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The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES)

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The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES) is a Large Programme that is collecting high-signal-to-noise (S/N) spectra with UVES of a large sample of O and B-type stars covering a large spectral range. The goal of the programme is to extract a unique sample of high-quality interstellar spectra from these data, representing different physical and chemical environments, and to characterise these environments in great detail. An important component of interstellar spectra is the diffuse interstellar bands (DIBs), a set of hundreds of unidentified interstellar absorption lines. With the detailed line-of-sight information and the high-quality spectra, EDIBLES will derive strong constraints on the potential DIB carrier molecules. EDIBLES will thus guide the laboratory experiments necessary to identify these interstellar "mystery molecules", and turn DIBs into powerful diagnostics of their environments in our Milky Way Galaxy and beyond. We present some preliminary results showing the unique capabilities of the EDIBLES programme.

The diffuse interstellar bands

One of the longest-standing problems in modern astronomical spectroscopy is associated with the identification of the chemical species that produce the diffuse interstellar bands (DIBs; see Cami & Cox, 2012 for a recent review) — a problem that first surfaced almost a century ago. The DIBs are a collection of over 400 absorption features that appear in the spectra of reddened stars. Their interstellar nature is clear, but their origin is unknown (although a few DIBs in the near-infrared part of the spectrum are attributed to C_{60}^{+}; see below). Given their strength and their widespread occurrence in harsh interstellar environments, the DIB carriers are most likely abundant, stable, carbonaceous species such as carbon chains, polycyclic aromatic hydrocarbons (PAHs), fullerenes or closely related species. Despite their unknown identity, the DIBs are being used increasingly often as tools, for example to map the interstellar medium in 3D (Bailey et al., 2016). The eventual identification of DIB carrier(s) will make DIBs very powerful diagnostics in the interstellar medium.

The definite identification of DIB carriers must come from an accurate match between the observed spectroscopic features in a low-temperature gas-phase laboratory experiment and the DIBs seen in astronomical observations. Indeed, laboratory data not only provide accurate rest wavelengths and bandwidths (including transitions beyond the origin band) of possible carriers, but the controlled conditions in the laboratory also allow the derivation of oscillator strengths that are needed to estimate column densities. However, the sheer number of possible DIB carrier candidates to measure experimentally is so challenging — for example, there are more than 1.2 million PAH species with 100 or fewer C atoms — that targeted astronomical observations are needed to guide the selection of the most promising candidates by providing

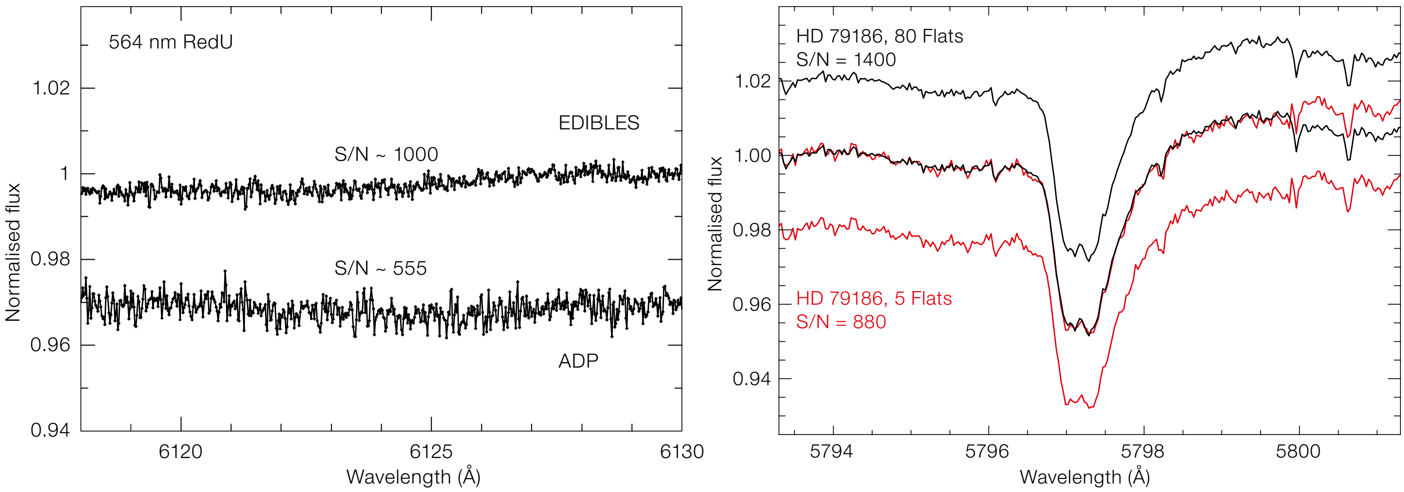


Figure 1. Left: A comparison between the results of the ESO Archive Data Products (ADP) and the EDIBLES processing pipeline (bin size: 0.02 Å). Figure from Cox et al. (2017), reproduced with permission from A&A. Right: The EDIBLES spectrum of HD 79186 around the 5797 Å DIB when using 80 flat fields (black) compared to the same observation using only five flat fields (red).

constraints on the carrier species. High-resolution observations of DIB line profiles can be used to estimate the size and geometry of the DIB carrier molecules as well as their excitation properties (see, for example, Marshall et al., 2015). Correlation studies and investigations of how DIB strengths change in different environments yield information about what drives variations in the DIB properties, such as the ionisation potential and chemical make up of the DIB carriers (see, for example, Ensor et al., 2017).

While there has been steady progress in the field over the years, most studies focus on the properties of a small number of DIBs, over particular wavelength ranges and in particular environments, or alternatively deal with large datasets and "average" properties of the DIBs (for example, Lan et al., 2015). Significant progress in the field can be expected from a high-quality, sensitive survey of interstellar features (DIBs, but importantly also known interstellar atoms and molecules) over a large spectral range and representing differing interstellar environments (Cami & Cox, 2014). The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES) is such a survey.

EDIBLES

The aim of EDIBLES is to collect a large sample of interstellar spectra with UVES (Smoker et al., 2009) at high spectral resolution (R ~ 70 000 in the blue and 100 000 in the red arm), with a very high signal-to-noise ratio (median S/N ~ 500–1000 per target) over a large spectral range (3050–10420 Å), and with targets that represent very different physical conditions along the lines of sight. DIB targets are typically bright, early-type (O- and B-type) stars whose optical spectra contain relatively few stellar lines. In these spectra, the DIBs are more easily recognised and characterised. We selected bright ($V < 8$ magnitudes) O- and B-type stars, and constructed our sample so that we can probe a wide a range of interstellar environment parameters including interstellar reddening $E(B-V)$ ~ 0–2 magnitudes, visual extinction A_V ~ 0–4.5 magnitudes, total-to-selective extinction ratio R_V ~ 2–6, and a molecular hydrogen fraction $f(H_2)$ range ~ 0.0–0.8. Our final target list contains 114 objects of which 97 have been observed to date. Further details about the goals, objectives and sample selection can be found in Cox et al. (2017).

EDIBLES is an approved Large Programme that started in September 2014 (ESO period 94) under Programme ID 194.C-0883. The total allocated telescope time, excluding daytime calibrations, is 284 hours. As a programme, EDIBLES has been optimised, in terms of selected targets and observing strategy, to obtain observations when weather conditions are typically too poor for regular programmes (called "filler conditions") and thus helps to optimise the use of the telescope. This makes it a less efficient process to reach a sufficiently high S/N, and we therefore require a large number of exposures.

A high S/N also requires a large number of flat field exposures. We have developed a custom data reduction procedure to process flat field frames so that we can attain the highest possible S/N (see Cox et al., 2017). Figure 1 illustrates how the addition of a large number of flat fields can greatly improve the quality of the resulting spectra. Using the same recipes and a higher number of flat field frames — even when obtained on different dates — can increase the S/N of other good-quality science observations in the UVES archive. In the red part of the spectrum, we could also improve and fine-tune the wavelength calibration using the large number of telluric lines available in our high-resolution spectra.

EDIBLES is unique in its combination of spectral resolution, wavelength coverage, sensitivity and sample size and this promises great advances in the field. As illustrated below, the high spectral resolution allows us to study individual DIB line profiles for a large number of DIBs, yielding size estimates for their carrier molecules when clear substructures are present. The high sensitivity facilitates studying both strong and weak DIBs simultaneously. This is important since laboratory spectra of typical DIB carriers often result in several transitions of comparable strength in the optical range, in contrast with the fact that no two DIBs have been found that undeniably originate from the same species (with the possible exception of the C_{60}^{+} DIBs). We expect that EDIBLES will reveal the first pair of perfectly correlating DIBs.

The large spectral coverage combined with the high resolution — which allows very good telluric corrections — will explore wavelength ranges over which few or even no sensitive DIB searches have ever been carried out. Furthermore, this range includes a large number of known interstellar absorption lines — due to atoms and small molecules such as CN or C_2 — which play an important role in EDIBLES. They enable us to accurately define the physical conditions in a large sample of lines of sight along which DIBs are measured, which is unprecedented on this scale. All these characteristics will enormously constrain the number of possible carrier molecules.

EDIBLES is also ideally suited for serendipitous studies that are not directly related to the DIBs. The large number of observations of O and B stars will turn out to be very useful for studies of massive stars and their stellar winds. Since our survey also includes observations of the same lines of sight at different epochs, the survey can also be used and complemented by archival data, to study small-scale variations in interstellar lines over time.

Resolved substructures in DIB line profiles

The high-resolution, high-S/N spectra of the EDIBLES survey reveal profile substructures in a large number of DIBs, and subtle variations in these profiles from one line of sight to another. A good example is the well-known triplet structure found in the 6614 Å DIB towards HD 170740 and HD 147165 (σ Sco), shown in Figure 2. We compare the DIB profiles, normalised to a common integrated intensity using an approach introduced by Marshall et al. (2015). It is notable that the absorption depths for the sub-peaks that are redwards and bluewards of the strongest central absorption differ for the two sightlines, and that the redward tail is stronger and more extended for HD 147165; this characteristic has been

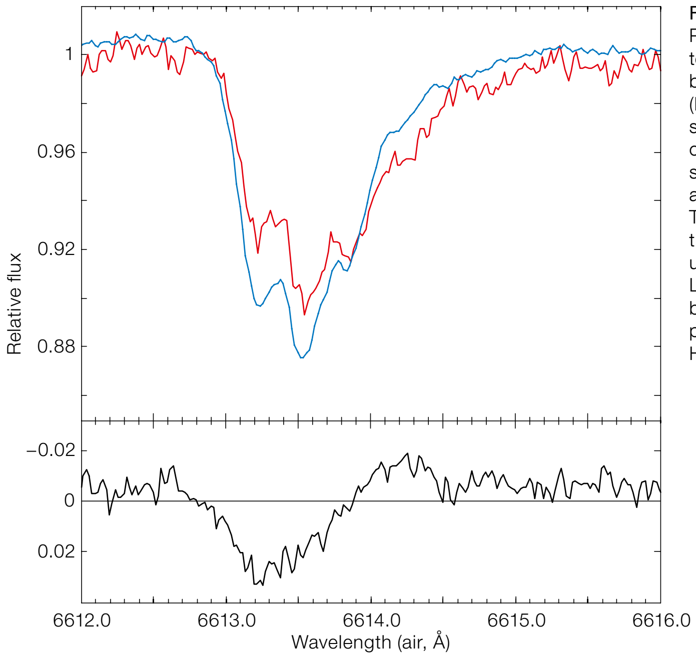


Figure 2. Upper panel: Profiles of the 6614 Å DIB towards HD 170740 (deeper, blue trace) and HD 147165 (broader, red trace). The spectra are normalised to a common integrated intensity and the ordinate values are those for HD 170740. The spectra are shifted to the interstellar restframe using K I radial velocities. Lower panel: The difference between the normalised profiles of the DIB in HD 170740 and HD 147165.

interpreted as arising from a stronger hot band contribution (Marshall et al., 2015).

The details of the band profile depend on the rotational and vibrational temperatures and EDIBLES is designed to make progress in our understanding of precisely how these temperatures cause spectral changes. Indeed, the large numbers of EDIBLES sightlines sample the possible range of rotational and vibrational temperatures in interstellar clouds, and information on these temperatures can be derived from other molecular absorption lines in the EDIBLES spectral range. Modelling of these band profiles will thus provide the link between the observed spectral variations and the changes in temperature; in turn, this will greatly constrain the properties (for example, size and geometry) of the possible carrier molecules.

The C_2-DIBs

A particularly intriguing subset of the DIBs are the so-called C_2-DIBs (Thorburn et al., 2003); these are features that correlate especially well with the column density of C_2 molecules along the line of sight. This could imply that C_2-DIB carriers are chemically linked to C_2. Moreover, several C_2-DIBs appear in pairs that are separated by the same spacing of about 20 cm^{-1}, reminiscent of the spectroscopic signature of spin-orbit interaction in a linear molecule (Thorburn et al., 2003). Further constraints on the properties of the carrier will come from detailed analyses of the line profile shape of the C_2-DIBs. Since many of the C_2-DIBs are weak and high spectral resolution is required to resolve the profiles, substructure in the profiles of the C_2-DIBs was only reliably established for three to four C_2-DIBs, although asymmetries in observed profiles suggested that more of the C_2-DIBs could exhibit substructure (Galazutdinov et al., 2002).

In the EDIBLES dataset, we detect C_2 A-X rovibronic bands around 7700, 8800 and 10 100 Å in 25 sightlines, representing one of the largest samples to date for this important species (Cordiner et al., in preparation). This is another demonstration of the unique, extremely high sensitivity of our EDIBLES survey for the detection of weak spectral features. Excitation modelling of these C_2 spectra permits new insights into the temperatures and densities of diffuse molecular gas.

From this sample, we selected several EDIBLES targets that exhibit strong C_2 lines and that are "single clouds", i.e., there is only one dominant interstellar cloud along the direct line of sight to the target. For this sample of targets, we find that *all* C_2-DIBs have resolved structure in their profiles (Elyajouri et al., in

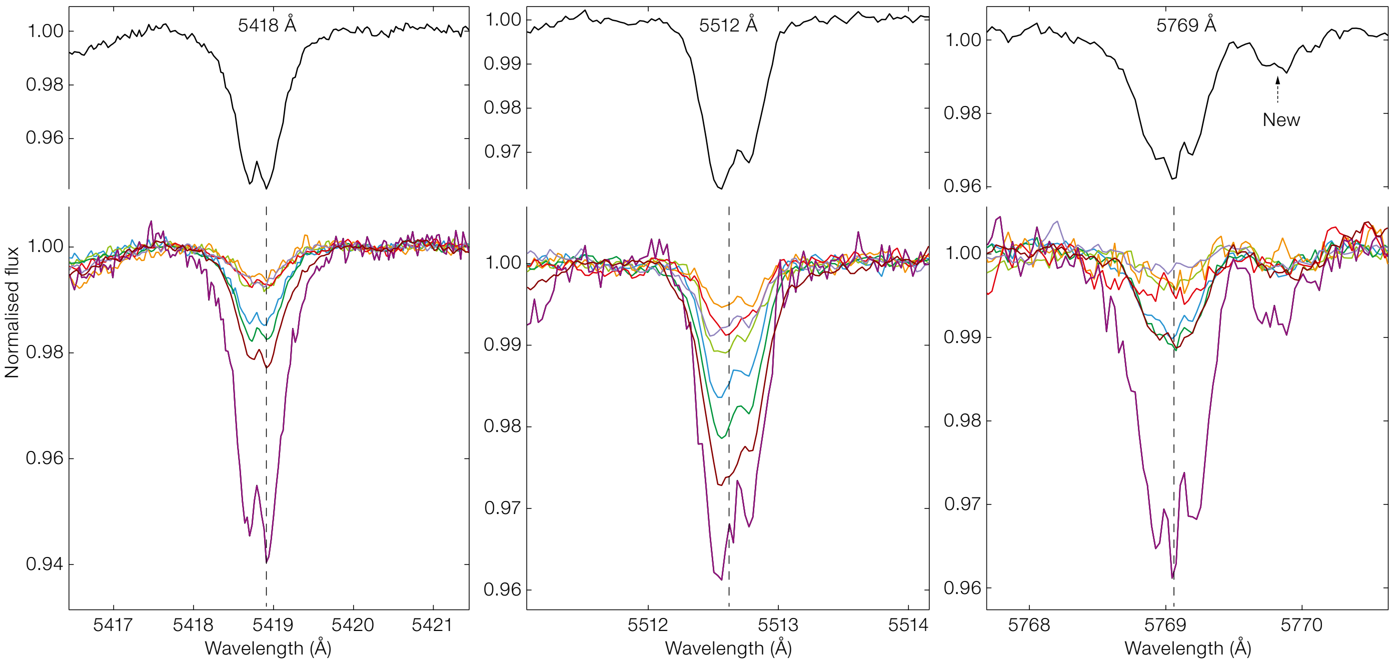


Figure 3. A few examples of the C_2-DIB profiles at 5418.91, 5512.62 and 5769.08 Å. Coloured lines display the individual sightlines. The black profile on top is the average normalised profile obtained by stacking the deepest bands of three single cloud targets.

preparation; Figure 3). The high resolution and S/N allow us to conclude with confidence that these substructures are neither telluric nor stellar in origin, and that the single-cloud nature of the targets eliminates multi-cloud confusion as well. These substructures are thus intrinsic to the C_2-DIBs and will reveal a lot about the properties of their carrier molecule(s).

The DIBs attributed to C_{60}^+

Foing & Ehrenfreund (1994) used laboratory measurements to predict that interstellar, gas-phase C_{60}^+ molecules would exhibit transitions near 9577 Å and 9632 Å. A dedicated search did indeed result in the discovery of two DIBs near those wavelengths with band characteristics that were expected for this species. However, the laboratory data that they used were obtained in cryogenic matrices in which the band positions and profiles may be affected. Obtaining a gas-phase spectrum at low temperatures has proven to be very challenging, but Campbell et al. (2015) succeeded in developing a technique to reliably measure the electronic spectrum under conditions that are appropriate for comparison with interstellar spectra. The central wavelengths of the two strongest bands in the laboratory experiments agree with the central wavelengths of the two DIBs, within uncertainties of ~ 0.1 Å. The laboratory spectrum furthermore exhibits three weaker bands and several authors have found evidence for these bands as well (for example, Walker et al., 2017; Cordiner et al., 2017).

Unequivocally confirming even the presence of these weaker bands, however, is greatly complicated by the many strong telluric spectral features in the wavelength range over which the C_{60}^+ bands occur (Figure 4, top). Typically, the analysis is performed on a corrected spectrum, created by dividing out the telluric lines by means of a transmission model or the spectrum of a telluric standard star. However, with such strong telluric lines — also variable on short timescales — residuals are unavoidable and can result in severe artefacts. Figure 4 (middle) shows that, even when dividing out a spectrum with a very similar telluric profile (in this case of HD 54662), such residuals occur.

In the corrected spectrum, a clear feature shows up at 9412 Å; this is a known DIB that is unrelated to C_{60}^+. At the same time, at the expected position of the 9428 Å C_{60}^+ band, there appears to be a depression (somewhat masked by telluric residuals) and a Gaussian fit to that depression has an absorption depth that agrees with predictions, given the strength of the other C_{60}^+ bands. While this does not yet prove beyond any doubt that the 9428 Å DIB is present, the EDIBLES data support the identification of these DIBs with C_{60}^+ (Lallement et al., 2018).

The high spectral resolution of the EDIBLES data furthermore allows the study of some of the C_{60}^+ DIBs profiles despite the telluric contamination. For example, in the lower panel of Figure 4 we show how co-adding 79 individual observations of 43 different targets reveals the first evidence for an enormous amount of detail in the substructure of the strong 9577 Å C_{60}^+ DIB. This is possible because this DIB is only partially affected by telluric lines; the different interstellar cloud radial velocities then cause different parts of the band to appear in the “telluric-free” window (Lallement et al., in preparation). Small-scale variations in these substructures from one line of sight to another can then be used to study the fullerene molecular physics and the impact of the local physical conditions.

OH^+ and the cosmic ray ionisation rate

When Bhatt & Cami (2015) performed a sensitive survey of interstellar lines in the near-ultraviolet by stacking 185 UVES archival observations of reddened

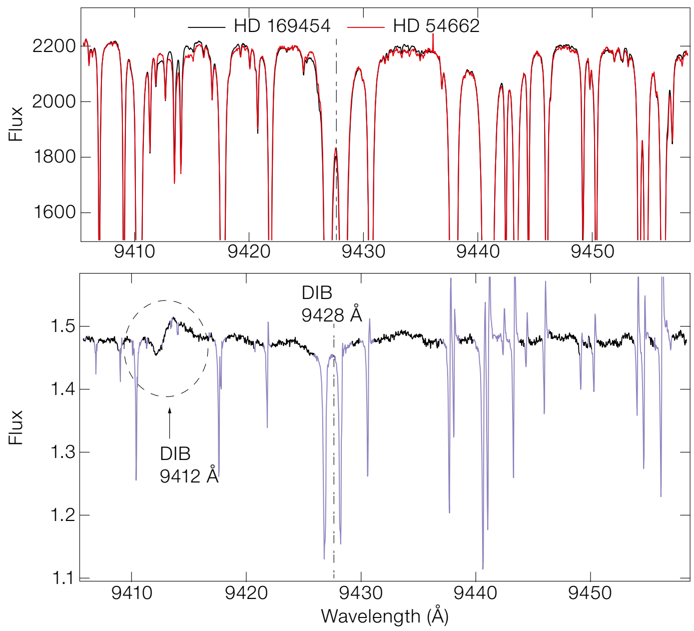
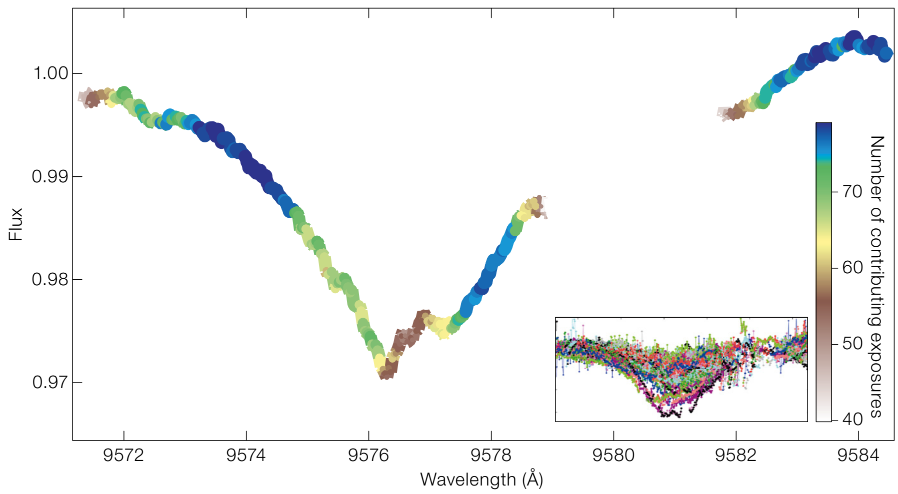


Figure 4. Upper: The EDIBLES spectra of HD 169454 and HD 54662 in the range of two weak DIBs: the 9412 Å DIB (unrelated to C_{60}^{+}) and a weak DIB at 9428 Å which is due to C_{60}^{+} (adapted from Lallement et al., 2018). Middle: The HD 169454 spectrum divided by the one of HD 54662. Lower: A composite showing partially resolved substructure in the strong 9577 Å C_{60}^{+} DIB. All fluxes are in arbitrary units.



a time series since 1995 of the He I line profile at 5876 Å in HD 148937, a magnetic Of?p star that is at the centre of the bipolar emission nebula NGC 6164. This object has been monitored for a long time, and small variations in stellar line profiles have been attributed to rotational modulation (Nazé et al., 2008). We noticed that the EDIBLES observations that were carried out in 2015 revealed a very different line profile compared to all previously published profiles (c.f. Figure 14 in Cox et al., 2017). Many more stellar lines show clear variations in their shapes and their wavelengths. A careful analysis reveals that this object is a massive spectroscopic binary, with a preliminary period of at least 18 years. The EDIBLES observations just happened to be acquired close to periastron passage, where effects on the spectrum would be most pronounced (Wade et al., in preparation).

targets, they discovered five new narrow interstellar features in the stacked spectrum that were too weak to be discerned in a single observation. Zhao et al. (2015) confirmed two of these features and identified them with transitions due to OH^+; they also found several more OH^+ lines in addition to the already well known line at 3583.76 Å. With several lines available that all arise from the ground state level, it is possible to accurately derive the corresponding population and infer the cosmic ionisation rate in diffuse interstellar clouds, something which has only been possible using space telescopes, and which yields comparable results.

The high S/N in the EDIBLES data and the wavelength coverage in the near-ultraviolet now show these very weak features almost routinely, and enable the calculation of the cosmic ray ionisation rate for a much larger sample than before, thus expanding the available line-of-sight information potentially also relevant for the DIBs analysis (Bacalla et al., in preparation; Figure 5). Indeed, the detection and analysis of such diagnostic molecules allow the community to interpret the DIB measurements within the context of their physical surroundings.

Variability in HD 148937

As an example of the potential for serendipitous discoveries, we show in Figure 6

Outlook

With EDIBLES, we have currently observed 97 early-type stars at high spectral resolution and at high S/N over a large spectral range. The first studies, some of which we have presented here, clearly show the enormous potential for new discoveries with this dataset. To ensure optimal exploitation and interpretation of this unique data set, the EDIBLES team is composed of researchers from a diverse community, including observational astronomers as well as experts in molecular astrophysics, interstellar physics and chemistry, and laboratory astrophysics. In addition to the scientific analyses, we have tested and demonstrated a recipe that is available to the community, which can significantly increase the S/N of UVES observations. The EDIBLES team is furthermore committed to providing the community with a catalogue detailing a large number of interstellar quantities for these sightlines — including DIB measurements. This catalogue is likely to serve as the DIB benchmark reference for many years to come. While the EDIBLES team focuses on the interstellar studies, the same data will also be fruitful ground for a diverse range of other projects, including stellar spectroscopy analyses. It is clear that EDIBLES will leave a significant legacy to the astronomical community at large.

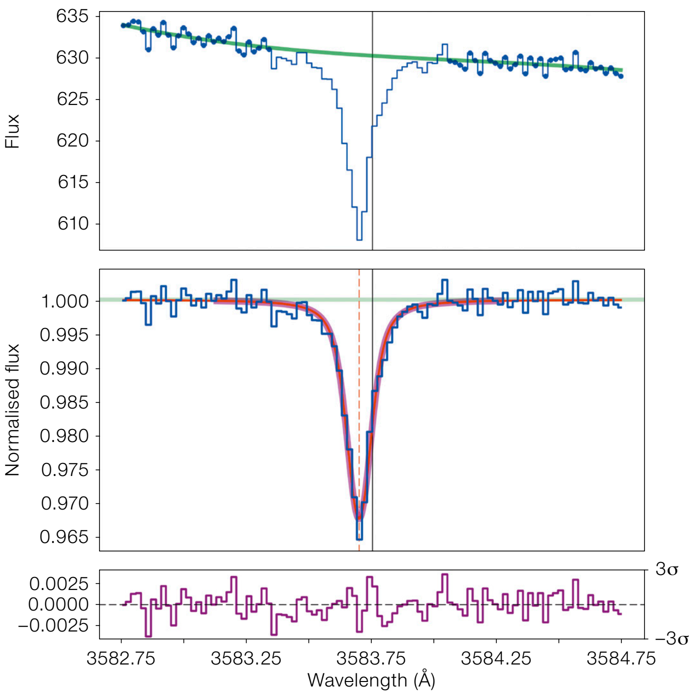


Figure 5 (above). The strongest OH^+ line at 3584 Å in the EDIBLES spectrum of HD 80558, with a Voigt profile fit.

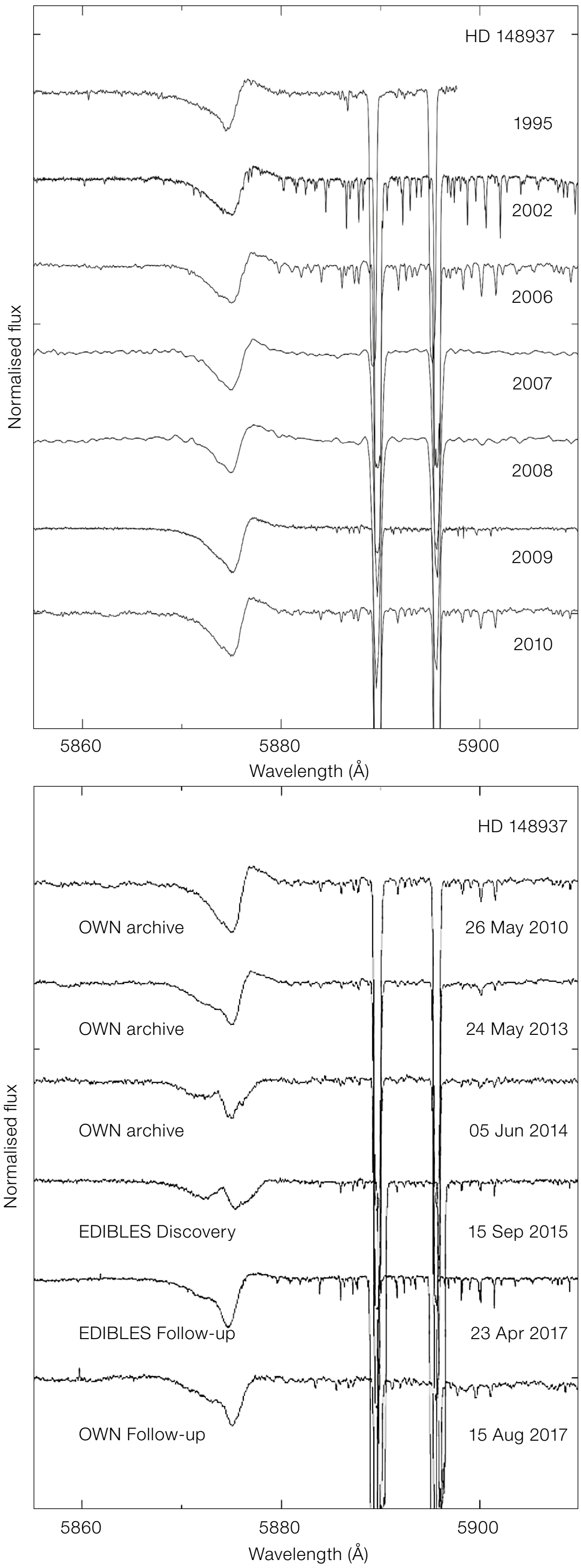


Figure 6. Upper Right: Archival observations showing the line profiles of the He I line at 5876 Å in HD 148937 between 1995 and 2010. Right: Archive observations from the Southern Galactic O- and WN-type stars (OWN) campaign (Barba et al., 2010) and EDIBLES observations of the same line between 2010 and 2017. Note how the character of the line profile changed markedly in 2014–2015 (Figure from Wade et al., in preparation).

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