The diffuse interstellar bands - a brief review

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The diffuse interstellar bands - a brief review

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Abstract.
The diffuse interstellar bands, or DIBs, are a large set of absorption features, mostly at optical and near infrared wavelengths, that are found in the spectra of reddened stars and other objects. They arise in interstellar gas and are observed toward numerous objects in our galaxy as well as in other galaxies. Although long thought to be associated with carbon-bearing molecules, none of them had been conclusively identified until last year, when several near-infrared DIBs were matched to the laboratory spectrum of singly ionized buckminsterfullerene \( \text{C}_{60}^+ \). This development appears to have begun to solve what is perhaps the greatest unsolved mystery in astronomical spectroscopy. Also recently, new DIBs have been discovered at infrared wavelengths and are the longest wavelength DIBs ever found. I present the general characteristics of the DIBs and their history, emphasizing recent developments.

1. Introduction
The diffuse interstellar bands, which are commonly known as DIBs, are a class of absorption features that are observed in the spectra of objects in our galaxy and other galaxies. They arise in the interstellar medium, but are not due to atoms or simple molecules. When the first bands, at 5780 Å and 5797 Å, were discovered it was suspected, but not definitively shown that the absorptions were physically associated with interstellar medium; that became clear later. Originally the absorptions were only seen in optical spectra, but subsequently DIBs have been found at both longer and shorter wavelengths. They are most easily seen in the spectra of hot stars, because spectra of such stars contain fewer interfering photospheric lines than spectra of cooler stars.

Recent reviews of DIBs [1,2] are available and are considerably more comprehensive than the present paper. Readers are referred to them and references therein for more detailed information and discussion.

2. Description and Early history
The discovery of the first diffuse interstellar bands was made by a graduate student at Lick Observatory in California, Mary Lea Heger, almost a century ago during her search for "stationary" sodium D lines toward orbiting pairs of hot stars [3], whose intrinsic spectra shifted due to the changing orbital velocities. An excellent recounting of the discovery by McCall and Griffin is available [4]. The bands that Heger observed, as well as several additional ones discovered later by Merrill and his collaborators were shown by the latter investigators to arise in interstellar gas [5], not due to their stationary behavior, but because their strengths increased with increasing reddening of the stellar spectra. Although as discussed below the bands are
found predominantly in the diffuse (low density) interstellar medium, in the name DIB the term “diffuse” applies to their appearance on photographic plates where the first absorptions discovered are broader (more “diffuse”) than interstellar absorption lines of atomic and molecular species.

In 1975 Herbig [6] listed 39 DIBs between 4400 Å and 6850 Å. With the advent of modern instrumentation and advances in spectroscopy, particularly in the near-infrared, the number has skyrocketed to the present value of \( \sim 500 \), through the work of many but in particular Hobbs and his collaborators [7,8]. However, as of the beginning of 2015, not a single DIB had been unequivocally identified with a specific carrier. Many have referred to the unknown identities of the DIBs as the greatest unsolved mystery in astronomical spectroscopy.

Figure 1 from Lan et al. [9] is a synthetic pure DIB spectrum for a reddening \( E(B−V) \) of one-tenth mag, based on observations and analysis by Jenniskens and Désert [10] who averaged a large number of stellar spectra after removing the emission and/or absorption lines intrinsic to the stars themselves. For this reddening the strongest DIBs have optical depths less than 0.02. Most of the optical DIBs detected in the last decade are considerably weaker than those shown in Fig. 1 and are narrow (sub-Angstrom); detection and characterization of them requires high spectral resolution and high sensitivity [7,8].

3. Interstellar environment

Convincing evidence that most DIBs are formed predominantly in the diffuse interstellar medium comes from the strong correlations of their strengths vs \( E(B−V) \) for small values of that parameter. Figure 2 from Lan et al. [9] shows this behavior for a number of DIBs, using as background sources objects both inside and outside of the Galaxy. Low values of \( E(B−V) \) generally imply lines of sight passing through diffuse clouds rather than dense clouds. As shown in these figures the correlation with \( E(B−V) \) disappears at higher values of reddening, which correspond to sightlines that are more likely to include regions of denser and/or UV-shielded gas. Thus the flattening at these higher values suggests that most DIBs do not exist in the denser interstellar medium. Indeed it has also been found that on average DIB strengths are either uncorrelated with or anti-correlated with \( N(H_2) \) [9].

However, there is convincing evidence that some DIBs are formed in denser or more shielded environments. The best known examples of this are the so-called C\(_2\) DIBs, whose strengths roughly scale with \( N(C_2)/E(B−V) \) [11]. Their carriers presumably are more susceptible to destruction by UV radiation than other DIBs carriers, and thus they exist mainly in regions where the molecular fraction is high, in either diffuse cloud cores or in dense clouds.
4. DIB - DIB correlations
The large numbers of DIBs coupled with the absence of convincing identifications for them has led many to search for correlations between the strengths of individual DIBs as a way to constrain the numbers of carriers and possibly identify bands produced by the same carrier. Quoting Adámkovics, Blake and McCall [12], “Any group of features arising from a particular carrier, or set of chemically related carriers, must maintain the same relative intensities in all lines of sight.” Although there are noteworthy counterexamples of this even among the stronger DIBs (a glaring instance is the aforementioned 5780 and 5797 Å bands [13], in most cases band strengths show a rough correlation from direction to direction, suggesting that most DIBs carriers tend to form under similar physical conditions. A very tight correlation between the strengths of two DIBs might suggest that each arises from the same carrier, but such correlations are very rarely the case. McCall [14] reported that in a study of 58 DIBs observed on 40 sightlines only 1.5% of the pairs had strength correlation coefficients of 0.95 or higher. This suggests that the DIBs must be produced by many species.

5. Free molecules or solids?
The strengths of many DIBs scale roughly with the visual interstellar extinction for small values of the latter. Because extinction is produced by dust particles, this behavior suggested to early investigators that DIBs carriers are physically associated with the dust particles. However, there are a number of arguments strongly suggesting otherwise and indicating that the carriers are free molecules rather than molecules bound to grains.

- Solid state absorption features tend to be much broader than the DIBs [15].
- The central wavelengths of the DIBs do not vary from sightline to sightline and the absorption profiles have been found to vary only in a very few cases [15]. In solids the
central wavelengths and shapes of absorption bands are influenced by the interaction of the absorbing molecules with their neighboring molecules, and significant differences are observed on different sightlines.

- At very high spectral resolution fine structure is observed in some DIBs [16,17] (see Fig. 3), which is suggestive of rotational structure and thus the absorbers being free molecules [17,18,19].

- Polarization studies of a few DIBs in a highly reddened star show that while the continuum is polarized, as one would expect due to magnetically aligned dust grains, there is no excess polarization at the wavelengths of the absorptions, which would occur if the absorbing material is on the aligned grains of standard sizes (∼0.1 μm), regardless of whether the grains are silicates or are carbonaceous [20].

Thus it may be safely concluded that most if not all DIBs arise in free molecules. That the DIBS occur at optical and short infrared wavelengths implies that the transitions are vibronic in nature.

6. Identification

Identifications for DIBs have been proposed since the time that they were recognized as having an interstellar origin. The proposals can generally be separated into two groups: individual carriers, and classes of carriers. Proposed individual identifications typically have linked single or small numbers of DIBs with single species and in the first instance have usually appealed to wavelength matches. None of them have survived scrutiny. In most cases the wavelength matches were found to be imprecise, absorption features by the candidate species at other wavelengths were not seen in space, or astrophysical or astrochemical arguments precluded the candidates from being sufficiently abundant to account for the strengths of the observed features.

There have only been a few suggestions of classes of carriers. These have been prompted by arguments that the DIBs carriers are likely to be large, carbon-bearing molecules [21,22].

Figure 3. High resolution spectra of two DIBs toward two stars, showing resolved structure [16]. The interstellar lines of K I are shown to the right of each DIB spectrum.
The most recent of these proposed candidates are polycyclic aromatic hydrocarbons (PAHs) [23,24,25], fullerenes [26,27] and fulleranes [28]. The arguments in their favor have not been based on wavelength correspondences. Instead the proposers have noted the stability of these classes of molecules against destruction, their compatibility as carbon-based compounds with abundance constraints, and either their known presence or likely presence, based on astrophysical and astrochemical considerations, in the diffuse interstellar medium. This approach has been necessary, as not only have accurate wavelengths of optical and near-IR transitions of these species as free molecules not been known (and indeed are extremely difficult to measure in the laboratory in the gas phase or in conditions approximating the gas phase – e.g., in a matrix of low mass inert atoms), but also because there are so many DIBs and vast numbers of PAHs, fullerenes, and fulleranes, each with its own unique spectrum.

Nevertheless, definitive proof of an association between a DIB and a carrier does require an accurate wavelength match. The lack of specific match of any DIB to a member of any of the above classes began to change in the early 1990s when laboratory spectroscopy of the fullerene \( \text{C}_{60}^+ \) embedded in a Ne matrix revealed transitions at 9590 Å and 9640 Å [29]. It was expected that in the gas phase these lines would occur at slightly shorter wavelengths, but the precise wavelength shift was uncertain. Shortly thereafter two DIBs were found at wavelengths consistent with the expected shift and proposed to be due to \( \text{C}_{60}^+ \) [30,31]. Finally, last year a laboratory spectrum of \( \text{C}_{60}^+ \) trapped in dense, gaseous, and cold helium demonstrated that the central wavelengths of the two bands accurately match those observed in space, as shown in Fig. 4 [32]. Further confirmation has come with the detection in space of two additional DIBs, whose wavelengths match two weaker absorptions in the laboratory spectrum in Fig. 4 [33]. Based on these successes it seems plausible that fullerenes and their analogues produce many of the DIBs. Verifying that would likely require a large number laboratory studies.
7. New infrared DIBs

The vast majority of DIBs are at optical and near-infrared wavelengths. The four absorptions of $C_{60}^+$ in Fig. 4 are not the longest wavelength DIBs. Prior to their discovery, in 1990, two DIBs, at 1.18 and 1.31 $\mu$m, had been found in spectra toward optically bright stars on known DIBs sightlines [34]. For two decades they were the longest wavelength DIBs known.

Recently a much longer wavelength set of DIBs were discovered at 1.5–1.8 $\mu$m toward stars in the Galactic center [35], for which spectroscopy at wavelengths below $\sim$1.0 $\mu$m is virtually impossible due to the extremely high extinction. These are shown in Fig. 5. Some of them, as well as several additional DIBs, mostly in the 1.0–1.3 $\mu$m region have also been found toward optically bright stars on known DIBs sightlines with much lower extinctions [35,36,37]. The infrared DIBs can be employed to investigate the diffuse interstellar medium in directions that are too highly obscured for optical spectroscopy. Recently the strongest of these DIBs, at 1.53 $\mu$m, has been used to map the Galaxy’s interstellar medium [38].

8. Conclusion

Considerable progress has been made recently in understanding DIBs behavioral patterns, isolating DIBs families, and especially in convincingly identifying a few of the DIBS. It is possible that fullerenes and their analogues, and perhaps eventually PAHs, will be shown to be the keys to understanding a significant fraction of the DIBs. The recent success in linking four DIBs to $C_{60}^+$ demonstrates that, while proposed identifications based on blind suggestions...
and wavelength coincidences alone are unlikely to be a successful way forward, educated guesses followed by laboratory spectroscopy can succeed. Clearly big challenges remain to be overcome in order to more fully solve this great mystery in astronomical spectroscopy.

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References

Tom Geballe listening to a question from the audience after his talk.