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Probing the Local Bubble with Diffuse Interstellar Bands (DIBs)

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Abstract. The Sun lies in the middle of an enormous cavity of a million degree gas, known as the Local Bubble. The Local Bubble is surrounded by a wall of denser neutral and ionized gas. The Local Bubble extends around 100 pc in the plane of Galaxy and hundreds of parsecs vertically, but absorption-line surveys of neutral sodium and singly-ionized calcium have revealed a highly irregular structure and the presence of neutral clouds within an otherwise tenuous and hot gas. We have undertaken an all-sky, European-Iranian survey of the Local Bubble in the absorption of a number of diffuse interstellar bands (DIBs) to offer a novel view of our neighbourhood. Our dedicated campaigns with ESO's New Technology Telescope and the ING's Isaac Newton Telescope comprise high signal-to-noise, medium-resolution spectra, concentrating on the 5780 and 5797 Å bands which trace ionized/irradiated and neutral/shielded environments, respectively; their carriers are unknown but likely to be large carbonaceous molecules. With about 660 sightlines towards early-type stars distributed over distances up to about 200 pc, our data allow us to reconstruct the first ever 3D DIB map of the Local Bubble, which we present here. While we confirm our expectations that the 5780 Å DIB is relatively strong compared to the 5797 Å DIB in hot/irradiated regions such as which prevail within the Local Bubble and its walls, and the opposite is true for cooler/shielded regions beyond the confines of the Local Bubble, we unexpectedly also detect DIB cloudlets inside of the Local Bubble. These results reveal new insight into the structure of the Local Bubble, as well as helping constrain our understanding of the carriers of the DIBs.

Key words. ISM: atoms – ISM: bubbles – ISM: individual objects: Local Bubble – ISM: molecules – ISM: structure – local interstellar matter

1. Introduction

The Solar System currently finds itself in an area within the Milky Way Disc of relatively low interstellar density called the "Local Bubble" (Fitzgerald 1968). It is not a void, though, and while filled largely with million-degree plasma (Snowden et al. 2015) it is far from homogeneous and contains denser, cooler "local fluff" (Redfield & Linsky 2000).

Table 1. The UK–Iran ultra-deep all-sky survey of DIBs in and around the Local Bubble.

	Southern	Northern	Combined
telescope	3.6m NTT	2.5m INT	~ 3m
observatory	ESO La Silla	ING La Palma	±29° latitude
period	2011–2012	2011–2013	2011–2013
$\lambda/\Delta\lambda$	5500	2000	2000–5500
signal-to-noise	1000–2000	1000–2000	1000–2000
# sight-lines	238	432	655 unique
types	O,B	B,A	O,B,A
reference	Bailey et al. (2016)	Farhang et al. (2015a,b)	Farhang et al. (2016)

The structure of the Local Bubble has been mapped in three dimensions using stars with known distances from parallax measurements, through Na I and Ca II spectral line absorption by neutral and ionized gas (Lallement et al. 2003; Welsh et al. 2010) and photometric reddening by dust (Lallement et al. 2014). Given the importance of the local interstellar environment for the effectiveness of the heliosphere to protect life on Earth, and to better understand the dynamics of the multi-phase interstellar medium (ISM) in spiral galaxies, novel ways of mapping the Local Bubble remain highly desirable.

A tracer of weakly-ionized gas, the diffuse interstellar bands (DIBs) that are ubiquitous in the optical spectra of stars have been known for almost a century (Heger 1922). They show a huge variety in widths, strengths and shapes, yet their carriers remain elusive (Herbig 1995; Sarre 2006). It is likely that the carriers are carbonaceous molecules, possibly charged, and they could include members of the family of fullerenes (Foing & Ehrenfreund 1994; García-Hernández & Díaz-Luis 2013; Campbell et al. 2015).

DIBs are increasingly recognised as powerful tools to map the ISM, since the pioneering work by van Loon et al. (2009) who used the λ5780 Å and λ5797 Å DIBs to map the extra-planar gas in front of hundreds of metal-poor, blue horizontal branch stars in the largest Galactic globular cluster, ω Centauri. These maps revealed parsec-scale structure, and anti-correlated behaviour of these two DIBs confirming that the λ5780 Å and λ5797 Å DIBs trace different interstellar conditions. In a subsequent study, van Loon et al. (2013) mapped the strong λ4428 Å and λ6614 Å DIBs using the spectra of about 800 stars within the Tarantula Nebula in the Large Magellanic Cloud (LMC). These maps showed the presence of DIBs in both the diffuse ionized and neutral ISM but their disappearance near strong sources of UV radiation; this behaviour resembles that of the equally unidentified infrared emission features (commonly attributed to polycyclic aromatic hydrocarbons). Due to the Doppler shift of the LMC, the foreground component arising in the local Galactic ISM could be mapped separately, again showing pc-scale structure in the DIB carriers, excitation conditions, or both, but this time at even higher Galactic latitude.

Kos et al. (2014), Lan, Ménard & Zhu (2015) and Zasowski et al. (2015) utilized the SDSS, RAVE and APOGEE surveys to map the kiloparsec-scale distribution of DIBs across the Galactic Disc and Halo. To map the low column density material in and around the Local Bubble requires much higher signal-to-noise than what is typical in stellar and extragalactic spectroscopic surveys, and hence we initiated an ultra-deep, all-sky survey dedicated to the detection of DIBs at the sub-percent level.

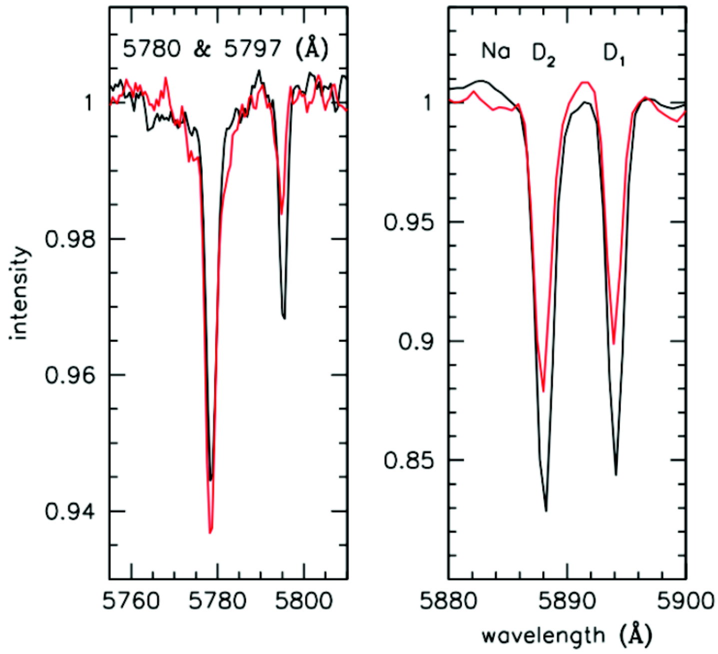

Fig. 1. Difference in behaviour between the λ5780 Å DIB (*leftmost*) and the λ5797 and 6614 Å DIBs and the Na I D lines; the higher-latitude sight-line towards HD 186500 is an example of the σ conditions in which the λ5780 Å DIB is relatively strong, whereas the opposite, ζ conditions are found towards HD 179406. Expanded on Bailey et al. (2016).

2. The UK–Iranian ultra-deep all-sky Local Bubble DIBs survey

Starting with a survey in the Southern hemisphere (including targets up to about +10° declination), with the New Technology Telescope (NTT) at the European Southern Observatory (ESO) at La Silla, Chile (Bailey et al. 2016), it was extended to an all-sky survey by a complementary Northern hemisphere component conducted with the Isaac Newton Telescope (INT) at La Palma, Canary Islands (Farhang et al. 2015a,b) – see table 1. By virtue of the prevailing climatic conditions near the tropical circles the La Silla and La Palma observatories are at almost exact opposite sides from the Earth's equator!

Targets were chosen to be predominantly early-type stars (O and B type), but additional, later-type (A type) stars were included in the Northern survey to improve coverage – most targets are naked-eye stars in order to reach the very high signal-to-noise (> 1000). The spectra of the cooler stars were fitted with synthetic model atmosphere spectra to separate interstellar from photospheric absorption, and even in the spectra of the hotter stars some interfering features had to be fitted simultaneously and removed from the interstellar band. All stars have known parallaxes (and proper motions), and are mostly within a few hundred pc from the Sun; their three-dimensional spacings are typically 10–40 pc. In total, 655 unique sight-lines were probed, of which 15 were observed in both hemisphere survey components (reassuringly, their measurements were found to agree very well).

An example of two sight-lines probing different environments is presented in figure 1. The λ5797 Å DIB, and also the λ6614 Å DIB, generally traces the neutral gas that also dominates the column density probed by the Na I D lines (and reddening), but the λ5780 Å DIB exhibits large variations, likely depending on

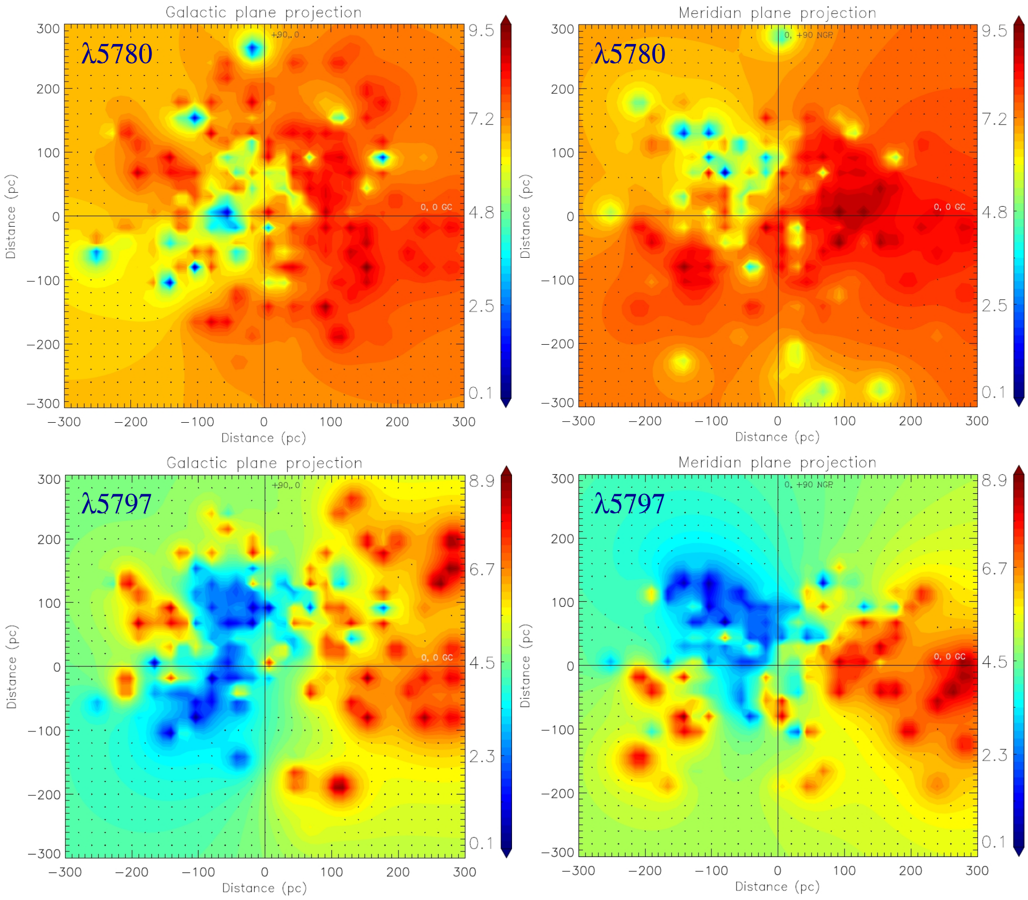

Fig. 2. Projections of the three-dimensional density (in arbitrary units) onto the (*left:*) Galactic plane and (*right:*) meridional plane perpendicular to the former, of the (*top:*) λ5780 Å and (*bottom:*) λ5797 Å DIB. The DIB carriers are clearly depleted within a region near to the Sun (located at the centre of these panels), but – like in the corresponding atomic maps – there is evidence for small-scale structure and for variations in the relative abundances of the (unknown) carriers of these diffuse interstellar bands. Farhang et al. (2016).

the level of irradiation and/or the contact with hot gas. This dichotomy is well known since Krełowski & Westerlund (1988) compared the spectrum of ζ Ophiuchi (relatively strong λ5797 Å DIB, henceforth called ζ clouds) with that of σ Scorpii (relatively strong λ5780 Å DIB, henceforth called σ clouds) – despite their near-identical reddening.

Indeed, we found a large λ5780/λ5797 DIB ratio within the Local Bubble and generally in the extra-planar gas. The ratio is often low for sodium equivalent widths of $EW(\mathrm{Na\,I\,D_2}) > 0.2$ Å, which corresponds to column densities where the sodium D lines become affected significantly by saturation. For denser columns the sodium equivalent width increases more easily as a result of the increasing multiplicity of clouds along the sight-line; higher resolution studies confirm that is the case.

Likewise, the correlations between DIBs seem not as simple at low column densities than at moderate-to-high column densities. We thus conjecture that the good – at times near perfect (McCall et al. 2010) – correlations seen between some DIBs and between DIBs and other tracers such as atomic lines or red-

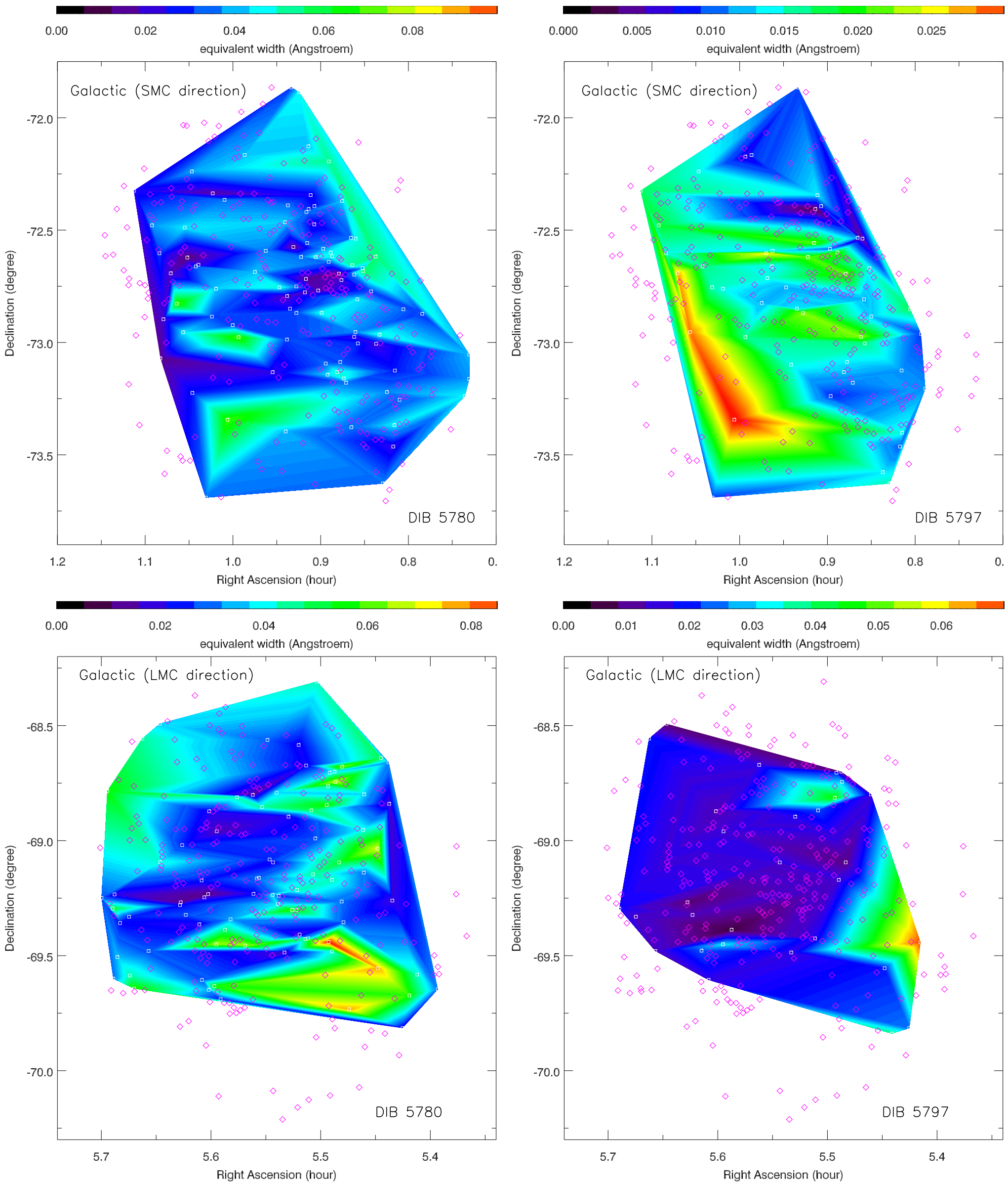

Fig. 3. Sub-degree variations across the sky in the Galactic foreground absorption in front of the Small (*top*) and Large (*bottom*) Magellanic Clouds; λ5780 Å (*left*) and λ5797 Å DIB (*right*). Bailey et al. (2015a).

dening (Friedman et al. 2011) can be misleading and in part (or wholly) the result of the net averaging of clouds with varying conditions. Even higher signal-to-noise, and higher spectral resolving power, measurements of weak absorption may be much more revealing about the carriers of the DIBs than the strong DIBs found in the spectra of distant stars.

The ultimate result of the survey is a three-dimensional map of the relative density of the DIB carriers (figure 2; absolute values are not known as the oscillator strength of the DIB transition remains unknown without the carrier having been identified), using an inversion method (Vergely et al. 2001). The method was tested on Na I measurements from the same survey data, and the resulting map compares well with the result by Welsh et al. (2010) for a much larger sample of stars. In figure 2 we show two projections, for the λ5780 Å and λ5797 Å DIBs: onto the Galactic mid-plane and onto the meridional plane perpendicular to the Galactic plane. The former show the Local Bubble as traced by the DIBs extending mostly away from the Galactic Centre direction (even though on this scale, the Galactic Centre is some 25 times more distant than the extent of the map, and it is unlikely that we are detecting a Galactic radial gradient in density – it is much more likely that there is a local spiral arm or spur at that side of the Sun). The latter, the meridional projection shows the Local Bubble opening into the extra-planar regions and possibly all the way out into the Halo.

These three-dimensional maps already indicate a highly complex structure also in the DIBs. Indeed, even smaller structures were found in degree-size maps, towards extragalactic targets (van Loon et al. 2009, 2013). In figure 3 we show for the first time maps of the Milky Way absorption in the λ5780 Å and λ5797 Å DIBs as detected in the foreground of over 300 stars in each of the Small and Large Magellanic Clouds (Bailey et al. 2015a). Again, variations are seen on scales corresponding to about a parsec if these structures are around 100 pc distant from us. And again, these two DIBs do not seem to coincide very much.

3. What's next?

The surveys described here have demonstrated that it is possible to create maps of DIBs across vast areas of galaxies also at low column densities where we are most likely to see clear and true relations between – and mutual exclusions of – different DIBs that can help us to identify their carriers. The surveys have also highlighted the need for dedicated observations at much higher signal-to-noise levels than what is typical in stellar or extragalactic spectroscopic surveys (even if the latter often provide an opportunity for interesting secondary science using DIBs). To distinguish different kinematic components in the narrower DIBs, and help combat the interfering effects from telluric and stellar photospheric spectral lines, high resolution (at least $\lambda/\Delta\lambda > 10\,000$) is highly desirable. Atomic and molecular lines will become increasingly useful in such surveys. While the relatively strong λ4428 Å, λ5780 Å, λ5797 Å and λ6614 Å are the most obvious DIBs to target there are many other DIBs both at optical and infrared wavelengths that could reveal information left hidden by measurements of the above four DIBs, e.g. a triplet of DIBs in the 470nm range (van Loon et al. 2013).

We thus advocate the concept of a next generation of high resolution, high signal-to-noise, broad range, multi-object spectroscopic surveys of thousands of nearby stars and stars in the Magellanic Clouds. The requirements for these surveys transcend current large spectroscopic programmes such as SDSS or GAIA-ESO and even DIBs specific surveys such as EDIBLES at the ESO-VLT (PI: Nick Cox). We note that the envisaged DIBs surveys would provide unprecedented serendipitous scientific progress, in particular of an astrophysical nature. They would need large investments of time at 4–10m class telescopes, but this has become possible. They will also rely on accurate stellar atmosphere modelling and spectral synthesis, but this too has become possible (Puspitarini et al. 2015). The paybacks will be huge given that long-standing and wide-ranging problems can finally be addressed accurately and comprehensively. Apart from better understanding the multi-phase ISM, we will know what the Solar System is moving through and we may finally find out what material it is that causes DIBs.

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