The Diffuse Interstellar Bands
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Anomalously Broad Diffuse Interstellar Bands and Excited CH^+ Absorption in the Spectrum of Herschel 36

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Abstract. Anomalously broad diffuse interstellar bands (DIBs) at 5780.5, 5797.1, 6196.0, and 6613.6 Å are found in absorption along the line of sight to Herschel 36, an O star system next to the bright Hourglass nebula of the HII region Messier 8. Excited lines of CH and CH^+ are seen as well. We show that the region is very compact and itemize other anomalies of the gas. An infrared-bright star within 400 AU is noted. The combination of these effects produces anomalous DIBs, interpreted by Oka *et al.* (2013, see also this volume) as being caused predominantly by infrared pumping of rotational levels of relatively small molecules.

Keywords. ISM: lines and bands, ISM: molecules, Line: profiles, Stars: individual: Herschel 36

1. Introduction

The diffuse interstellar bands (DIBs) have been observed in the spectra of reddened stars for over 90 years (Heger 1922). The known number of DIBs has increased slowly since 1922 and now exceeds 540 between 4100 Å and 9000 Å, to a limit of a few mÅ equivalent width and FWHM from 0.35 Å to >40 Å (Hobbs *et al.* 2008, 2009). Searches in the UV, optical and infrared are underway (Snow & McCall 2006; Geballe *et al.* 2011). Small differences in the profiles of optical DIBs from line-of-sight to line-of-sight have been noted by many authors, but only on scales of <10 km s^{-1} except where widely spaced interstellar components are involved. A detailed summary is given by Dahlstrom *et al.* (2013). Shifts and profile changes were once thought to be indicative of possible grain surface origins of DIB carriers, but recent polarization measurements of DIBs by Cox *et al.* (2011) seem to rule that out.

Thus, recent evidence has strengthened the view that the source of the DIB absorption is molecules, even though numerous laboratory studies have failed to produce convincing matches (see, e.g. Motylewski *et al.* 2000, as well as numerous contributions to this volume). Assuming the DIB carriers are molecules, the combination of blended absorption features of excited rotational levels pumped by the Cosmic Microwave Background and local infrared sources, together with internal broadening mechanisms including internal conversion and lifetime broadening (Oka *et al.*, this volume) may explain DIB profiles, though detailed proof is yet lacking.

After describing the morphology of the region around Herschel 36 in Section 2, we present observations of anomalous DIBs and excited CH^+ toward Herschel 36 in Section 3. In Section 4, we discuss the several anomalies of a small gaseous region in this direction. Section 5 summarizes our conclusions. Details of wavelengths adopted for DIBs and our velocity scales can be found in Dahlstrom *et al.* (2013). The extended DIB absorption to the red is referred to as ETR.

2. Morphology of the Region near Herschel 36

The star Herschel 36 (R.A. $18^h03^m40^s.4$; Dec -24°22′44″) was observed as part of our extensive, high signal-to-noise survey of spectra of hot stars, in search of correlations of DIBs with other interstellar parameters (Thorburn *et al.* 2003; Friedman *et al.* 2011). We aim to obtain a signal-to-noise (S/N) ratio of 1000 in our target stars at resolving powers of 37,000 to 50,000. The survey is being conducted with the ARC echelle spectrograph (ARCES) at Apache Point Observatory (Wang *et al.* 2003); with archival spectra from the Fiber-fed Extended Range Optical Spectrograph (FEROS; Kaufer *et al.* 1999) at ESO; and with the MIKE spectrograph on the Magellan Clay Telescope.

A triple system probably consisting of three O stars (Arias *et al.* 2010), Herschel 36 was first catalogued by Sir John Herschel (Herschel 1847). It is a member of the very young star cluster NGC 6530. Two other cluster O stars of still earlier spectral type, HD 164794 (9 Sgr) and HD 165052, appear to be primarily responsible for exciting the large, resulting H II region M8 (NGC 6523; the Lagoon Nebula). Owing to its proximity, however, Herschel 36 is primarily responsible for ionizing the brightest part of M8, the Hourglass Nebula (Thackeray 1950). While the typical reddening for cluster stars is $E(B-V) = 0.33$ (Walker 1957), the higher color excess of Herschel 36 and its anomalous extinction (Hecht *et al.* 1982) raise the level of visual extinction by $A_V = 4$ mag, compared to even nearby cluster stars. Herschel 36 sits behind (in projection, presumably) a dark lane that extends SW from Herschel 36 for about 6″, and intersects the Hourglass to the west of Herschel 36, which is 10″ from Herschel 36. The region was extensively discussed by Thackeray (1950).

Goto *et al.* (2006) found a bright IR source (designated Her 36 SE) only 400 AU (0.25″) from Herschel 36 in K-band, VLT imaging. The optically obscured source is inferred to be an early B star with $A_V > 60$ mag – deeply embedded in dense, warm dust and powering a very compact H II region. A portion of the dark lane shows up in the Goto *et al.* (2006) image as being bright at 3.8 μm. That section is about 2100 by 6600 AU and centered 1300 AU from Herschel 36. This portion may be at a temperature of a few hundred Kelvin, but the rest of the dark lane does not show up at 3.8 μm.

Images of the region may be found, on successively larger scales, in Goto *et al.* (2006) and Dahlstrom *et al.* (2013) and at the website

`http://www.starshadows.com/_img/image/gallery/4/Lagoon_Master1.jpg`

3. DIBs and Molecular Lines in the Spectrum of Herschel 36

Thirty-five spectra, each 1/2 hour long, were accumulated with ARCES: the co-added spectrum has a signal-to-noise ratio of about 600 per 0.17Å resolution element near 6500Å. Fig. 1 shows (to the left) spectra of four DIBs in Herschel 36, compared with HD 18326, a similar star with similar reddening. On the right are the ARCES spectra of

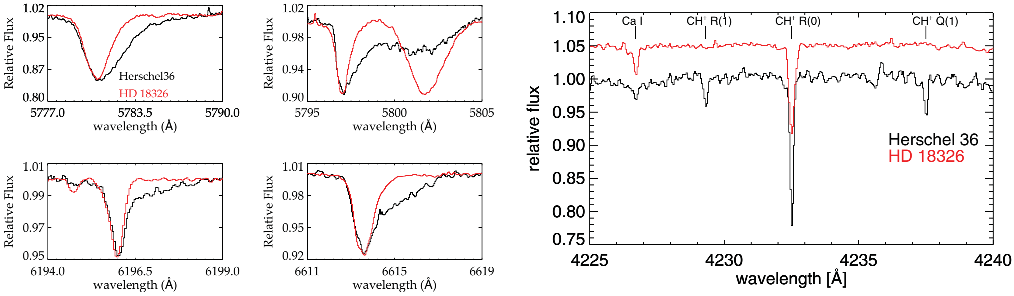

Figure 1. APO spectra of the DIBS $\lambda5780.5$, $\lambda5797.1$, $\lambda6196.0$ and $\lambda6613.6$ (*left*), and of lines near CH^+ (*right*), toward Herschel 36 and HD 18326. The two stars are well matched in spectral type and reddening. All four DIBs show ETR in the spectrum of Herschel 36, but not in the spectrum of HD 18326. For CH^+, the $R(1)$ and $Q(1)$ lines are seen, but the $R(2)$ and $Q(2)$ lines are not detected (Oka *et al.* 2013; see also Oka *et al.*, this volume). The spectra have been scaled to match the depths of the DIBs at the line cores. Note the obvious stellar line at 5802Å, which should be ignored.

the CH^+ region. The resolving power is 37,000. These DIBs and other interstellar lines were confirmed in spectra of higher resolving power by examination of spectra from the AAT, in archival FEROS spectra and in new spectra obtained by us with MIKE in 2012. While we focus here on the extended red wings, other details of the profiles are considered by Dahlstrom *et al.* (2013). Seven other DIBs in Herschel 36 showed ETR while 22 cases showed no significant ETR and 11 cases were ambiguous for want of high enough S/N. A few DIBS seem unexpectedly weak, so further observations are needed.

To explore the size of the region that shows the anomalous wings, we show in Fig. 2 the profiles of the four DIBs toward four stars: Herschel 36, a foreground star (HD 165814, 580 pc from Earth) and two bright stars in NGC 6530. The respective angular separations from Herschel 36 are 1.6°, 3′ (1.3 pc) and 1.5′ (0.7 pc). Spectra were taken with $R \sim 50,000$, the first and third with MIKE, the others from the FEROS archive. All four lines-of-sight are relatively simple in K I, CH, and CH^+ – with a single dominant component (at these resolutions) near $v \sim -5.5\,\mathrm{km\ s^{-1}}$ but these features are stronger toward Herschel 36 than the other stars, by more than a factor of two. Only Herschel 36 shows the ETR and the excited CH^+. The profiles for the other two stars in NGC 6530 and for the foreground star HD 165814 resemble those typically seen in the local Galactic ISM. The molecules CN and C_2 are not detected. Molecular hydrogen is seen toward the last three stars and is presumably also to be found toward the top star.

Strong absorption from vibrationally excited H_2, presumably caused by UV pumping, is found only toward Herschel 36. It is comparable to that noted toward HD 37903 (Meyer *et al.* 2001) and attributed to proximity to that B star. The even greater proximity of the gas to a triple O-star and the anomalous flat UV extinction curve make the presence of excited H_2 not unexpected toward Herschel 36.

4. Discussion

The excitation of CH^+ toward Herschel 36 – and its absence in all other lines of sight in our database (and in the literature) – implies that both the excited CH^+ and the DIB carriers producing the extended redward wings in this sight line are located in a relatively small region near Herschel 36. From the spectra presented above, and consideration of eleven additional lines of sight within 2 degrees of Herschel 36, the region can reasonably be located less than 0.7 pc from Herschel 36. From structures seen in IR emission in the

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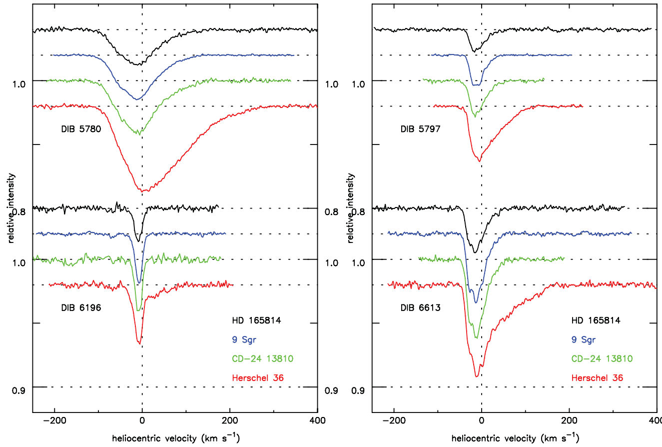

Figure 2. Profiles for four DIBs in each of four stars, all labeled on the plots. The stars are in order of distance from the Sun and angular proximity to Herschel 36 (see text).

region, (see above), it may not be unreasonable to think that the region is even smaller, perhaps on the order of a few thousand AU, with a density as high as 1000 H nuclei per cubic centimeter.

What are the properties of this special region? From a study of the additional stars noted above in NGC 6530, we computed average properties, to compare with the properties of Herschel 36. Herschel 36 has $\log N(\mathrm{H\,I}) = 21.95$ (5 times the average for other stars in NCG 6530); $\log N(\mathrm{H_2})$ less than or about 20 (no more than any other star in the sample); a fraction by number of H nuclei in molecular hydrogen compared to atomic hydrogen of $< 1/3$ of what is typical for the other stars; as high as 10 times more ground state CH and CH^+ as is found toward other stars; an R_V value ~ 6 vs. ~ 3 for other stars; a total color excess, $E(B-V)= 0.87$, compared to an average of 0.35 for other cluster stars in our sample; DIB strengths that are twice the average of that found in the comparison stars; a ratio of DIB strengths to $N(\mathrm{H\,I})$ that is lower than average by about a factor of two (though not as deficient as found by Friedman *et al.* (2011) and Herbig (1993) for several Orion Trapezium stars); and a fraction of vibrationally excited molecular hydrogen that is below 0.1 but far exceeds values in any other comparison star. These comparisons do not imply that the small region of interest is homogeneous in density or radiation temperature: the latter appears not to be true and there are no data to allow comment on the former. It is noteworthy that the ratio of $N(\mathrm{CH})$ to $N(\mathrm{H_2})$ is quite different from what is found elsewhere in the Galaxy, suggesting the CH comes from a formation mechanism involving the abundant CH^+ (Zsargó & Federman 2003), rather than the apparently depleted H_2. The data uniformly point to an elevated optical and UV radiation field in the special region near Herschel 36. We note that some of the material seen toward all the stars may be much closer to the Sun than NGC 6530. Riegel & Crutcher (1972) argue for a large sheet of gas, seen in H I and Na I, ∼150 pc from the Sun and extending over much of NGC 6530. HD 165814 (Fig. 2) is at 580 pc and may sample that cloud. Removal of the foreground contribution would imply even more extreme properties for the material near Herschel 36.

More data are obviously required. Spectra with a resolving power of 600,000 may allow separation of overlapping components and could constrain the temperature and turbulent conditions in the special region. HST/STIS observations of C I would indicate the density in the region compared to clouds toward other stars: the width of the many

H_2 vibrational lines could show if CH^+ and H_2 are co-located. If both were at 1000 K, the line widths would differ by a factor of two. Higher S/N observations of DIBs in Herschel 36 are needed to determine how many DIBs have ETR.

5. Conclusions

Extended redward DIB wings and excited CH^+ toward Herschel 36 appear to arise in a small region near the star, coincident, in part, with an optical dark lane and very near an IR-bright star. Oka *et al.* (2013, this volume) interpret the broad DIB wings in terms of IR pumping of the closely spaced high-J levels of relatively small (5-6 atoms) DIB carrier molecules with strong permanent dipole moments, suggested by the unique presence of excited CH and CH^+ from the same region. A search for additional anomalies in this and other stars is underway.

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