LETTER

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Infrared diffuse interstellar bands in the Galactic Centre region

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The spectrum of any star viewed through a sufficient quantity of diffuse interstellar material reveals a number of absorption features collectively called 'diffuse interstellar bands' (DIBs). The first DIBs were reported about 90 years ago[1], and currently well over 500 are known[2]. None of them has been convincingly identified with any specific element or molecule, although recent studies suggest that the DIB carriers are polyatomic molecules containing carbon[3–5]. Most of the DIBs currently known are at visible and very near-infrared wavelengths, with only two previously known at wavelengths beyond one micrometre (10,000 ångströms), the longer of which is at 1.318 micrometres (ref. 6). Here we report 13 diffuse interstellar bands in the 1.5–1.8 micrometre interval on high-extinction sightlines towards stars in the Galactic Centre. We argue that they originate almost entirely in the Galactic Centre region, a considerably warmer and harsher environment than where DIBs have been observed previously. The relative strengths of these DIBs towards the Galactic Centre and the Cygnus OB2 diffuse cloud are consistent with their strengths scaling mainly with the extinction by diffuse material.

Figure 1 shows spectra of three Galactic Centre stars, namely GCS3-2 (ref. 7), X174516 (ref. 8) and qF362 (ref. 9) in a small portion of the H band (wavelength 1.5–1.8 μm). These three stars have very different intrinsic spectra, yet they have four common absorption features in this wavelength interval. These features appear to be present in the spectra of all six Galactic Centre stars that we have observed to date, whose spectral classifications range from late B to Wolf-Rayet. A weaker fifth feature is detected in most of the stars. Their full H-band spectra show considerable diversity, as expected, with the exception of these absorptions and a number of additional ones reported below. This is evidence that the newly discovered absorption features are formed in interstellar material. Further evidence comes from their fixed wavelengths from star to star, in comparison to the wavelength shifts in the Brackett lines due to the radial velocities of the stars and in some cases their stellar winds. The strengths of the stronger features are the same to within 20% from star to star. GCS3-2 and qF362 are separated from each other on the plane of the sky by about 1 pc (we assume a Galactic Centre distance of 8 kpc), whereas X174516 is separated from each of them by about 55 pc and thus is observed on a distinctly different sightline.

Searches of atomic line databases show that none of the absorption features corresponds within 0.002 μm to atomic or ionic lines with low-lying lower energy levels. The irregular pattern of their wavelengths and their differing intensities do not lend themselves to identification as one or more simple molecules. None has been reported in the spectra of young stars embedded in dense molecular clouds. However, previously unpublished spectra of bright stars in the Cygnus OB2 cluster contain four of the five absorption features (Fig. 1). The Cygnus OB2 cluster lies behind a diffuse cloud that attenuates optical light by 5–6 mag (ref. 10) and is responsible for the numerous DIBs in the optical spectra of these stars[11], as well as the two previously discovered J-band DIBs[6,12]. Finally, as discussed below, in the J-band (1.1–1.35 μm) spectrum of qF362 (the only one of the six that we have observed in that band), the longer wavelength of the two previously discovered J-band DIBs[6] is clearly detected at 1.318 μm; the signal-to-noise ratio at the wavelength

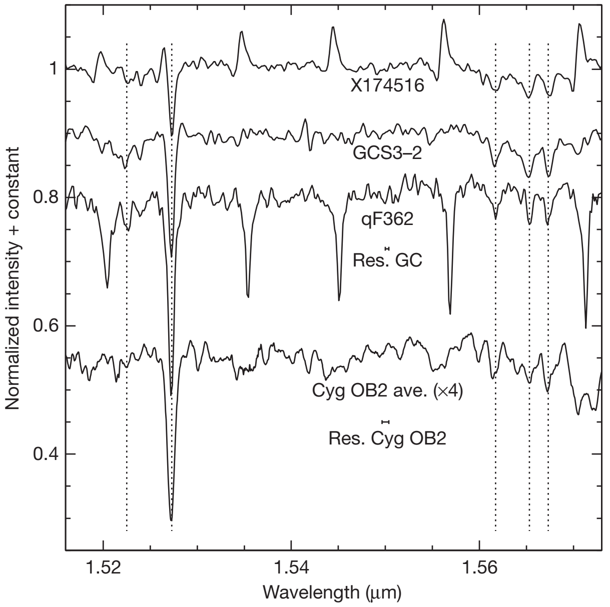

Figure 1 | Observed spectra of three hot stars in the Galactic Centre and an average spectrum of seven stars in the Cygnus OB2 association. Shown (top to bottom) are spectra of stars X174516, GCS3-2 and qF362, and the Cygnus OB2 average spectrum. The wavelengths of five newly discovered diffuse interstellar bands (DIBs) are indicated by vertical dotted lines. The prominent emission lines in the spectrum of X174516 and absorption lines in the spectrum of qF362 are Brackett series transitions of atomic hydrogen (lower-level quantum number 4 and upper-level quantum numbers 15–20), which are often present in hot and luminous stars. The strongest DIB, at 1.5273μm, is blended with one of the Brackett lines in the spectra of X174516 and qF362, but is uncontaminated in the spectrum of GCS3-2. The observations of the Galactic Centre sources were carried out in July 2010 on Mauna Kea at the Frederick C. Gillett Gemini North Telescope using its near-infrared integral field spectrograph, NIFS. Spectra of the unreddened early A-type dwarf stars, HD 156721 and HD 174249, located outside the Galactic Centre and far from Galactic Centre sightlines and observed at similar airmasses, served as telluric standards. The prominent hydrogen absorption lines in their spectra were removed by dividing by a model spectrum of the A-star Vega. The spectra of the Galactic Centre objects were divided by these 'de-lined A-star spectra in order to remove telluric absorption lines. The continuum of each resultant spectrum was fitted with a spline function and divided by that function to produce the normalized spectra, shown here at $R \approx 4{,}000$ (equivalent to a wavelength resolution of 0.00038 μm at 1.54 μm; scale bar 'Res. GC'). Wavelength calibration, obtained using telluric absorption lines, is accurate to 0.0001 μm. The Cygnus OB2 average spectrum (resolution $R = 2{,}250$, scale bar labelled 'Res. Cyg OB2') is based on individual spectra obtained in 2002 at the Telescopio Nazionale Galileo on La Palma, which were reduced using similar techniques as described below.

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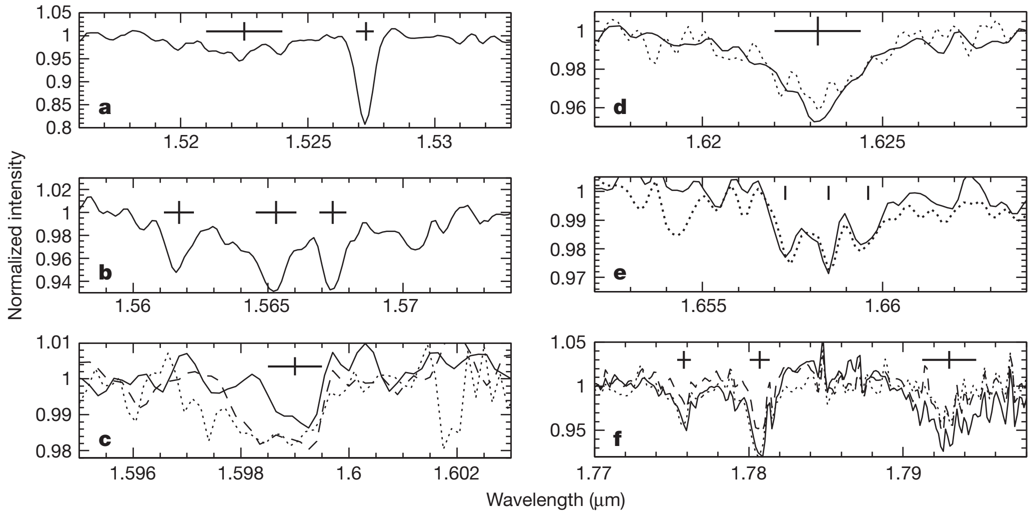

Figure 2 | Spectra of the newly discovered DIBs. Vertical lines in **a**–**f** indicate peak wavelengths, and horizontal lines the observed full-widths at half-maximum. Spectra are shown for three stars: GCS3-2 (continuous lines), X174516 (dashed lines) and qF362 (dotted lines). The DIBs are at the following wavelengths: 1.5225, 1.5273, 1.5617, 1.5653, 1.5673, 1.5990, 1.6232, 1.6573, 1.6585, 1.6596, 1.7758, 1.7807 and 1.7930 μm. Most are considerably weaker than the four strongest ones (see Fig. 1 and **a** and **b** here). In **c**–**f**, the spectrum of more than one star is shown. As the spectra of the individual stars are diverse, we cannot rule out the presence of contaminating stellar lines in some of these spectral regions. The spectrum of GCS3-2 is the least contaminated by stellar lines; thus its spectrum has been weighted most strongly by us in deciding which absorption features are DIBs. The H-band DIBs have a wide range of spectral widths. The optical depth of the strongest DIB at 1.5273 μm is at least twice that of any of the other H-band DIBs. Panels **b**, **e**, **f** contain absorption triplets, centred near 1.565 μm, 1.658 μm and 1.784 μm, respectively. The triplet near 1.658 μm (in **e**) appears to be partially blended and might be regarded as one DIB. However, as discussed in the text, the large velocity dispersion of the diffuse gas in which we believe the bulk of the absorptions arise may be mostly responsible for this blending.

of the shorter wavelength J-band DIB is too low to yield a high-confidence detection.

We conclude, on the basis of all the above evidence, that the newly discovered features are members of the family of DIBs. They are the longest-wavelength DIBs reported to date. Our longer-wavelength K-band (2.0–2.4 μm) spectra of these stars do not reveal additional DIBs, to optical depth limits of ~0.02 or better over most of that band. Figure 2 shows spectra of the complete set of newly discovered H-band DIBs, and Table 1 lists their properties.

Where along the 8-kpc-long sightline to the Galactic Centre are the carriers of the H-band DIBs located? The dust along that sightline produces approximately 30 visual magnitudes of extinction[9], rendering the Galactic Centre unobservable at optical wavelengths. Approximately one-third of the extinction occurs in dense molecular clouds, presumably located in intervening spiral arms, whereas the remaining two-thirds arises in diffuse clouds[13]. The newly discovered DIBs are thus associated with about 20 visual magnitudes of extinction. It is not surprising then that they are considerably stronger towards the Galactic Centre than towards Cygnus OB2.

Table 1 | Properties of DIBs measured towards GCS3-2

Wavelength* (μm)	FWHM†‡ (Å)	τ_{obs}† (max.)	W_λ§ (Å)	No. of detections‖
1.5225	30 ± 10	0.04 ± 0.01	1.6 ± 0.4	4
1.5273	6 ± 1	0.19 ± 0.01	1.5 ± 0.1	6
1.5617	10 ± 2	0.05 ± 0.01		5☆
1.5653	15 ± 4	0.07 ± 0.01	2.8 ± 0.3¶	6
1.5673	9 ± 2	0.07 ± 0.01		6
1.5990	9 ± 2	0.015 ± 0.007	0.15 ± 0.05	4
1.6232	24 ± 3	0.045 ± 0.005	1.3 ± 0.3	6
1.6573	ND	0.022 ± 0.006		4
1.6585	ND	0.028 ± 0.006	0.56 ± 0.12¶	6
1.6596	ND	0.018 ± 0.006		5
1.7758	8 ± 2	0.05 ± 0.01	0.6 ± 0.2	6
1.7807	12 ± 3	0.08 ± 0.01	1.0 ± 0.3	6
1.7930	35 ± 15	0.06 ± 0.02	1.5 ± 0.5	6

FWHM, full-width at half-maximum; τ_{obs}, observed optical depth; W_λ, equivalent width; ND, not determined.

* Uncertainty in wavelength is 0.0010 μm; values obtained assuming peak absorption occurs at v(LSR) = 0 km s^{-1}, where v(LSR) is the radial velocity relative to the Local Standard of Rest.

† Visual estimates; uncertainties depend on strength of DIB and signal-to-noise ratio in the wavelength region of the DIB.

‡ Deconvolved, assuming Gaussian DIB profile and Gaussian instrumental profile.

§ Determined by numerical integration.

‖ Towards Galactic Centre sources, out of six sightlines observed (three shown here, three not shown).

¶ Includes W_λ of DIBs at adjacent wavelengths.

☆ Probably present in the sixth star, but low signal-to-noise ratio of spectrum, and strong and broad emission lines, prohibit clear detection.

There is strong evidence that the diffuse interstellar gas on the sightline to the Galactic Centre is found, almost in its entirety, very close to the centre, in a region of radius ~200 pc known as the Central Molecular Zone (CMZ). Spectroscopy of the molecular ion H_3^+ towards Galactic Centre sources, including GCS3-2, has shown that the CMZ contains a vast quantity of diffuse gas[14,15]. Because the temperature of the gas in the CMZ, which can be measured using H_3^+, is much higher than in diffuse clouds in the Galactic plane, and because of the high velocity dispersion of the gas in the CMZ (~150 km s^{-1} in the direction of GCS3-2; ref. 14), high-resolution spectroscopy of H_3^+ can be used to clearly distinguish between diffuse material inside and outside the CMZ. There is no evidence on these sightlines for a significant fraction of the diffuse cloud material being located outside the CMZ. If, as we suspect, the H-band DIBs largely originate in the CMZ's diffuse gas, their widths are probably Doppler-broadened similarly to H_3^+. That broadening, corresponding to ~0.0008 μm in the H band, is greater than the resolution of the spectrum (0.0004 μm). Thus some of the newly discovered DIBs may have intrinsic spectral widths that are much less than they appear towards the Galactic Centre, perhaps only a few ångströms. This is not unusual, as many DIBs at visual wavelengths have widths of ~1 Å (ref. 16). However, as the precise velocity distribution of the material producing these DIBs is not known, the laboratory wavelengths of the new bands currently should be considered accurate to only ±0.0010 μm (±10 Å).

Spectroscopy of Galactic Centre sources is much more difficult in the J band than in the H band, because the attenuation by dust is nearly an order of magnitude greater in the former. Nevertheless, we have secured a J-band spectrum of qF362, in which the previously discovered 1.318 μm DIB is prominently present. Figure 3 shows the portion of the spectrum containing this DIB. The strengths of the 1.318-μm and 1.527-μm DIBs in the Galactic Centre sources are both about four times greater than they are in the spectra of stars in Cygnus OB2. If the strengths of these DIBs scale roughly with extinction[16], they imply that

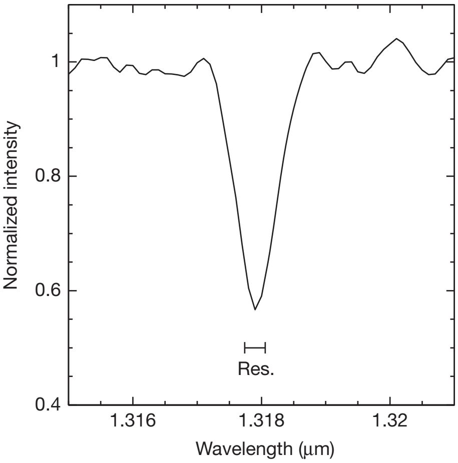

Figure 3 | Profile of the 1.318-μm diffuse interstellar band towards qF362. The equivalent width of the feature is 3.13 Å, with an uncertainty of ±0.10 Å, compared to 0.86 ± 0.06 Å in the Cygnus OB2 cluster star BD +40°42203, which suffers a visual extinction of 5.97 mag (ref. 20). Scaling extinction with the equivalent width of the 1.318 μm feature results in an estimated diffuse cloud visual extinction towards qF362 of 21.7 ± 1.7 mag, which is consistent with a previously estimate of diffuse cloud extinction towards the Galactic Centre[12]. The resolution of the spectrum is $R \approx 4,000$ (equivalent to a wavelength resolution of 0.00033 μm at 1.32 μm; scale bar 'Res.').

there are ~20 mag of visual extinction in diffuse clouds towards the Galactic Centre, which is consistent with previous estimates[13].

The diffuse interstellar medium in the Galactic Centre is a considerably harsher environment than the diffuse clouds where DIBs have been previously observed. The gas temperatures in the centre are 200–300 K (ref. 13), compared to 30–100 K in Galactic diffuse clouds[18], and the cosmic ray ionization rate is an order of magnitude higher[14,17]. The finding that the strengths of the J-band and H-band DIBs in Cyg OB2 and the Galactic Centre are in rough proportion to the extinction suggests that the carriers of these bands survive equally well in both environments.

Interstellar extinction is mainly caused by silicate-based dust particles[18], and thus it is not obvious that the strengths of the 1.318-μm and 1.527-μm DIBs should depend only on the extinction in diffuse clouds if, as suspected, their carriers are carbonaceous. Indeed, in the Galactic plane the strengths of many visual wavelength DIBs do not correlate well with extinction[19] or with one another from source to source[4,19]. Owing to the high extinction towards the Galactic Centre, no information on the strengths of visual DIBs in that direction is available, and thus comparisons of them with the new H-band DIBs cannot be made.

In contrast to the H-band DIBs, the strength of the 3.4-μm interstellar hydrocarbon absorption band is 2–3 times higher towards the Galactic Centre than one would predict by scaling its strength in Galactic diffuse clouds by the ratio of extinctions[20]. The different behaviours of two families of probable carbonaceous particles—the carriers of the H-band DIBs and the carriers of the 3.4-μm feature—indicate that their abundances respond differently to the different physical conditions inside and outside the Galactic Centre, and suggest that the carriers are not closely coupled by interstellar chemistry. A similar conclusion has been drawn for a limited number of visual wavelength DIBs observed in several other sightlines[21]. Differences in the interstellar carbon abundance in diffuse clouds in the Galactic plane and in the Galactic Centre could also affect the relative strengths of the bands in those locations, but little information on the carbon abundance in the Galactic Centre is available.

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