^\circ \), yields very similar intercepts, that is \( C_{\text{obs}} = 8623.10 \pm 0.016 \text{ Å} \) at \( \ell = 0^\circ \) and \( C_{\text{obs}} = 8623.52 \pm 0.023 \text{ Å} \) at \( \ell = 180^\circ \). Nevertheless, both of the slopes toward GC and GAC become larger and much closer to each other: \( 47 \pm 14 \text{ mÅ deg}^{-1} \) for GC and \( 45 \pm 20 \text{ mÅ deg}^{-1} \) for GAC. These slopes are also consistent with the values of \( 57 \pm 8 \text{ mÅ deg}^{-1} \) derived by Zasowski et al. 2015 for the DIB at 1.5273 \( \mu \)m, \( 47 \text{ mÅ deg}^{-1} \) derived from the CO rotation curve (Clemens 1985), and \( 40 \text{ mÅ deg}^{-1} \) derived from the stellar rotation curve (Bovy et al. 2012).

Considering the effect of solar motion, \( \lambda_0 \) in vacuum is derived as \( c/(c-U_0) \times C_{\text{obs}} = 8623.41 \text{ Å} \) for GC, and \( c/(c+U_0) \times C_{\text{obs}} = 8623.23 \text{ Å} \) for GAC, where \( c \) is the speed of the light and \( U_0 = 10.6 \text{ km s}^{-1} \) is the radial solar motion. The difference between them may be caused by non-circular motion of the DIB 1862 carrier about the Galactic centre, which makes the LSR velocity non-zero. We believe this systematic effect is less pronounced in the direction of the GAC, and so we use this value to derive its counterpart wavelength in the air of 8620.86 Å. This number agrees well with our previous result from the Giraffe Inner Bulge Survey (Zoccali et al. 2014) towards the GC (8620.83 Å; Zhao et al. 2021b). The obtained value in this work is slightly larger than the values of 8620.70 \( \pm 0.3 \) Å (Sammer et al. 1978), 8620.75 Å (Herbig & Leka 1991), and 8620.79 Å (Galazutdinov et al. 2000b). The result of Jenniskens & Desert (1994), namely 8621.11 \( \pm 0.34 \) Å, is very close to our result towards GC (8620.03 Å in air). Based on 68 hot stars from RAVE, Munari et al. (2008) measured a mean \( C_{\text{obs}} \) toward GC as 8620.4 \( \pm 0.1 \) Å, corresponding to a \( \lambda_0 = 8620.70 \) Å after the solar-motion correction, which is also smaller than our result. Han et al. (2019) obtained a much smaller \( \lambda_0 = 8620.18 \pm 0.25 \) Å, an average value of 17 for their program spectra, which was measured in the averaged optical-depth profiles and corrected by the interstellar K I line at 7699 Å. The lower quality of their spectra at longer wavelengths and the complex velocity structure of the atomic species could be the cause of the large difference between their results and others (Haoyu, priv. communication).

8. Kinematics of the DIB carrier

Although most of the DIB carriers are unknown, they have been proven to be a powerful tool for ISM tomography and consequently can probe the Galactic structure and interstellar envi-

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**Fig. 15.** Determination of the scale height of the 1862 carrier by the DIB measurements with \( 4^\circ < |b| < 12^\circ \), and upper panel: \( 240^\circ < \ell < 330^\circ \); lower panel: toward all available longitude directions, respectively. The data points at different latitude slabs are coloured according to the central latitude values \( (b_0). \) The dashed green line indicates \( z = 0.4 \text{ kpc}. \) The red curve in the upper panel is the fit to data points with \( z < 0.4 \text{ kpc}, \) while in the lower panel, the red curve is the fit to all the data points.

\[ z_0 = 133.15 \pm 4.72 \text{ pc} \]

\[ z_0 = 98.69 \pm 10.81 \text{ pc} \]

\[ z_0 = 133.15 \pm 4.71 \text{ pc} \]

\[ z_0 = 98.69 \pm 10.81 \text{ pc} \]

\[ \lambda_0 = 8620.18 \pm 0.25 \text{ Å} \]
Fig. 16. Observed central wavelengths ($C_{\text{obs}}$, in vacuum) of DIB 1527 in the heliocentric frame as a function of the angular distance from the longitude centre ($\Delta \ell$) for the Galactic centre (left panel) and the Galactic anti-centre (right panel), respectively. The grey points are the individual measurements with the fitted uncertainties. The red dots are the median values taken in each $\Delta \ell = 1^\circ$ bin with the standard deviation. The red lines are the linear fit to the red dots.

Fig. 17. (Left panel): Longitude–velocity diagram for the Gaia HQ DIB 1527 sample. The circles indicate the median $V_{\text{LSR}}$ and standard uncertainty of the mean for each field. Velocity curves calculated by Model A5 in [Reid et al. (2019)] for different galactocentric distances ($R_{\text{GC}}$) are overplotted. (Right panel): Same as left panel but superimposed on the $^{12}\text{CO}$ data from [Dame et al. (2001)]. The colour-scale displays the $^{12}\text{CO}$ brightness temperature in a logarithmic scale integrated over the velocity range.

The most comprehensive kinematic study to date was performed by [Zasowski et al. (2015)] using APOGEE (SDSS-III) data, and allowed the authors to reveal the average Galactic rotation curve of the $\lambda1527$ DIB carriers spanning several kiloparsecs (kpc) from the Sun. They probed the DIB $\lambda1527$ carrier distribution in 3D and showed that DIBs $\lambda1527$ can be used to trace large-scale Galactic structures, such as the Galactic long bar and the warp of the outer disk. [Zhao et al. (2021)] studied the kinematics of the DIB 1527 in the Galactic Bulge using Gaia-ESO [Gilmore et al. (2012)] and GIBS data [Zoccali et al. (2014)]. These authors concluded that the DIB $\lambda1527$ carrier is located in the inner few kpc of the Galactic disk based on their rotation velocities and radial velocity dispersion. However, these studies are based on specific pencil beams with a limited number of objects. Figure 17 demonstrates the enormous potential of Gaia for studying the kinematic behaviour of the DIBs 1527; it shows the Galactic rotation curve of the DIB 1527 carrier for $|b| < 5^\circ$ and in bins of 10 degrees in galactic longitude. Indicated are Galactic rotation curves computed by Model A5 in [Reid et al. (2019)] with different galactocentric radii ($R_{\text{GC}}$). For sightlines with $\ell \gtrsim 150^\circ$, the DIB 1527 velocities are consistent with the model rotation curves for $R_{\text{GC}} \sim 9$ kpc. On the other hand, for the inner disc with $\ell \lesssim 30^\circ$ the DIB 1527 carrier is best represented by $R_{\text{GC}} \sim 7.5$ kpc, thus closer to the Sun. This is different from the findings of [Zasowski et al. (2015)], namely that the DIB $\lambda1527$ carrier in the inner Galaxy is farther from the Sun. Indeed, the inner disc sample of these latter authors shows higher velocities compared to our sample by a factor of almost two. This is most likely due to the fact that APOGEE observes in the infrared and so probes the DIB $\lambda1527$ in the inner Galaxy.
up to larger distances compared to Gaia. The majority of stars in APOGEE are within ~6 kpc from the Sun while our sample is mostly confined to ~2–3 kpc.

Assuming a galactic rotation model, Zhao et al. (2021b) demonstrated that kinematic distances of the DIB at 862nm can be obtained, allowing the real 3D distribution of the DIB carrier to be traced. We plan to present this in a forthcoming paper.

Correlations between the DIB at 862nm carrier and gas kinematics using different tracers such as CO and HI can provide additional clues as to the origin of the DIB at 862nm carrier. Figure 17 shows one example with the comparison of the CO data from Dame et al. (2001). In the present study we use the momentum-masked cube restricted to the latitude range $|\ell| < 30^\circ$. We see that, in general, the DIB at 862nm closely follows the CO gas pattern, especially in the Galactic anticentre region, while higher velocities are seen in CO for $|\ell| < 50^\circ$. This close relation between the DIB at 862nm and the gas reinforces the suggestion that the DIB at 862nm carrier could be related to macromolecules. We want to stress again that Gaia data allow us to discuss such a large-scale picture for the first time.

9. Conclusions

We present the largest sample of individual DIBs at 862nm published to date, as obtained by the Gaia RVS spectrometer. This is the first homogeneous and all-sky survey of the DIB at 862nm, and allows us to study the global properties of this DIB at 862nm carrier in detail. Defining a high-quality sample, we demonstrate that DIBs at 862nm show a tight relation with interstellar reddening such as E(B−P) or E(B−V). Despite the use of different algorithms in the measurement of DIBs at 862nm between hot stars ($T_{\text{eff}} > 7000$ K) and cool stars ($T_{\text{eff}} < 7000$ K), we see very similar relations between EW at 862nm and E(B−P) or E(B−V), demonstrating the robustness of the DIB at 862nm measurement. While we see similarities in the spatial distributions between the DIB at 862nm carrier and the interstellar reddening, we also notice some differences, in particular that the scale height of the DIB at 862nm carrier is smaller compared to the dust and that the DIB at 862nm carrier is concentrated within the inner kpc from the Sun. A similar conclusion can be drawn from the comparison with the total Galactic extinction map. The main and most striking difference between the DIB at 862nm carrier and dust distributions is that DIB at 862nm carriers are present in the Local Bubble around the Sun, while this region is known to contain almost no dust. To first order, the spatial distribution of DIB at 862nm carriers follows a simple slab model. We derive its local density and scale height, which can be used to predict the expected EW of the DIB at 862nm towards any star up to ~3 kpc from the Sun.

Taking advantage of the full sky coverage of the DIB at 862nm, we determined the rest-frame wavelength of the DIB at 862nm in the Galactic anticentre with an estimated $\lambda_0 = 862.086 \pm 0.019$ Å in air. This is the most precise determination of $\lambda_0$ to date. We note that using a large number of sources diminishes the formal measurement errors and, more importantly, largely negates the systematic errors of unknown radial velocities of clouds of DIB carriers which may influence any studies based on a small number of sources. For the first time, we demonstrate here the Galactic rotation curve traced by the DIB at 862nm carrier within 1–2 kpc from the Sun and reveal the remarkable correspondence between the DIB at 862nm velocities and the CO gas velocities, re-inforcing the suggestion that DIB at 862nm carriers could be related to gaseous macromolecules.

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ADQL Queries

Use Case: Retrieve full DIB sample

```
SELECT *
FROM user_dr3int5.astrophysical_parameters AS gaia
INNER JOIN user_dr3int5.astrophysical_parameters_supp AS m
ON gaia.source_id = m.source_id
WHERE gaia.dibqf_gspspec >= 0
```

Use Case: Retrieve DIB results for HQ sample

```
SELECT *
FROM user_dr3int5.astrophysical_parameters
WHERE (flags_gspspec LIKE '0%') OR (flags_gspspec LIKE '1%')
AND ((flags_gspspec LIKE '_0%') OR (flags_gspspec LIKE '_1%'))
AND ((flags_gspspec LIKE '__0%') OR (flags_gspspec LIKE '__1%'))
AND ((flags_gspspec LIKE '___0%') OR (flags_gspspec LIKE '___1%'))
AND ((flags_gspspec LIKE '____0%') OR (flags_gspspec LIKE '____1%'))
AND ((flags_gspspec LIKE '_____0%') OR (flags_gspspec LIKE '_____1%'))
AND (dibqf_gspspec = 0) AND (dibqf_gspspec = 2)
```

Hot star outliers
Table A.1. Outliers found in the hot stars sample (Fig. 9). Description of the table columns: number (col.1), GDR3 ID (col.2), Simbad ID and spectral/object type between brackets when available (col.3), effective temperatures from ESP-HS and spectral type found in the field (col.4), GSP-Spec (col.5), and GSP-Phot (col.6).

| n | DR3 ID | ID Simbad | Teff ESP-HS | Teff GSP-Spec | Teff GSP-Phot |
|---|--------|-----------|-------------|---------------|--------------|
| 1 | 2066753415480268800 | 2MASS J20500395+4300117 | 54 705 (O) | 6 904 | 7 690 |
| 2 | 444955867385000832 | - | 54 650 (O) | 6 248 | 7 023 |
| 3 | 4054566946966876288 | CD-32 12958 | 54 706 (B) | 7 115 | - |
| 4 | 2164089679515345280 | TYC 3589-1199-1 | 13 541 (B) | 8 404 | - |
| 5 | 5537927056196905984 | TYC 7659-1313-1 | 16 054 (B) | 8 339 | 12 109 |
| 6 | 1730824030187372416 | FQ Aqr | 17 364 (B) | 8 289 | - |
| 7 | 3455454953759211264 | LS V +35 26 (OB-e) | 20 000 (B) | 8 068 | - |
| 8 | 2005574977916673792 | BD+53 2784 (B3 III) | 17 695 (B) | 7 869 | - |

GSP-Phot, middle panel of Fig. 9

| n | DR3 ID | ID Simbad | Teff GSP-Phot |
|---|--------|-----------|---------------|
| 1 | 5999123049637219072 | IRAS 15212-4624 | - (M) 7 316 | 3 641 |
| 2 | 5843278232842959872 | IRAS 12365-6959 | - (M) 7 312 | 3 523 |
| 3 | 5878260883212542208 | - | 7 843 | 6 495 |
| 4 | 5854026787978149760 | IRAS 14112-6224 | - (M) 8 000 | 3 712 |
| 5 | 5889006272967734144 | IRAS 15230-5132 (LP?) | - (M) 7 348 | 3 584 |
| 6 | 4152556797623844608 | TYC 5702-740-1 | - (O) 7 679 | 8 061 |
| 7 | 4134885451076972416 | IRAS 17170-1756 | - (M) 7 900 | 3 707 |
| 8 | 5341747587387330432 | IRAS 11464-5753 (M7) | - (M) 7 900 | 3 500 |
| 9 | 1931994246725494400 | V608 And (M7/M8) | - (M) 7 298 | 3 623 |
| 10 | 4478836843125274496 | IRAS 18313+0720 | - (M) 8 000 | 3 637 |