C$_{60}$ cation as the carrier of the $\lambda 9577$ Å and $\lambda 9632$ Å diffuse interstellar bands: Further support from the VLT/X-Shooter spectra

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ABSTRACT

Ever since their first detection over 100 years ago, the mysterious diffuse interstellar bands (DIBs), a set of several hundred broad absorption features seen against distant stars in the optical and near infrared wavelength range, largely remain unidentified. The close match both in wavelengths and in relative strengths recently found between the experimental absorption spectra of gas-phase buckminsterfullerene ions (C$_{60}^+$) and four DIBs at $\lambda 9632$ Å, $\lambda 9577$ Å, $\lambda 9428$ Å and $\lambda 9365$ Å (and, to a lesser degree, a weaker DIB at $\lambda 9348$ Å) suggests C$_{60}^+$ as a promising carrier for these DIBs. However, arguments against the C$_{60}^+$ identification remain and are mostly concerned with the large variation in the intensity ratios of the $\lambda 9632$ Å and $\lambda 9577$ Å DIBs. In this work we search for these DIBs in the ESO VLT/X-shooter archival data and identify the $\lambda 9632$ Å, $\lambda 9577$ Å, $\lambda 9428$ Å, and $\lambda 9365$ Å DIBs in a sample of 25 stars. While the $\lambda 9428$ Å and $\lambda 9365$ Å DIBs are too noisy to allow any reliable analysis, the $\lambda 9632$ Å and $\lambda 9577$ Å DIBs are unambiguously detected and, after correcting for telluric water vapor absorption, their correlation can be used to probe their origin. To this end, we select a subsample of nine hot, O- or B0-type stars of which the stellar equivalent widths, after normalized by reddening to eliminate their common correlation with the density of interstellar clouds, exhibit a tight, positive correlation, supporting C$_{60}^+$ as the carrier of the $\lambda 9632$ Å and $\lambda 9577$ Å DIBs.

Key words: ISM: dust, extinction — ISM: lines and bands — ISM: molecules

1 INTRODUCTION

The diffuse interstellar bands (DIBs) are a series of over 600 broad absorption bands seen in the optical and near infrared (IR) spectra of stars as the starlight passes through the diffuse interstellar clouds (Sarre 2006, Fan et al. 2019, McCabe 2019, Linnartz et al. 2020). They were first observed in 1919 at 5780˚ by McCabe 2019, Linnartz et al. 2020). They were first observed in 1919 at 5780˚ and 5797˚ in the spectrum of the distant supergiant ζ Persei by Mary Lea Heger (1922), a then graduate student at Lick Observatory, and nearly two decades later, the interstellar origin of these bands was established by Merrill & Wilson (1938), based on the strong correlation between the band strength and the interstellar reddening.

Almost every article on DIBs started by stating that, "... since the discovery that DIBs are interstellar", as Désert et al. (1995) put it, “the nature of their carriers is still unknown”. This remained true until Campbell et al. (2015, 2016a,b), Walker et al. (2015, 2017) and Campbell & Maier (2018) for the first time measured the gas-phase spectrum of buckminsterfullerene cation (C$_{60}^+$) and found that the spectral characteristics (i.e., wavelengths and relative strengths) of gas-phase C$_{60}^+$ are in agreement with four DIBs at $\lambda 9365.2$ Å, $\lambda 9427.8$ Å, $\lambda 9577.0$ Å, and $\lambda 9632.1$ Å, arguably as well as a weaker DIB at $\lambda 9348.4$ Å. Further support for this identification was provided by space observations obtained with the Hubble Space Telescope (HST) which were free of telluric absorption contamination (Cordiner et al. 2019).

The original idea of C$_{60}^+$ being a possible DIB carrier dates back to the pionering work by Foing & Ehrenfreund (1994), who linked the neon/argon matrix spectra of C$_{60}^+$ recorded by Fulara et al. (1993) to two strong DIBs at $\lambda 9577$ Å and $\lambda 9632$ Å. A direct comparison was not possi-
ble, though, because the inert gas matrix environment would broaden the band widths and shift the wavelengths. More recently, the presence of C\textsubscript{60}\textsuperscript{+} in the interstellar medium (ISM) has been revealed through the detections of the 6.4, 7.1, 8.2 and 10.5\,\mu m emission features of C\textsubscript{60}\textsuperscript{+} in reflection nebulae, planetary nebulae and the Large and Small Magellanic Clouds (Bernet et al. 2013, Strelunkov et al. 2015). These detections may not be too surprising, as its parent molecule C\textsubscript{60}, first experimentally synthesized by Kroto et al. (1985), has also been detected in various astrophysical environments through its characteristic IR emission features at 7.0, 8.45, 17.3 and 18.9\,\mu m (Camii et al. 2010; Sellgren et al. 2010; García-Hernández et al. 2010, 2011; Zhang & Kwok 2011).

If the \(\lambda 9348\) A, \(\lambda 9365\) A, \(\lambda 9428\) A, \(\lambda 9577\) A, and \(\lambda 9632\) A DIBs indeed share the same carrier and arise from C\textsubscript{60}\textsuperscript{+}, their strengths should correlate. Although the assignment of these five DIBs to C\textsubscript{60}\textsuperscript{+} has gained wide acceptance, challenge has been continuously posed. Particularly, the intensity ratio of the two strongest bands of C\textsubscript{60}\textsuperscript{+} at 9577 and 9632\,\AA\ has become a topic of discussion. While the laboratory spectrum of gas-phase C\textsubscript{60}\textsuperscript{+} indicates an intensity ratio of \(\sim 0.84\) for the 9632\,\AA\ band to the 9577\,\AA\ band (Campbell & Maier 2018), Galazutdinov et al. (2017) found that, after correcting for the Mg\textsc{ii} stellar contamination through model atmosphere calculations, the ratio of the equivalent width of the \(\lambda 9632\) A DIB to that of \(\lambda 9577\) A DIB is variable within a broad range. Given that both the \(\lambda 9632\) A band and the \(\lambda 9577\) A band of C\textsubscript{60}\textsuperscript{+} originate from electronic transitions starting from the same level in the \(^{2}\text{Au}\) ground state (but also see Lykhin et al. 2019, Hrdomarsson et al. 2020), such a varying value is not a priori expected. As a result, Galazutdinov et al. (2017) argued against the assignment of the \(\lambda 9577\) A and \(\lambda 9632\) A DIBs to C\textsubscript{60}\textsuperscript{+} since their relative strengths are too poorly correlated to be caused by a single source. Using close spectral standards to correct for the Mg\textsc{ii} stellar contamination, Walker et al. (2017) examined some of the same spectra of Galazutdinov et al. (2017) and found that, within the uncertainties, the \(\lambda 9577\) A and \(\lambda 9632\) A DIBs are somewhat correlated. They further argued that the use of close spectral standards is superior to model atmosphere calculations in correcting for contamination by the Mg\textsc{ii} stellar lines. More recently, Galazutdinov et al. (2021) again reported a lack of correlation between the equivalent widths of the \(\lambda 9577\) A and \(\lambda 9632\) A DIB for a sample of 43 stars.

To test the C\textsubscript{60}\textsuperscript{+} assignment of DIBs, we search for these DIBs in the ESO VLT/X-shooter archival spectra and examine their interrelations. We base on the ESO VLT/X-shooter archival data and identify the \(\lambda 9577\) A and \(\lambda 9632\) A DIBs superimposed on the stellar spectra of a number of stars. We find that their strengths are well correlated and therefore provide further support for the C\textsubscript{60}\textsuperscript{+} assignment of DIBs. This paper is organized as follows. We first briefly describe in §2 the ESO VLT/X-shooter data set. In §3 we report and discuss the results on the DIB search and measure the DIB strengths, and also explore their correlations. The major conclusions are summarized in §4.

2 ESO VLT/X-SHOOTER SPECTRAL DATA PRODUCTS

The X-shooter is the first of the 2nd generation instruments installed on the European Southern Observatory (ESO) Very Large Telescope (VLT). It is a very efficient single-target, medium-resolution spectrometer (\(R \sim 4,000–17,000\)), covering the spectral range from 300 to 2,500\,nm in a single exposure (Vernet et al. 2011). We searched for the \(\lambda 9348\) A, \(\lambda 9365\) A, \(\lambda 9428\) A, \(\lambda 9577\) A, and \(\lambda 9632\) A DIBs from the X-shooter archival spectra in the ESO Spectral Data Products\(^1\). We found 25 stars which simultaneously exhibit the \(\lambda 9365\) A, \(\lambda 9428\) A, \(\lambda 9577\) A and \(\lambda 9632\) A DIBs. The \(\lambda 9428\) A DIB, the weakest band in the experimental absorption spectrum of gas-phase C\textsubscript{60}\textsuperscript{+} (Campbell et al. 2015, Walker et al. 2017, Campbell & Maier 2018), is not seen in the X-shooter spectra. This does not necessarily mean that the \(\lambda 9348\) A DIB is absent; instead, it may merely be weak enough to have escaped detection.

It is interesting to note that Galazutdinov et al. (2017) reported the nondetection of the three weak absorption bands of C\textsubscript{60}\textsuperscript{+} at 9348, 9365 and 9428\,A in a sample of 19 heavily reddened interstellar sight lines observed from the ground at high signal-to-noise (S/N). The apparent absence of these weak bands in sight lines where the \(\lambda 9577\) A and \(\lambda 9632\) A bands are strong casts strong doubt on the C\textsubscript{60}\textsuperscript{+} assignment. However, the wavelength region where the weak absorption bands of C\textsubscript{60}\textsuperscript{+} occur is heavily contaminated in ground-based studies due to strong telluric absorption. To circumvent the telluric contamination issues, Cordiner et al. (2019) obtained high S/N, telluric free HST spectra of seven heavily reddened stars and reported unambiguous detections of two weak bands at 9365 and 9428\,A, and one strong band at 9577\,A. The intensity ratios of the \(\lambda 9577\) A, \(\lambda 9428\) A, and \(\lambda 9365\) A DIBs measured for early B stars were about 1.0:0.08:0.23, comparable to the experimental ratios of 1.0:0.15:0.25 derived from the laboratory spectrum of C\textsubscript{60}\textsuperscript{+} (see Cordiner et al. 2019). Unfortunately, the HST \textit{Space Telescope Imaging Spectrograph} (STIS) grating setting adopted by Cordiner et al. (2019) did not allow them to survey the \(\lambda 9632\) A DIB. Therefore, it is not possible to analyze the relation between the \(\lambda 9577\) A and \(\lambda 9632\) A DIBs based on the telluric free HST/STIS spectra.

As mentioned earlier, there are large numbers of telluric water vapor absorption lines in the wavelength range of C\textsubscript{60}\textsuperscript{+} bands. We employ Molecfit to correct X-shooter archive data products for telluric absorption. Molecfit is a tool to correct

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1 We note that in the literature these DIBs have been detected and their strengths have been reported for a number of sources. We prefer to search for these DIBs in archival data and derive their strengths by ourselves. This is because in the literature there is a certain arbitrarity in defining the continuum against the DIB absorption and the DIB strengths were often measured in different ways. When taking data from different sources, these differences actually play a role.

2 As noted by Linnartz et al. (2020), while Walker et al. (2015, 2016) reported the detection of three weak DIBs at 9348, 9365 and 9428\,A which coincide with the weak absorption features seen in the gas-phase spectrum of C\textsubscript{60}\textsuperscript{+}, these DIBs were not observed simultaneously along one line of sight, but merely complementary towards different targets. See Lallement et al. (2018) for an overview of the detectability of the DIBs attributed to C\textsubscript{60}\textsuperscript{+}.⁰
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Table 1. Stellar Parameters and the Equivalent Widths of the \( \lambda 9577 \) Å DIB (\( W_{9577} \)) and \( \lambda 9632 \) Å DIB (\( W_{9632} \)) for Our Sample of Nine Stars in the VLT/X-Shooter Archive

| Target Star          | Spectral Type | \( T_{\text{eff}} \) (K) | \( B^a \) (mag) | \( V^a \) (mag) | \( (B - V)_0^b \) (mag) | \( E(B - V) \) (mag) | \( W_{9577} \) (mÅ) | \( W_{9632} \) (mÅ) |
|----------------------|--------------|--------------------------|----------------|----------------|--------------------------|----------------------|---------------------|---------------------|
| 2MASS J17253421-3423116 | O5.5IV\( ^c \) | 40,000                   | 13.53          | 11.82          | −0.29                     | 2.00\( ^d \)           | 385.8±46.5         | 379.2±32.3          |
| 4U1907-09            | O8.5Iab\( ^c \) | 33,000                   | 19.41          | 16.35          | −0.27                     | 3.33\( ^d \)           | 349.2±36.4         | 278.8±7.4           |
| Cl Pismis 24 17      | O3.5I\( ^c \) | 44,000                   | 13.33          | 11.84          | −0.26                     | 1.75\( ^d \)           | 314.1±8.6          | 384.7±13.8          |
| B11                  | O4.5V\( ^e \) | 42,850\( ^e \)          | −             | −             | −                         | 1.35\( ^d \)           | 384.1±52.8         | 392.0±18.7          |
| B150                 | B0V\( ^f \)  | 30,000                   | −             | −             | −                         | 1.32\( ^d \)           | 497.8±41.6         | 492.6±29.0          |
| B164                 | O6V\( ^e \)  | 39,100\( ^e \)          | −             | −             | −                         | 1.76\( ^e \)           | 557.5±7.3          | 544.1±24.0          |
| B215                 | B0-B1V\( ^e \) | 28,000\( ^e \)          | −             | −             | −                         | 1.85\( ^e \)           | 466.1±77.8         | 423.1±10.7          |
| B289                 | O9.7V\( ^e \) | 33,800\( ^e \)          | −             | −             | −                         | 1.73\( ^e \)           | 570.9±57.5         | 436.7±21.3          |
| B311                 | O8.5V\( ^e \) | 35,950\( ^e \)          | −             | −             | −                         | 1.62\( ^e \)           | 699.7±55.0         | 645.7±24.6          |

\( a \) \( B \) and \( V \) photometric magnitudes taken from [http://cdsportal.u-strasbg.fr/](http://cdsportal.u-strasbg.fr/).
\( b \) Intrinsic colors \( (B-V)_0 \) taken from Wegner (2014).
\( c \) Stellar spectral types adapted from [http://cdsportal.u-strasbg.fr/](http://cdsportal.u-strasbg.fr/).
\( d \) Color excesses \( E(B - V) \equiv (B - V) - (B - V)_0 \).
\( e \) Ramírez-Tannus et al. (2018).
\( f \) Nielbock et al. (2001).

Figure 1. The \( \lambda 9577 \) Å and \( \lambda 9632 \) Å DIBs (solid black lines) seen in the VLT/X-shooter spectra of nine target stars. Each DIB is fitted either by a single Gaussian profile or by a combination of two Gaussian profiles. The solid red lines show the fitted profiles, while the dotted red lines show the Gaussian fitting components. Labeled in each panel are the DIB equivalent widths.
for telluric absorption lines based on synthetic modeling of the atmospheric transmission which can be used with data obtained with various ground-based telescopes and instruments (Smette et al. 2015, Kausch et al. 2015). Also, the λ9632 Å DIB coincides and therefore often blends with the stellar Mg ii absorption lines at 9631.9 and 9632.4 Å. However, it is far from trivial to correct for contamination by the stellar Mg ii lines. Nevertheless, it is well recognized that while the stellar Mg ii lines are strong in late B stars, they are negligibly weak in hot, O- and early B-type stars. We mention earlier, the stellar Mg ii of gas-phase C\(^+\) as shown in Figure 1, to allow for any reliable quantitative analysis. In contrast, the strongest absorption features in the experimental spectrum are absent or very weak in hot O- and early B-type stars. We therefore focus on a subsample of nine stars which consists of seven O stars and two B0 stars (see Table 1). In Figure 1 we show the X-shooter spectra around 4481 Å of sight to which the stellar Mg ii absorption line at 4481 Å is often not sufficient and two or more Gaussian bands in terms of Lorentzian or Drude profiles which are expected for damped harmonic oscillators (see Li 2009). However, both Lorentzian and Drude profiles are too broad in the blue and red wings to reproduce the DIB absorption bands.

3 We are only interested in the DIB band strength (i.e., the area obtained by integrating the absorption band over wavelength) and thus the exact functional profile adopted to fit the band is not critical. We have actually also tried to fit the DIB absorption bands in terms of Lorentzian or Drude profiles which are expected for mixed harmonics. (see Li 2009). However, both Lorentzian and Drude profiles are too broad in the blue and red wings to reproduce the DIB absorption bands.

4 The linear dependence of the wavelength redshift on the number of tagged He atoms remains valid up to 32 He atoms. From 33 He atoms onwards the redshift is not linear anymore (see Gatchell et al. 2019).

3 THE λ9577 Å AND λ9632 Å DIBS AND THEIR CORRELATIONS

As described in 2 although the X-shooter spectra of our target stars show evidence for the presence of all four DIBs at λ9365 Å, λ9428 Å, λ9577 Å and λ9632 Å DIBs, the spectral profiles of the λ9365 Å and λ9428 Å DIBs are too noisy to allow for any reliable quantitative analysis. In contrast, as shown in Figure 1 the λ9577 Å and λ9632 Å DIBs, the strongest absorption features in the experimental spectrum of gas-phase C\(^+\) (Campbell et al. 2015, Walker et al. 2017, Campbell & Maier 2018), are unambiguously detected in the X-shooter spectra. As mentioned earlier, the stellar Mg ii absorption lines which would pollute the λ9632 Å DIBs are absent or very weak in hot O- and early B-type stars. We therefore confine ourselves to nine O and B0 stars along the lines of sight to which the stellar Mg ii contamination is negligible. After correcting for the telluric contamination with the Molecfit tool, we fit the absorption profiles of the λ9577 Å and λ9632 Å DIBs by a single Gaussian profile or a combination of two Gaussian profiles. The λ9577 Å and λ9632 Å DIB profiles are often asymmetrical, therefore a single Gaussian profile is often not sufficient and two or more Gaussian profiles are required to closely reproduce the observed DIB profiles (e.g., see Rawlings et al. 2014). Indeed, as shown in Figure 1 a combination of two Gaussian profiles are needed for the majorities of the target stars (8/9 for both DIBs). In principle, we could also fit the DIB profiles in terms of one or two Lorentzian functions. This really does not matter since we are only interested in the area integrated over the DIB absorption profile.

We determine the absorption strengths of the λ9577 Å and λ9632 Å DIBs from the fitted Gaussian profile(s) in terms of their equivalent widths, W\(_{9577}\) and W\(_{9632}\). The equivalent width of a DIB is a measure of the DIB absorption strength which characterizes the “width” of a “virtual” rectangle whose area is equal to the area in the DIB profile and whose height is equal to the continuum level of the DIB profile. We tabulate in Table 1 the measured equivalent widths (W\(_{9577}\), W\(_{9632}\)) and their associated uncertainties of the λ9577 Å and λ9632 Å DIBs for the nine target stars.

If C\(^+\)\(_{60}\) indeed causes both the λ9577 Å and λ9632 Å DIBs, their equivalent widths should correlate. While a good correlation between two DIBs does not necessarily mean that they must share a common carrier, a non-correlation implies that different carriers are involved (e.g., see Moutou et al. 1999). We conduct a correlation analysis on W\(_{9577}\) and W\(_{9632}\) to investigate whether the λ9577 Å and λ9632 Å DIBs are related, so as to determine whether they are from the same carrier (e.g., C\(^+\)\(_{60}\)). As illustrated in Figure 3a, with a Pearson correlation coefficient of τ \(\approx\) 0.89 and a Kendall correlation coefficient of τ \(\approx\) 0.72 at a significance level of \(p \approx 1.32 \times 10^{-3}\), it is apparent that W\(_{9577}\) and W\(_{9632}\) are well correlated. The correlation coefficient becomes τ \(\approx\) 0.96 when the measurement uncertainties are taken into account.

On average, the strength ratio of the λ9632 Å DIB to the λ9577 Å DIB is \(\sim 0.94\), which agrees reasonably well with that of the experimental spectrum of gas-phase C\(^+\)\(_{60}\) (\(\sim 0.84\), Campbell & Maier 2018). The discrepancy of \(\sim 12\%\) between the observed ratio of W\(_{9632}\)/W\(_{9577}\) \(\approx 0.94\) and the experimental ratio of W\(_{9632}\)/W\(_{9577}\) \(\approx 0.84\) is acceptable. We note that the reported experimental intensity ratio was not for pure C\(^+\)\(_{60}\), but actually for small He-tagged C\(^+\)\(_{60}\)–He\(_{n}\) (n = 1–3) ion complexes in an ion trap (Campbell & Maier 2018). Upon tagged by He atoms, the laboratory rest wavelengths of C\(^+\)\(_{60}\) are slightly redshifted. As the redshift is linearly dependent on the number of He atoms (see Gatchell et al. 2019), the absorption wavelengths of bare C\(^+\)\(_{60}\) can be extrapolated from that of C\(^+\)\(_{60}\)–He\(_{n}\) complexes (e.g., see Campbell et al. 2016b, Spieler et al. 2017). The absence of actual data for bare C\(^+\)\(_{60}\) still leaves a concern about the exact W\(_{9632}/W_{9577}\) intensity ratio. Moreover, even the nature of the electronic transitions responsible for the 9632 and 9577 Å absorption bands seen in C\(^+\)\(_{60}\) remains unknown (e.g., see Lykkin et al. 2019, Hrodmarsson et al. 2020).

Nevertheless, as mentioned earlier, such a correlation between W\(_{9577}\) and W\(_{9632}\) does not necessarily mean that the λ9577 Å and λ9632 Å DIBs must arise from the same carrier. The equivalent widths of two DIBs resulting from different carriers for a random sample of lines of sight may somewhat correlate if their carriers are present in the interstellar medium (ISM) of different lines of sight in proportion abundances. In general, most interstellar quantities show a linear increase with the densities of the in-
As shown in Figure 3b, with a Pearson correlation coefficient of \( r \approx 0.94 \) and a Kendall correlation coefficient of \( \tau \approx 0.83 \) at a significance level of \( p \approx 8.08 \times 10^{-5} \), \( W_{9577}/E(B−V) \) and \( W_{9632}/E(B−V) \) are clearly well correlated. This supports that a common carrier is at the origin of the \( \lambda 9577 \) and \( \lambda 9632 \) DIBs. We derive a mean ratio of \( W_{9632}/E(B−V) : W_{9577}/E(B−V) \approx 0.95 \), which also agrees reasonably well with the experimental band ratio of gas-phase \( C^{+}_{60} \) (\( \sim 0.84 \), Campbell & Maier 2018).

Finally, we note that Galazutdinov et al. (2021) compiled the spectral data of 43 lines of sight for the \( \lambda 9577 \) and \( \lambda 9632 \) DIBs obtained with different instruments on different stars. The correlation coefficient essentially remains unchanged when the measurement uncertainties are taken into account.
board different telescopes. They found that, with a correlation coefficient of $r \approx 0.37$ (with the measurement uncertainties included), the equivalent widths of the $\lambda 9577$ Å DIB are poorly correlated with that of the $\lambda 9632$ Å DIB. We reanalyze the correlation and derive an uncertainty-included correlation coefficient of $r \approx 0.40$ \cite{galuzutdinov2021} ($r \approx 0.67$ if we ignore

$6$ The small difference in the correlation coefficient $r$ between ours and that of Galuzutdinov et al. (2021) probably arises from the fact that the sight lines we consider (see Table 2) may not
the measurement uncertainties; see Figure 4b). However, as discussed earlier, the relation between two DIBs could be affected by their common dependence on $E(B-V)$. To cancel out the common dependence on $E(B-V)$, we normalize the equivalent widths of both DIBs by $E(B-V)$ and be exactly the same as those considered by Galazutdinov et al. (2021); indeed, it is not very clear which sight lines were examined in Galazutdinov et al. (2021).

The measurement uncertainties; see Figure 4b). However, as discussed earlier, the relation between two DIBs could be affected by their common dependence on $E(B-V)$. To cancel out the common dependence on $E(B-V)$, we normalize the equivalent widths of both DIBs by $E(B-V)$ and be exactly the same as those considered by Galazutdinov et al. (2021); indeed, it is not very clear which sight lines were examined in Galazutdinov et al. (2021).
we believe that these two DIBs of the sample of Galuz utdinov et al. (2021) are also correlated. The mean ratio of \( W_{9632}/E(B-V) : W_{9577}/E(B-V) \approx 0.90 \) agrees well with the experimental band ratio of \( \sim 0.84 \) of gas-phase C\(_{60}\) (Campbell & Maier 2018).

4 CONCLUSION

We have searched for the DIBs at \( \lambda 9632 \), \( \lambda 9577 \), \( \lambda 9428 \), \( \lambda 9365 \), and \( \lambda 9348 \) which are attributed to C\(_{60}\) in the ESO VLT/X-shooter spectral data archive. We have identified 25 stars along the lines of sight to which all these DIBs (except the \( \lambda 9348 \) DIB, the weakest absorption band in the experimental spectrum of gas-phase C\(_{60}\)) are seen in the X-shooter spectra. To avoid the M2II stellar contamination to the \( \lambda 9632 \) DIB, we focus on a subsample of nine O and B0 stars in which the M2II stellar lines are absent or very weak. It is found that, after normalized by reddening (to eliminate their common correlation with the density of interstellar clouds), the equivalent widths of the \( \lambda 9632 \) and \( \lambda 9577 \) DIBs are well correlated, whereas the X-shooter spectra for the \( \lambda 9428 \) and \( \lambda 9365 \) DIBs are too noisy to allow any reliable quantitative analysis. We conclude that the correlation found between the strengths of the \( \lambda 9632 \) and \( \lambda 9577 \) DIBs, the strongest absorption bands in the experimental spectrum of gas-phase C\(_{60}\), supports C\(_{60}\) as the carrier of these DIBs.

ACKNOWLEDGEMENTS

We thank K. J. Li, A. N. Witt, X. J. Yang and the anonymous referee for helpful suggestions and comments. TPN and FYX are supported in part by the Joint Research Funds in Astronomy U2031114 under cooperative agreement between the National Natural Science Foundation of China and Chinese Academy of Sciences and the CCST Milky Way Survey Dust and Extinction Project. AL is supported in part by NSF AST-1816411.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding authors.

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