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Diffuse interstellar bands near 9600 Å: not due to C60$^+$ yet

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Abstract. High spectral resolution studies of the two Diffuse Interstellar Bands (DIB) previously assigned to C60$^+$ (λ9577 and λ9632) confirm that these DIBs have the same full-width-at-half-maximum and behave similarly in dense cloud environments where the DIBs are weakened relative to the diffuse interstellar medium. Their relative strength, however, is less than previously reported and differs from the relative intensities measured from matrix isolation spectroscopy. A simultaneous search for the two laboratory derived vibronic tranistions of C60$^+$ at about 9366 and 9419 Å has not lead to the detection of the two weak counterparts stronger than 15% of λ9577. We conclude that for the diffuse band spectrum to be consistent with C60$^+$, not only the measured band positions have to be slightly different in the gas-phase, but also the relative intensity of the two main lines has to differ significantly from that of the known laboratory data.

Key words: ISM: molecules – line: identification

1. Introduction

In search for the carriers of Diffuse Interstellar Bands (DIB), Foing & Ehrenfreund (1994) reported the discovery of two DIBs at 9577 and 9632 Å that are close to the laboratory position of two strong electronic transitions of C60$^+$, which were measured by matrix isolation spectroscopy in neon at 9580±4 and 9642±3 Å with an intensity ratio of 1:1.5 (Fulara et al. 1993). Fullerenes had been proposed as a possible candidate for the DIBs (Kroto 1987, Léger et al. 1988) and the identification was quickly embraced (e.g. Smith 1995) in spite of its far reaching implications (e.g. Herbig 1995), not in the least because there seemed to be only two such strong DIBs in a wide range of the infrared spectrum (Ehrenfreund et al. 1995, Foing & Ehrenfreund 1995). The implications were that C60$^+$ had to be a common molecule in the diffuse interstellar medium, where it should play an important role in gas phase chemistry and in the heating and cooling of the gas. Recently, it was shown that C60$^+$ might be formed in the gas phase through a chemical network involving ion-neutral reactions (Bettens & Herbst 1996), taking away earlier objections that a plausible ISM formation mechanism was lacking.

Questions were immediately raised. First of all concerning the observations, because the nature of the absorption features was not well established due to problems with the removal of water lines and the low detector and grating sensitivity at those near-infrared wavelengths. Observations from a dryer site were called for. Also, the Foing & Ehrenfreund (1994) paper did not report on the two weaker vibronic transitions that had been measured in the laboratory at 9366 and 9419 Å with a strength of about 29% and 15% of the two vibrationless transitions respectively. If observed, their equivalent width should scale to the reported bands in the 9600 range as in the matrix spectrum and should possess a comparable FWHM (Maier 1994).

Here, we report on a high spectral resolution study of the two "C60$^+$ bands" in the line of sight to three reddened stars with different stellar Doppler velocities. This allows us to discriminate between interstellar and stellar photospheric absorptions. We have also searched for the vibronic bands around 9400 Å. We confirm the existence of both DIBs, but find that the 9632 Å band relative to λ9577 is weaker in dense cloud environments than previously reported.

2. The observations

High resolution (R=100.000) spectra were obtained with the 1.4m ESO/CAT telescope and the CES spectrograph, configured with the long camera and CCD detector number 38, on November 19 and 21, 1996. With this setting, each resolution element is 0.07 Å and covered by 3 pixels. The bandwidth is about 100 Å centered at 9390 and 9604 Å.

Six early type stars were observed in each wavelength range. Because of heavy atmospheric lines in these spectra, near equality of airmass of the reddened and unreddened stars took priority

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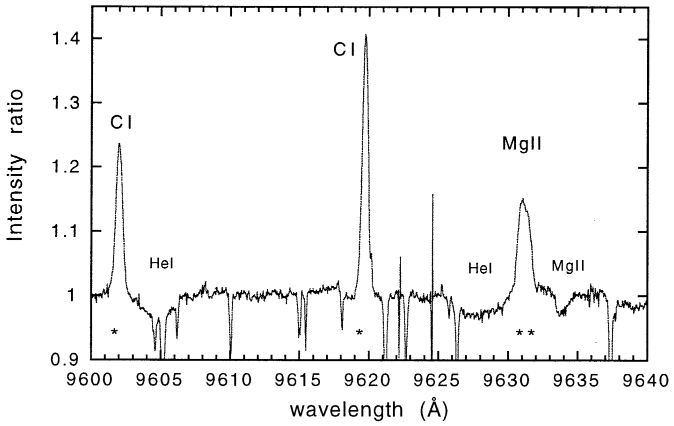

Fig. 1. Spectrum of the unreddened star HD 81188 (B2IV) after removal of the telluric lines using the spectrum of HD 47105 (A0IV) as reference. Stellar lines of HD 47105 show up as 'emission' features. Note the blend of two stellar lines near 9632 Å.

over an exact spectral type match. The three reddened stars are HD 80077 (B2Iape, E_{B-V} = 1.41), HD 63804 (A0Iap, E_{B-V} = 1.17) and HD 43384 (B3Ia, E_{B-V} = 0.57). Reddening values were derived from Hipparchos Input Catalogue data. In addition, we observed the reference stars HD 34085 (B8Ia, E_{B-V} = 0.00, only used for the 9400 Å window), HD 47105 (A0IV, E_{B-V} = 0.03), HD 81188 (B2IV, E_{B-V} = 0.05) and HD 52089 (B2II, E_{B-V} = 0.02).

Figure 1 shows part of the spectrum of the unreddened star HD 81188, after the telluric lines have been removed using HD 47105 as a reference: it is clear that the stellar lines of HD 47105 show up as 'emission' features, while some residual telluric lines are present due to different airmasses. Note that the 9632 Å line in HD 47105 is broad, showing two components. These are the MgII lines, at 9631.888 and 9632.435 Å (NIST Atomic Spectroscopic Database), recognized by Foing & Ehrenfreund (1994) as overlaying the DIB at 9632 Å.

Luckily enough, HD 47105 is either a very slow rotator or pole-on, so its stellar lines are rather narrow and very recognizeable as such. We made use of this fact to improve the removal of telluric contamination by adopting the following procedure: we first removed the telluric lines from the spectrum of HD 47105 using HD 81188 as a reference, then we fitted the stellar lines of HD 47105 with splines and finally divided them away from the original spectrum of HD 47105, obtaining a "pure" telluric spectrum. This pure telluric spectrum was used to remove the tellluric lines from other reference stars. That, in turn, allowed us to recognize and remove the (much broader) stellar lines before using these spectra as telluric reference for our program stars.

The 9400 window is even more affected by telluric water lines. We were unable, in this case, to accurately separate, and thus remove, the stellar lines from the spectra of our reference stars. Hence, the resulting spectra from this window show some 'emission' features due to stellar lines in the spectra of the telluric reference stars.

Table 1. Equivalent width (in mÅ) of absorption features in the 9600 Å window. *-shift: offset position stellar lines as observed from rest wavelength in air λ_{rest} (in Å).

Ident.	λ_{rest}	47105	81188	52089	43384	63804	80077
	Å	A0IV	B2IV	B2II	B3Ia	A0Iap	B2Iape
HI	9545.97	+	+	+	+	+	+
CI	9603.09	137	-	-	-	(44)	-
HeI	9603.50	-	50	143	102	-	(17)
CI	9620.86	211	-	-	-	(22)	-
HeI	9625.80	-	52	75	145	-	56
MgII	9631.89	141	31	64	107	130	156
MgII	9632.44						
CI	9658.49	203	-	-	-	(28)	-
λ9577	9577.4	-	-	-	41	123	172
λ9632	9632.6	-	-	-	(40)	113	(146)
s.d.:		±7	±12	±7	±18	±11	±14
$*$-shift:		–1.1	+1.8	+0.3	–0.1	+1.8	+0.0

3. Results

3.1. The 9600Å window

In the 9600 Å window, we expected to find two strong DIBs at 9577 and 9632 Å. Indeed, the spectra of reddened stars show two strong absorptions near these positions (Fig. 2).

The DIB λ9577 has a rest wavelength (in air) at 9577.4 ± 0.2 Å. The band profile is symmetric, with strong Lorenz-like wings. In HD 80077, the DIB has a Full-Width-at-Half-Maximum of FWHM = 3.0±0.2 Å. The equivalent width per unit E_{B-V} is 0.072±0.028, 0.105±0.011 and 0.122±0.013 respectively for HD 43384, HD 63804 and HD 80077. From the figure shown in Foing & Ehrenfreund (1994), we measure W/E_{B-V} = 0.19 (not 0.39 as given in their paper).

The absorption feature at 9632 Å is a blend of a DIB and the MgII stellar lines. The presence of the DIB λ9632 is indicated by the high relative intensity of the 9632 Å blend in the reddened stars as compared to that in non-reddened stars (Tabel 1). Fortunately, there is not much telluric contamination at this wavelength, which allows us to do the following analysis. Assuming that there is an underlaying DIB in the 9632 Å feature with a similar profile as λ9577, we substracted a λ9577 profile from the 9632 Å feature after proper translation and scaling. When the subtraction is applied to the spectrum of HD 80077, we obtained a residual absorption which has the correct Doppler shift for a MgII stellar line (see Fig. 3 and Tab. 1). When the procedure is applied to the spectrum of HD 63804, the same residual is now shifted by +1.8 Å, again consistent with a MgII line for this star (see Fig. 3 and Table 1). The best fit is obtained for a scaling factor of of 0.85 (0.7-0.9) (HD 80077) and 0.92 (0.8-0.95) (HD 63804) times the depth of λ9577, which measures the relative intensity of both bands. We find that λ9632 has W/E_{B-V} = 0.10±0.02 and rest wavelength 9632.6±0.2 Å.

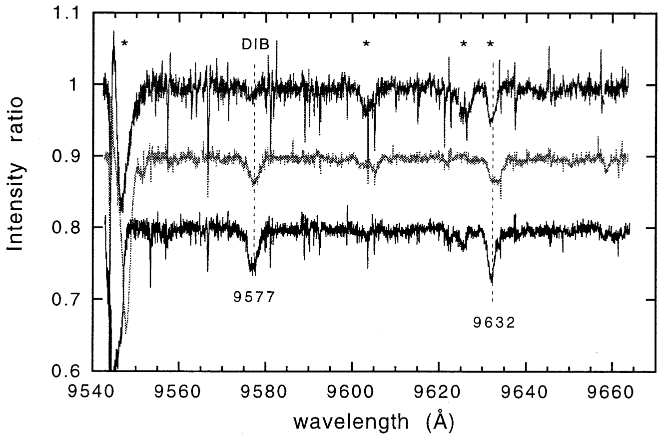

Fig. 2. Spectra of reddened stars divided by the spectra of unreddened stars from which the stellar lines were removed. Top: HD 43384 (B3Ia) corrected using HD 47105. Middle: HD 63804 (A0Iap) corrected with HD 81188. Bottom: HD 80077 (B2Iape) corrected with HD 81188. The last two spectra are displaced by -0.1 and -0.2 units.

In HD 43384, the DIB is weak compared to the stellar lines and the result is uncertain.

3.2. *The 9400 Å window*

In the 9400 window, we searched for two weak features at 9366 and 9419 Å (taking into account the matrix shift of the C60$^+$ bands).

There are four strong stellar lines in the spectra (Fig. 4). The two strong lines at 9387 and 9394 Å are due to N I (9386.79 and 9392.80). The CI line at 9405.77 is present in the standard star HD 52089. In the spectrum of HD 63804 is an emission feature at 9429 Å, which remains unidentified. A strong emission band in HD 52089 at 9413 Å (see the middle spectrum in Fig. 4) is probably a "ghost" from internal reflections in the spectrograph. The 9413.46 line of SI is not responsible for the feature, as there should also be similarly strong lines at 9421.93 and 9437.11 (Moore 1972).

We are able to put a strong upper limit for DIB absorption near 9419 Å in the spectrum of HD 80077 in this region, by using HD 52089 as a telluric standard. In that case, the baseline is not affected by the stellar line at about 9419 Å in the spectrum of HD 34085 (Fig. 4). The expected DIB at 9419±9 Å is not detected with certainty. There is a depression near 9428 Å, however, that would suggest W/E$_{B-V}$ $\sim$ 0.013 Å per magnitude, or about 9% of the intensity of λ9632, assuming a FWHM of 3.0 Å as expected if it is a C60$^+$ vibronic transition (Maier 1994). The reported ratio from laboratory measurements is about 15% (Fulara et al. 1993). However, that depression may well be caused by residual telluric lines.

For the expected position at 9366 Å, there are some candidate wiggles, with W/E$_{B-V}$ = 0.017 Å in HD 63804 and 0.021 Å per magnitude in HD 80077. These values should be considered upper limits, because the features may well be flatfield or atmosphere line remnants. Only in HD 80077 reduced with HD 52089 is there a suggestion of a DIB. If this is a DIB, then the peak intensity is about 16 % of that of λ9577. The expected ratio from laboratory measurements is about 30%.

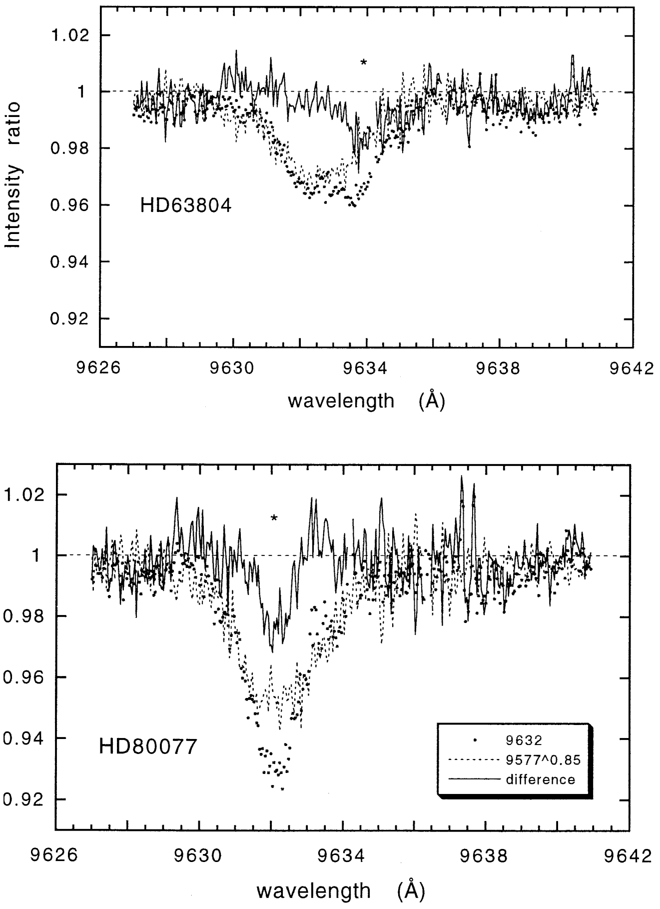

Fig. 3. Overlay of DIB λ9577 (dashed line) on the 9632 feature (dots). The difference spectrum (solid line) reveils the MgII stellar doublet.

4. Discussion

What are the implications of our data for the C60$^+$ assignment? Foing and Ehrenfreund (1994) pointed out that the DIB positions are close to absorptions measured in the laboratory in matrix environment. For the two DIBs to be due to C60$^+$, the gas-phase C60$^+$ spectrum has to have slightly different band positions, presumably due to matrix interactions in the present laboratory data. Comparison of laboratory data with our measured band positions would imply a matrix shift of 2.6±4.0 and 9.4±3.0 Å, which are the same within measurement error, as expected. A more accurate laboratory position of the C60$^+$ absorptions can make this a more important discriminant.

The two bands behave in a similar way in a dense cloud environment. In general, DIBs of a similar broadness class tend to weaken together when some dense cloud matter is in the line of sight (Jenniskens & Désert 1995). Our DIBs are weaker than those measured by Foing & Ehrenfreund in lines of sight that represent the diffuse interstellar medium. This suggests that some amount of dense cloud matter is in front of HD 63804 and HD 80077. A constant line ratio would be expected if both lines are caused by the same molecule. Our result is consistent with this, but does not prove that both bands are due to the same molecule.

Our most striking result is that the relative intensity of the bands (1:0.9) does not agree with the results by Foing & Ehrenfreund (1994) (1:1.6 - with an error of 30% according to Ehrenfreund & Foing 1995), nor with the band intensity ratio measured for C60$^+$ in a neon matrix (1:1.5 - Fulara et al. 1993). Whether or not C60$^+$ can be ruled out completely on the basis of this result depends on the question whether the gas phase spectrum of C60$^+$ has a similar band intensity ratio. Fulara et al. pointed out that the relative intensity of the two band systems at 9580 and 9642 Å depends on experimental conditions: in the case of mass-selected ion deposition, 9580 was slightly more intense than in photoionization experiments. Relative intensities varied from 1:1.5 to 1:2.0 (Maier 1994). Those variations are outside the range of values observed for the two DIBs in our data. The question remains what is responsible for these band strength changes. Fulara et al. interpreted the two bands as due to two configurations of the molecule imposed by the matrix environment. Only if the gas-phase spectrum differs significantly from present laboratory data, would this interpretation be consistent with the two DIBs being due to gas phase C60$^+$.

The smaller band ratio that we find compared to Foing & Ehrenfreund (1994) might suggest that the bands are intrinsically variable, which would exclude C60$^+$ as a carrier of both. However, it is possible that the band ratio of Foing & Ehrenfreund is simply in error. From their graphs, it is clear that the equivalent width of the features are very uncertain and large formal errorbars contradict with a smooth increase of the band strength with reddening. Some residual stellar lines seem to be present in the 9632 feature, inspite of attempts to divide out the lines by adopting telluric standards with similar spectral type. For example, the positions of the sharp and narrow features of HD 190603 and HD 21389 differ by 1.0±0.2 Å. The doppler velocities of interstellar matter account for only 0.06 Å (Jenniskens & Désert 1994). If, on the other hand, one of the lines has a strong stellar line contribution, then the expected variation is 0.8 Å, whereby HD 190603 should be redshifted, as observed.

Indeed, recent new observations presented by Foing & Ehrenfreund (1997), and obtained independently from our results, also imply a much lower band ratio. Our results are in good agreement with data in the latter paper. However, note that that is fortuous, because the observing procedure used by Foing & Ehrenfreund (1997) does also not guarantee that stellar lines are correctly removed. In fact, the somewhat higher band ratio in HD 183143 (1.17±0.2) and the slightly more sharper band profile at the peak is likely due to residual stellar lines.

5. Conclusions

We find that the band width and band profiles of two DIBs previously assigned to C60$^+$ are similar and that the bands weaken in dense cloud environments in a similar manner. We also find that the band positions are consistent with a similar shift for both lines, amounting to about +6.5 Å between gas-phase DIBs and the absorptions measured in the laboratory. These results argue in favor of the C60$^+$ assignment.

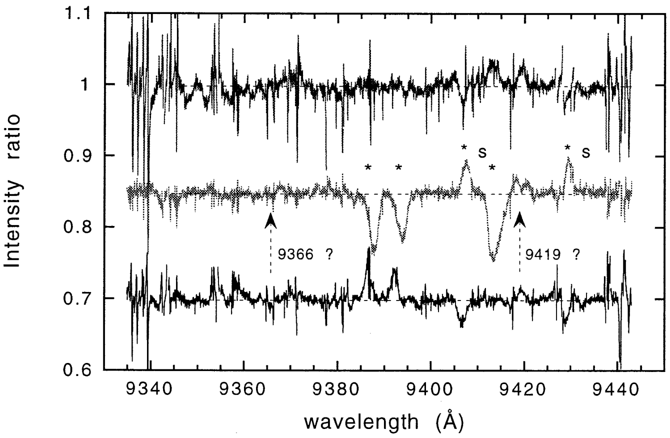

Fig. 4. As Fig. 2 - 9400 Å window. From top to bottom: HD 43384 (B3Ia) corrected using HD 34085 (B8Ia); HD 63804 (A0Iap) corrected with HD 52089 (B2II); HD 80077 (B2Iape) corrrected with HD 34085 (B8Ia). The last two spectra are displaced by -0.15 and -0.30 units.

However, we find that the ratio of λ9632 to λ9577 is less than previously reported and significantly less than the relative peak intensity of the corresponding laboratory positions of C60$^+$. Both DIBs are also weaker in the diffuse medium than previously reported. Only if gas-phase C60$^+$ has band intensity ratios much different from those measured in the neon matrix is there a chance that these DIBs are due to C60$^+$.

We do not find the corresponding vibrational excited transitions near 9400 Å which, however, were expected to be present at only 1-2 sigma above our detection limit.

The diffuse interstellar bands have still not been identified with certainty. At present, C60$^+$ merely joins a long queue of *promising* molecules proposed as carriers of the over 200 absorptions in the visible and near-infrared spectra of reddened stars. However, the case for C60$^+$ is better than for many other candidates and now rests in the court of laboratory spectroscopists.

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References

Bettens R.P.A., Herbst E., 1996, ApJ 468, 686
Ehrenfreund P., Foing B.H., 1995, Planet. Space. Sci. 43, 1183
Ehrenfreund P., Foing B.H., d'Hendecourt L., Jenniskens P., Désert F.X., 1995, AA 299, 213
Foing B.H., Ehrenfreund P., 1994, Nature 369, 296
Foing B.H., Ehrenfreund P., 1995, in The Diffuse Interstellar Bands, A.G.G.M. Tielens, T.P. Snow, eds., Kluwer, p. 65
Foing B.H., Ehrenfreund P., 1997, A& AL 317, L59
Fulara J., Lessen D., Freivogel P., Maier J.P., 1993, Nature 366, 439
Herbig G.H., 1995, ARA&A. 33, 19

Jenniskens P., Désert F.-X., 1995, in The Diffuse Interstellar Bands, A.G.G.M. Tielens, T.P. Snow, eds., Kluwer, p. 39

Jenniskens P., Désert F.-X., 1994, A& A Supp. Ser. 106, 39

Kroto H.W., 1987, in Polycyclic Aromatic Hydrocarbons in Astrophysics, Léger A., d'Hendecourt L., Boccara N., eds., Reidel, Dordrecht, p.197

Léger A., d'Hendecourt, L. Verstraete, L. Schmidt W., 1988, A& A 203, 145

Maier J.P., 1994, Nature 370, 423

Moore C.E., 1972, A Multiplet Table of Astrophysical Interest, NSRDS-NBS 40, National Bureau of Standards

Smith W.H., 1995, in The Diffuse Interstellar Bands, A.G.G.M. Tielens, T.P. Snow, eds., Kluwer, p. 3

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