

IDENTIFICATION OF MORE INTERSTELLAR C_{60}^+ BANDS*

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ABSTRACT

Based on gas-phase laboratory spectra at 6 K, Campbell et al. confirmed that the diffuse interstellar bands (DIBs) at 9632.7 and 9577.5 Å are due to absorption by the fullerene ion C_{60}^+ . They also reported the detection of two other, weaker bands at 9428.5 and 9365.9 Å. These lie in spectral regions heavily contaminated by telluric water vapor lines. We acquired CFHT ESPaDOnS spectra of HD 183143 close to the zenith and chopped with a nearby standard to correct for the telluric line absorption which enabled us to detect a DIB at 9365.9 Å of relative width and strength comparable to the laboratory absorption. There is a DIB of similar strength and FWHM at 9362.5 Å. A stellar emission feature at 9429 Å prevented detection of the 9428.5 Å band. However, a CFHT archival spectrum of HD 169454, where emission is absent at 9429 Å, clearly shows the 9428.5 Å DIB with the expected strength and width. These results further confirm C_{60}^+ as a DIB carrier.

Key words: ISM: general – ISM: lines and bands – ISM: molecules

1. INTRODUCTION

Hundreds of diffuse interstellar bands (DIBs) are seen in the spectra of stars dimmed and reddened by interstellar dust (Herbig 1995). There have been many unsuccessful attempts to assign neutral or charged molecular carriers to either individual or families of these bands. Foing & Ehrenfreund (1994) proposed that a pair of DIBs that they had detected at 9632 and 9577 Å were due to the fullerene ion C_{60}^+ because of their proximity to laboratory absorption wavelengths observed in a neon matrix (Fulara et al. 1993). Campbell et al. (2015) have now proved that these DIBs are indeed due to C_{60}^+ . This is based on measurement of not only the wavelengths, but also the FWHM and relative intensities of these bands in the gas phase at 6 K. This successful identification, which came long after Kroto first predicted the presence of C_{60}^+ in the interstellar medium (Kroto 1987), may be regarded as a first step toward unlocking the 90 year old mystery of the DIB carriers (Herbig 1995; Snow & McCall 2006).

Campbell et al. (2015) also reported two weaker bands of roughly equal strength (3:2) at 9428.5 and 9365.9 Å in their laboratory spectra (their Table 1). Unfortunately, for ground-based observations, both of these wavelengths lie in spectral regions heavily contaminated by telluric water vapor (WV) lines as can be seen in Figure 1. The standard technique for their removal is the division of the reddened star spectrum by one from an unreddened star of a similar spectral type observed through the same airmass.

In this Letter, we report observations of HD 183143 chopped with those of a similar standard lying within 2° on the sky. Atmospheric WV absorption is likely to change with both time and direction as well as with airmass, which is the reason for frequent chopping. HD 183143 is a bright, reddened, B7 supergiant that exhibits all of the known DIBs with

considerable strength (Herbig 1995), including those at 9632 and 9577 Å. It also passes through the zenith at CFHT where the atmospheric precipitable water level can be significantly lower than for sites at lower altitude.

2. OBSERVATIONS OF HD 183143

We were granted two hours of CFHT Director’s Discretionary Time with ESPaDOnS (Donati 2003) on the night of 2015 July 28 UT. HD 183143 and a nearby standard of a similar spectral type, HR 7437, were observed within one hour of meridian crossing with a sky temperature of $\sim -38^\circ\text{C}$, indicating a low WV level. ESPaDOnS happened to be configured in spectropolarimetric mode; a single spectrum consisted of four individual sub-exposures taken at different polarimeter retarder configurations. All of the spectra were reduced at CFHT with the Upena pipeline using the Libre-ESPRIT code (Donati et al. 1997). The spectral resolution is approximately 65,000 or 0.05 Å per pixel. Details of the stars are given in Table 1, which includes V and I magnitudes and color excess, $E_{(B-V)}$.

Observations alternated between the two targets. In this way, four sets of spectra were acquired with airmasses differing by <0.01 within each pair. The total exposure times of 600 and 720 s within each set for HD 183143 and HR 7437, respectively, were chosen to give similar signal levels for both stars in the 9400 Å region.

Telluric lines in typically 20 Å regions of interest in the spectrum of HD 183143 were removed using the subsequent HR 7437 spectrum as standard in the IRAF⁴ telluric program. The four corrected spectra of HD 183143 from each of these spectral regions were then combined to produce the single high signal-to-noise ratio (S/N) spectra in Figure 2. Estimation of S/N is complicated by the presence of the telluric lines within which the

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⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

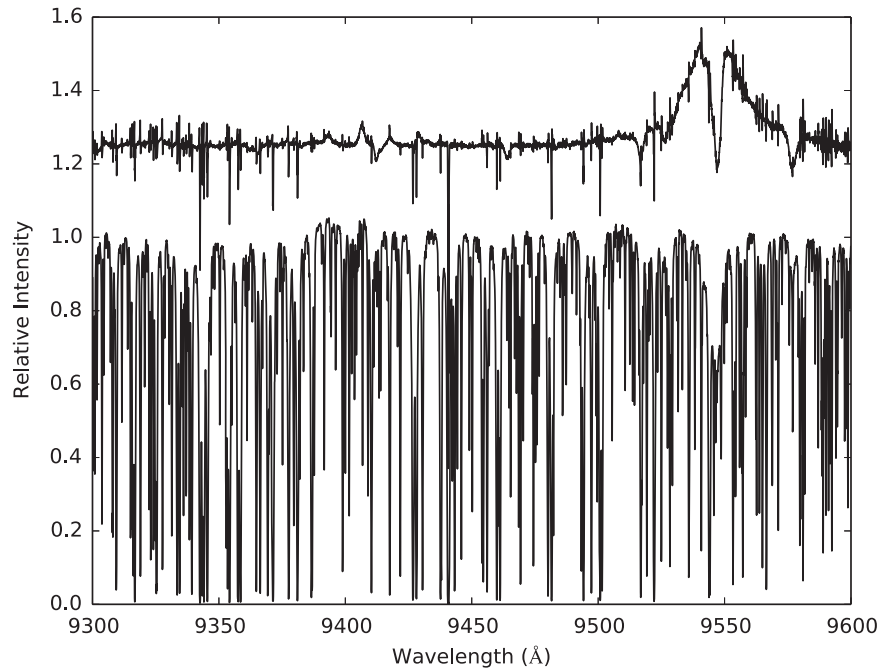


Figure 1. Lower spectrum of HD 183143 taken at CFHT contains the region of the C_{60}^+ absorption bands observed in the laboratory. The spectrum is dominated by strong telluric water vapor absorption lines. The upper plot follows the division of the lower HD 183143 spectrum by that of HR 7437, which eliminates most of the water vapor lines. The feature at 9546 Å is caused by hydrogen (P8); the narrow absorption component is from HD 183143, while the broad reflex (apparent emission) is from the broader P8 absorption line in HR 7437. Weak emission features from HD 183143, as well as a number of DIBs, can be seen throughout the upper plot. The C_{60}^+ 9577.5 Å band is clearly visible.

Table 1
CFHT ESPaDOnS Observations

Star	Sp/L	I	V	$E_{(B-V)}$
HD 183143	B7 Ia	4.79	6.86	1.28
HR 7437	B8 IIIIn	5.10	5.00	0.00
HD 169454	B1 Ia	5.13	6.71	1.12
HD 177724	A4 IV-Vnn	2.98	2.99	0.00

S/N is low. Based on our calculations, $S/N \sim 1500 \text{ Å}^{-1}$ (~ 330 per pixel) for HD 183143 in the region of the 9577.5 Å line after WV removal.

There is a short gap in the ESPaDOnS spectral coverage between 9608 and 9636 Å where the order lies off the detector. This gap prevented our looking for the 9632.7 Å band.

3. RESULTS

The wavelength region of interest from 9300 to 9600 Å is covered in a single échelle spectral order (24) and shown in the lower plot of Figure 1 for HD 183143. All of the strong lines, some near saturation, are due to telluric WV. The upper plot is the result of division by the spectrum of HR 7437. Note that the telluric line cancelation has not been optimized in the figure since, in this case, a single correction was applied to the full 300 Å region displayed. The narrow stellar hydrogen P8 line at 9546 Å in HD 183143 is superimposed on the reflex of the much broader P8 line in HR 7437, illustrating the impact of absorption lines in the standard star. The strong 9577.5 Å band of C_{60}^+ is easily seen. Several other DIBs are also visible.

To optimize telluric line removal, we performed these corrections over more limited spectral ranges containing the wavelengths of the C_{60}^+ laboratory absorptions. This produced higher S/N spectra for the 9577.5, 9428.5, and 9365.8 Å

regions as well as a region centered on the interstellar potassium line at 7699.0 Å in order 29.

Small zero-point adjustments were made to the levels of the HD 183143 and HR 7437 spectra to minimize residuals in the ratios at the centers of the strongest WV lines. The ratios are shown for the four regions in Figure 2. The persistence of some residuals at the centers of the strongest telluric lines is likely associated with nonlinearity of the analog to digital converter over the extreme range of intensity of the lines rather than inequality of WV optical depth.

Figure 2 also shows the two components of the HD 183143 interstellar 7699.0 Å potassium absorption line after removal of nearby telluric lines. The stronger component has a radial velocity of -12 km s^{-1} , the other component $+4 \text{ km s}^{-1}$. At 9577.5, 9428.5, and 9365.8 Å, -12 km s^{-1} corresponds to a displacement of -0.4 Å . We use this value in what follows assuming that the corresponding cloud is the main contributor to the detected DIBs.

Campbell et al. (2015) fitted Gaussians to the laboratory absorptions at 6 K and listed wavelengths and FWHMs (their Table 1). The DIBs in Figure 2 were also fitted with unconstrained Gaussians as shown by the dashed lines, including the obvious DIB at 9362.5 Å. No DIBs could be observed in the region of the 9428.5 Å laboratory absorption because of the emission feature at 9429 Å. The emission must be associated with HD 183143 because the comparison star, HR 7437, is a rapid rotator ($v \sin i = 265 \text{ km s}^{-1}$) such that absorption lines in HR 7437 would produce much broader ($>8 \text{ Å}$) apparent emission features in the ratio. There are many such emission lines between 9300 and 9600 Å for HD 183143. Jenniskens et al. (1997) published spectra in this region and encountered emission lines in either their reddened or standard stars (their Figure 4). It is interesting to note that in the latter study, which was published long before the gas-phase spectrum

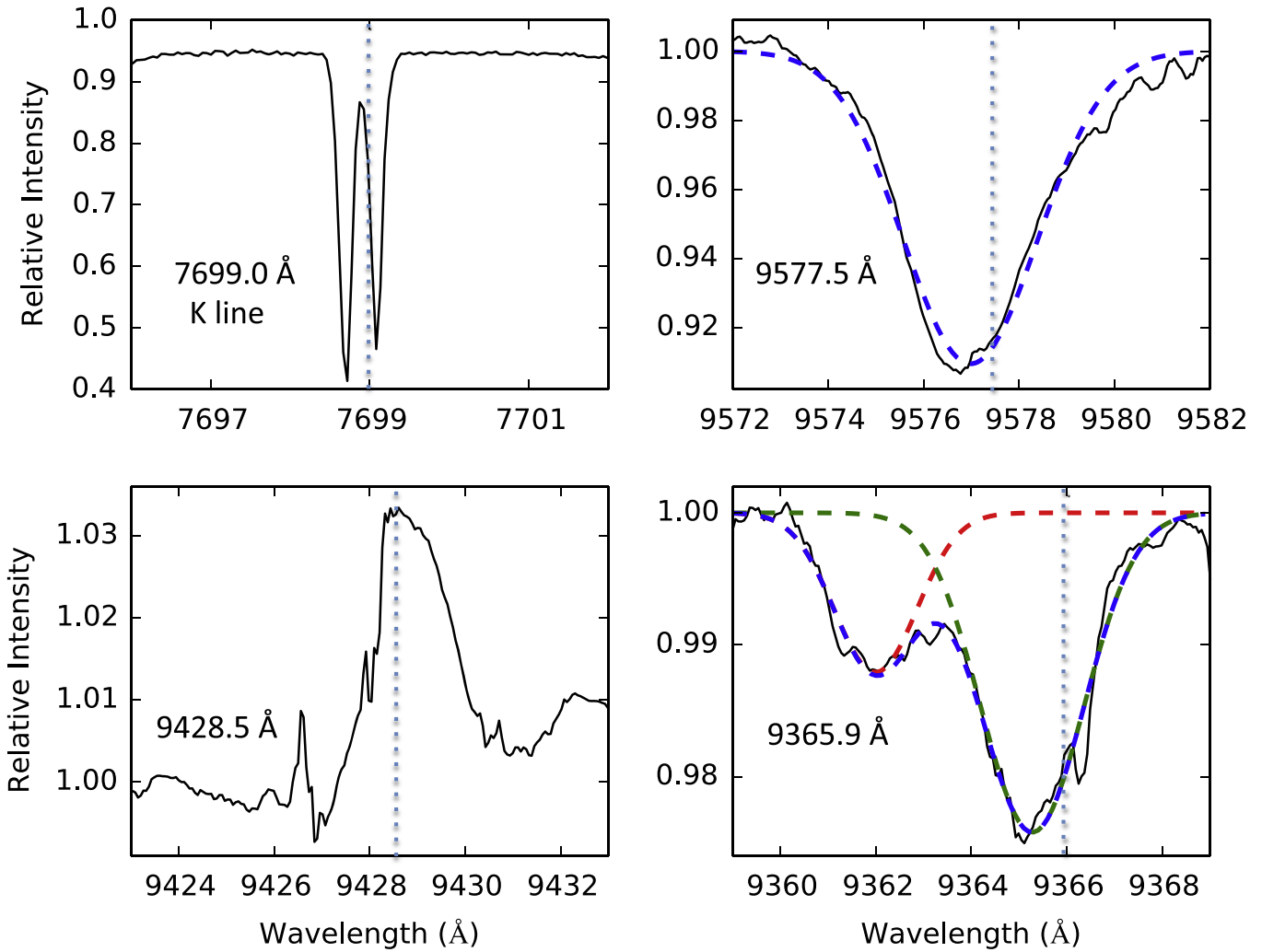


Figure 2. Spectral regions of interest for HD 183143 after cancellation of telluric water vapor lines by division with HR 7437 and adjustment of zero levels. The vertical dotted lines indicate laboratory rest wavelengths for the 7699.0 Å potassium line and the absorption bands of C_{60}^+ . The dashed lines are Gaussian fits for which parameters are listed in Table 2. The emission feature at 9429 Å prevented any interstellar band detection for HD 183143. A DIB is also seen at 9362.5 Å and fitted separately with a Gaussian.

of C_{60}^+ was recorded, both a “depression” near 9428 Å and the suggestion of a weak feature around 9366 Å were reported.

Figure 3 shows the regions of the 9577.5, 9428.5, and 9365.9 Å laboratory bands for the B1 Ia star HD 169454 divided by the spectrum of the rapidly rotating ($v \sin i = 317 \text{ km s}^{-1}$) AO V star HD 177724, again using the IRAF telluric program. Details of the stars are given in Table 1. These processed spectra were downloaded from the Canadian Astronomy Data Centre’s CFHT archive. Both stars were observed in the “object only” spectroscopic configuration of ESPaDOnS on 2005 May 21 UT. We selected HD 169454 because it has none of the emission features found in HD 183143. Unfortunately, the standard was not observed at an identical airmass and so there are large WV line residuals at 9427.5 and 9428.2 Å that have been omitted and replaced by averages in the plots and when fitting a Gaussian. The principal interstellar K line (7699.0 Å) is unresolved with a radial velocity of -11 km s^{-1} , which translates to -0.4 Å at 9400 Å. Table 2 summarizes the results of unconstrained Gaussian fits to the features in all of the ratioed spectra.

Given the weakness ($\sim 1\%$) of the detected bands and the presence of apparent emission features, setting of continua was

subjective, particularly in the case of HD 169454. Further, the CCD detector is partially transparent at such long wavelengths, which generates interference fringes. These are not well canceled in the flat-fielding process, but the additional normalization when dividing by the telluric standard considerably reduces their amplitude. Consequently, it is hard to establish values for systematic errors with confidence particularly for the FWHM in the case of HD 169454. In the table, only formal fitting errors are given.

4. COMPARISON WITH C_{60}^+ LABORATORY BANDS

The agreement of the astronomical and laboratory wavelengths is remarkably good considering the somewhat ad hoc nature of assigning an interstellar velocity. In addition, support for the assignment to C_{60}^+ comes from comparison with the relative intensities reported in the laboratory measurements. The depth of the astronomical bands (Table 2) can be used to estimate the relative intensity of the absorption bands for symmetric profiles. The observations toward HD 183143 give a ratio of 1:0.3 for the 9577.5 and 9365.9 Å bands. This matches with the laboratory ratio of 1:0.2 that was reported with an

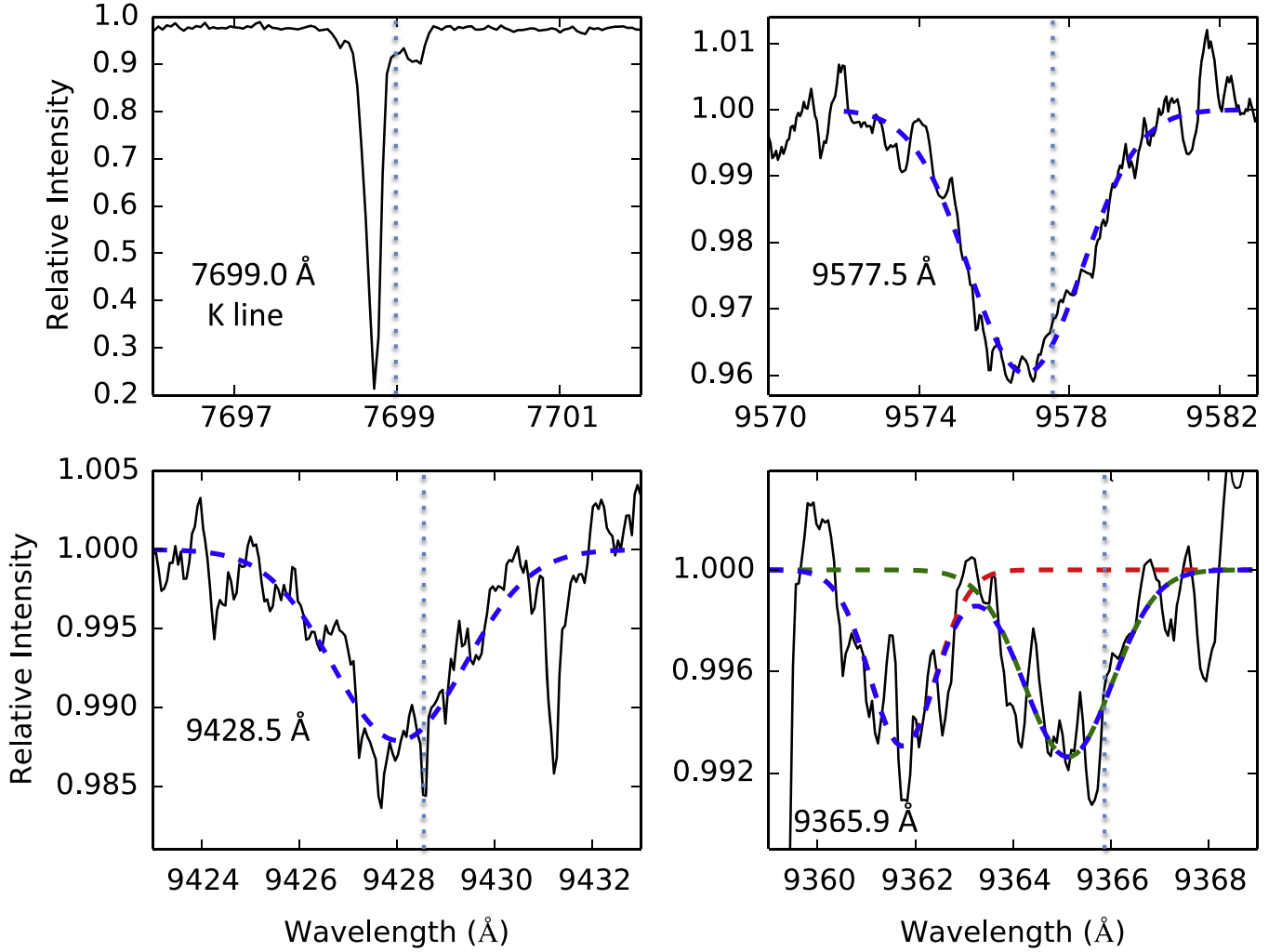


Figure 3. Same spectral regions for HD 169454 after cancellation of telluric water vapor lines by division with HD 177724 and adjustment of zero levels. The vertical dotted lines indicate laboratory rest wavelengths for the 7699.0 Å potassium line and the absorption bands of C_{60}^+ . The dashed lines are Gaussian fits for which parameters are listed in Table 2. In the panel for 9428.5 Å, large water vapor line residuals at 9427.5 and 9428.2 Å have been omitted and replaced by averages. The DIB seen at 9362.5 Å is fitted with a separate Gaussian.

Table 2
Laboratory and Interstellar C_{60}^+ Bands^a

λ_c Å	Laboratory σ_{rel} ^b	FWHM Å	λ_c Å	HD 183143 depth %	FWHM Å	λ_c Å	HD 169454 depth %	FWHM Å
9577.5 ± 0.1	1	2.5 ± 0.2	9577.4 ± 0.02	9.1 ± 0.05	3.3 ± 0.04	9577.2 ± 0.03	4.0 ± 0.06	3.5 ± 0.06
9428.5 ± 0.1	0.3	2.4 ± 0.2	9428.4 ± 0.1	1.2 ± 0.05	3.2 ± 0.1
9365.9 ± 0.1	0.2	2.4 ± 0.2	9365.7 ± 0.02	2.4 ± 0.03	2.5 ± 0.04	9365.6 ± 0.1	0.7 ± 0.1	2.1 ± 0.2

Notes.

^a Central wavelengths (λ_c), depths, FWHMs, and errors from Gaussian fits to the lab and astronomical bands. No systematic errors are included.

^b Relative cross section.

^c Corrected by +0.4 Å for the interstellar K line offset.

estimated uncertainty of around 20% (Campbell et al. 2015). Furthermore, the ratio of the depth values derived from the archive HD 169454 spectra, 1:0.3:0.2 for the 9577.5, 9428.5, and 9365.9 Å DIBs, are also in agreement with 1:0.3:0.2 measured in the laboratory (Campbell et al. 2015).

The FWHM of 3.3 Å for the interstellar 9577.5 Å band in HD 183143 is comparable to the value of 2.85 Å reported by Foing & Ehrenfreund (1997) and 3.0 Å by Jenniskens et al. (1997) for other reddened stars. In the laboratory study at 6 K,

the measured FWHM are 2.5 Å. At this low temperature, the FWHM of the C_{60}^+ rotational profile is around 1 Å (Edwards & Leach 1993). This indicates that the laboratory bands are broadened by the 2 ps lifetime of the excited electronic state. Only at temperatures above 30 K would one see a further broadening of the rotational profile. The FWHM values for HD 169454 are not robust because of incomplete correction for telluric contamination and arbitrariness in setting the continuum. A more likely source for the extra broadening of the

9577.5 Å band in HD 183143 would be near coincidence with another DIB. For example, there is a close DIB to the 9365.9 Å band at 9362.5 Å (Figure 2).

5. ASTRONOMICAL IMPLICATIONS

The confirmation of the presence of C_{60}^+ in diffuse clouds raises the question of its interstellar abundance. This has been considered previously; see, for example Herbig (2000 and references therein). The calculation of column density relies on the knowledge of the individual band oscillator strength, $f(\lambda)$; the wavelength of the absorption band maximum, λ_c ; and the equivalent width, W . For this purpose, the value for the electronic transition that was estimated in the matrix isolation spectroscopy study by Fulara et al. (1993), $f_e = 0.003\text{--}0.006$, has invariably been used. However, this value is an order of magnitude smaller than indicated by theory (Bendale et al. 1992). We believe that the value from the matrix study is underestimated, and in the following, $f_e = 0.05$ is used.

In order to evaluate the $f(\lambda)$ value for the 9577.5 Å band, the electronic oscillator strength must be weighted by the Franck–Condon factor. In the case of C_{60}^+ , most of the oscillator strength is localized in the two strong features at 9632.7 and 9577.5 Å (Campbell et al. 2015). Based on observation of only weak C_{60}^+ laboratory absorptions to shorter wavelengths than 9428.5 Å, we estimate the 9577.5 Å band to account for $\sim 30\%$ of the intensity, and therefore obtain $f(9577.5 \text{ Å}) \simeq 0.02$. For the 9577.5 Å DIB observed toward HD 183143, the equivalent width is estimated to be $W \sim 0.3 \text{ Å}$ (Table 2). Using these values gives a column density, $N(C_{60}^+)$, of around $2 \times 10^{13} \text{ cm}^{-2}$. For comparison, this is an order of magnitude smaller than that of H_3^+ , but is similar to CH^+ , both of which were observed toward HD 183143 (McCall et al. 2002).

6. CONCLUSION AND OUTLOOK

Two weak DIBs have been detected with wavelengths, FWHMs, and relative intensities in agreement with the laboratory spectrum of C_{60}^+ (Campbell et al. 2015). These results provide further compelling evidence for the presence of this molecular ion in the interstellar medium. It has been

suggested that the 9632.7 and 9577.5 Å absorptions, and hence C_{60}^+ , are also present in protoplanetary nebulae (Iglesias-Groth & Esposito 2013). The existence of the neutral fullerenes C_{60} and C_{70} in a young planetary nebula (Cami et al. 2010) and reflection nebulae (Sellgren et al. 2010) has been confirmed through their infrared (IR) transitions. There is also a report of IR emission features from a reflection nebula that have been proposed to be due to C_{60}^+ (Bérne et al. 2013). The identification of C_{60}^+ in diffuse clouds leads to intriguing questions regarding the role of fullerenes with respect to the formation of smaller carbon-based molecules such as those identified in dense interstellar clouds by radioastronomy.

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