Diffuse Interstellar Bands: A Cosmic Mystery!

by Pam Graham

Overview and History

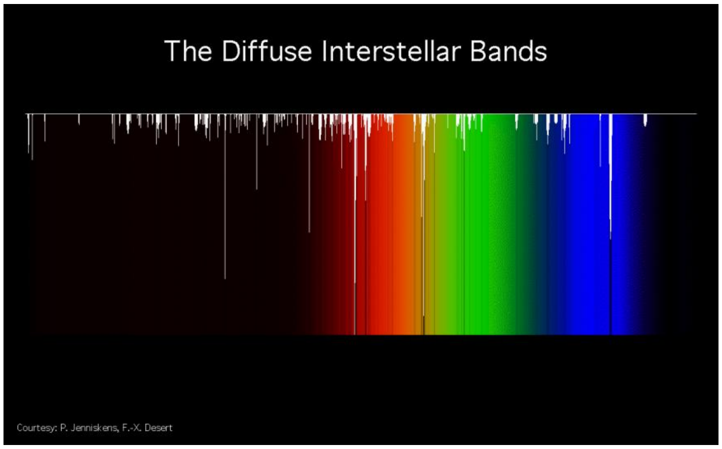
There is an unidentified light thief in the interstellar medium (ISM). Out there in the vast spaces between all the stars we can see, in every direction we can aim a telescope, there lurks a mystery material that has evaded positive identification for almost 90 years.

Back in 1922, Mary Lea Heger, a graduate student at Berkeley's Lick Observatory, photographed two peculiar features in the spectra of distant binary stars. These features appeared as absorption lines–dark lines resulting from the absence of photons at distinct frequencies in a continuous spectrum–but they were much wider and more diffuse than the atomic spectral lines ordinarily seen in stars. They also appeared to be stationary, even though spectral lines produced by stars in a binary system should shift back and forth in wavelength due to the Doppler effect.

Berkley's Lick Observatory where Diffuse Interstellar Bands were discovered in 1929
http://astro.berkeley.edu/~jrg/chabot/Slide12.JPG

By 1938, astronomer Paul Merrill had confirmed the unidentified nature of these broad absorption features, called absorption bands, and established their origin in interstellar rather than circumstellar regions.

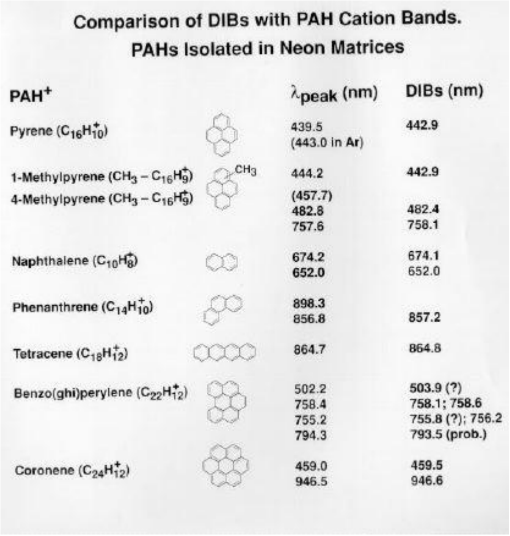
For the remainder of the twentieth century, the puzzle of the diffuse interstellar bands (DIB) continued to baffle scientists. A huge amount of observational, theoretical and laboratory effort has been applied to the attempt at identifying the carriers responsible for the roughly 300 DIBs currently verified in the wide optical spectrum between the ultraviolet and infrared.



Diffuse Interstellar Bands
http://en.wikipedia.org/wiki/File:Diffuse_Interstellar_Bands.gif

The difficulty in identifying the DIB carriers is surprising, given that spectra of other components of the ISM, such as H, Na, K and Ca+, are easily reproduced and matched in the laboratory. Yet not one of the bands has been positively assigned.[1]

Most researchers today believe that organic matter, probably in the form of large polycyclic aromatic hydrocarbon (PAH) structures, are responsible for the absorptions.



Comparison of DIBs with PAH Cation Bands.
PAHs Isolated in Neon Matrices

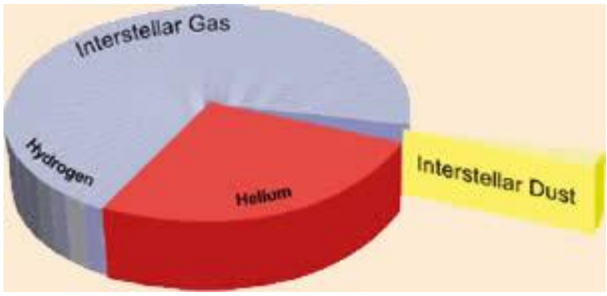
PAH^+	λ_{peak} (nm)	DIBs (nm)
Pyrene ($C_{16}H_{10}^+$)	439.5 (443.0 in Ar)	442.9
1-Methylpyrene ($CH_3-C_{16}H_9^+$)	444.2	442.9
4-Methylpyrene ($CH_3-C_{16}H_9^+$)	(457.7) 482.8 757.6	 482.4 758.1
Naphthalene ($C_{10}H_8^+$)	674.2 652.0	674.1 652.0
Phenanthrene ($C_{14}H_{10}^+$)	898.3 856.8	 857.2
Tetracene ($C_{18}H_{12}^+$)	864.7	864.8
Benzo(ghi)perylene ($C_{22}H_{12}^+$)	502.2 758.4 755.2 794.3	503.9 (?) 758.1; 758.6 755.8 (?); 756.2 793.5 (prob.)
Coronene ($C_{24}H_{12}^+$)	459.0 946.5	459.5 946.6

Similarity between the DIBs and spectral data on PAHs from Ames Research Center's astrochemistry lab and especially Dr. Farid Salama.
http://www.astrochemistry.org/DIBS.html

To better understand the challenges involved and the motivation for solving this outstanding astrophysical problem, it's helpful to take a closer look at the ISM and the spectroscopic concepts employed in the quest.

Interstellar Medium

Even though most of outer space has a lower density of atoms than the strongest vacuums we can create in laboratories on Earth, it is far from empty. To get an idea of scale, compare the density of the air we breathe, which is about 10^9 molecules per cubic centimeter, with the lowest density regions of interstellar space at approximately 0.1 atoms per cubic centimeter.[2] Over astronomical distances, even that extremely sparse distribution adds up to an estimated 5-10 billion solar masses, which means that interstellar matter in the Milky Way comprises several percent of the total mass of visible stars in our galaxy.

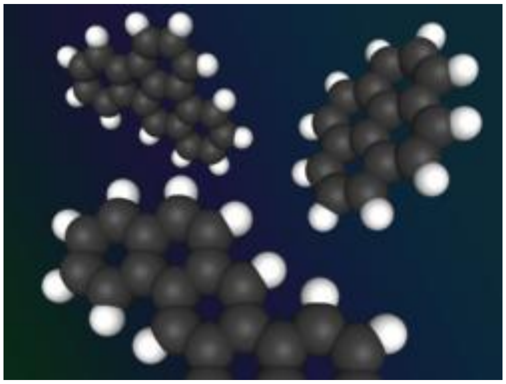


Composition of Interstellar Matter
http://www-ssg.sr.unh.edu/ism/what1.html

Because only a few large molecules (like the PAHs that top the list of likely DIB carriers) can survive the high radiation fields in the interstellar environment, most of this material is in the form of gas (99%) and dust (1%).

Far from being evenly distributed among the stars, the ISM exhibits a wide range of temperatures and densities. Deep-sky images show regions where the gas and dust collects to form diffuse clouds that scatter and absorb photons coming from remote stars. Due to the typical size of interstellar dust (which corresponds to the wavelength of blue light), when starlight passes through a region rich in interstellar matter, the blue photons are more easily and efficiently scattered than the red photons. Not only is the intensity of the light decreased (interstellar (IS) extinction), it is also reddened (IS reddening).[3] Because of their general correlation with dust extinction, DIBs were originally attributed to dust particles.[4]

Unlocking the secret of the diffuse interstellar bands is not purely a matter of astronomical observation. The field of spectral analysis offers equally valuable tools for straightening out the conundrum.



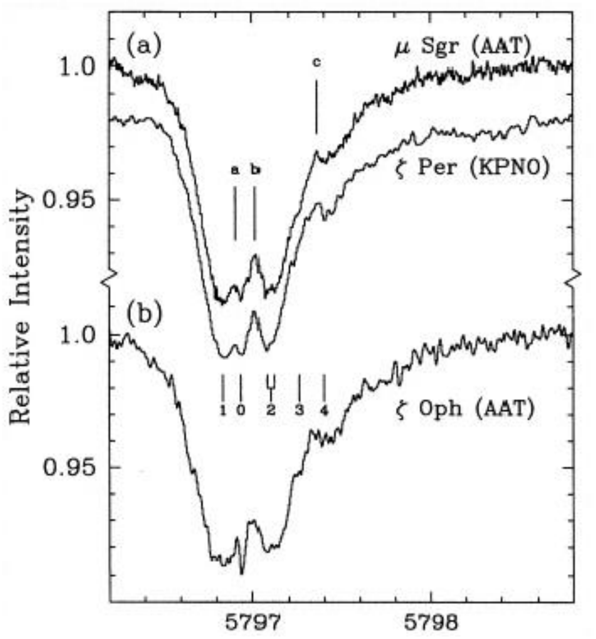
Typical polycyclic aromatic hydrocarbons
http://en.wikipedia.org/wiki/File:Polycyclic_Aromatic_Hydrocarbons.png

Spectral Characteristics

The atomic spectrum is an effect of the quantized orbits of electrons around the atom. In other words, a single mechanism, electronic transition, produces atomic spectra, which are characterized by sharp lines.

Molecular spectra are much more complex than atomic spectra. Molecules, formed when atoms bind together, also exhibit electronic transitions similar to those of an atom. However, in the more complex molecular structure, internuclear distances are quantized in discrete vibrational energy states, with consequent vibrational transitions. Additionally, a molecule has the freedom to rotate in space about various axes, resulting in discrete rotational energy states.

While atomic spectra can undergo a number of weak line broadening processes, the three classes of molecular transitions lead to numerous spectral lines superimposed on each other, closely spaced in wavelength and displaying an easily recognizable banded structure. It was the first detection of these substructures in the profiles of several DIBs that pointed to the molecular nature of DIB carriers.



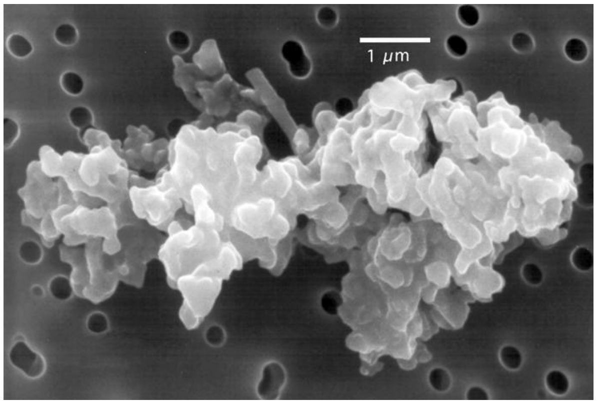
The λ6614 diffuse band showing three (possibly four) components. The band shape conforms to P, Q and R rotational branch structure that is common in molecular electronic spectra.
Sarre, Peter. Organic compounds as carriers of the diffuse interstellar bands. Organic Matter in Space: Proceedings IAU Symposium No. 251, 2008.

Armed with these basics concerning the ISM and spectral analysis, a survey of the main DIB theories that have come and gone, as well as a brief discussion of why tracing the DIB carriers is an important pursuit, becomes more straightforward.

DIB Theories and Importance to Astrophysics

The extensive list of proposed DIB carriers has at times included such diverse candidates as H^-, H_2, porphyrins, polycyclic aromatic hydrocarbons, nanodiamonds, fullerenes, nanotubes, and alien bacteria.

Merrill and Wilson (1938) [Merrill, P.W. and Wilson, O.C. Astrophysical Journal 87: 9, 1938] were the first to speculate, based on the dependence of DIB strength on IS reddening, that small solid particles were the carriers. However, the development of more refined techniques for measuring DIB strengths and reddenings has subsequently diminished, but not conclusively dismissed, support for dust grains as DIB carriers.[5]



Porous chondrite interplanetary dust, an early candidate for the cause of Diffuse Interstellar Bands
http://en.wikipedia.org/wiki/Cosmic_dust

Two arguments for keeping the dust grain possibility alive include: 1. Many families of DIBs corresponding to different carriers can be expected to emerge, and since only a few of the known structures have been thoroughly investigated, dust cannot be excluded as the origin of at least some of the remaining DIBs. 2. Different IS clouds may present a different ratio of large grains to small grains, altering the points in DIB strength-reddening diagrams that seem to exclude dust as carriers.[6]

One fascinating, but highly controversial line of questioning came from outside the astronomical community. In 1996, two laser spectroscopists from IBM, Peter Sorokin and James Glownia, suggested that the mystery compound is none other than the hydrogen molecule, H_2, the simplest and most abundant molecule in space. Their model was able to account for the wavelengths of about 70 DIBs, but it also relied on a hydrogen molecule simultaneously absorbing a photon of visible light and a photon of ultraviolet light. Such two-photon hits are rare, and to get enough of them would require an extremely intense flux of ultraviolet light. Nevertheless, the search for DIB carriers had become so frustrating to scientists, Sorokin and Glownia's theory received enough interest to earn them some observing time on a telescope aboard the space shuttle Columbia in late 1996.

The H_2 model of Sorokin and Glownia was eventually deemed an intriguing suggestion that overlooks several critical spectroscopic and astrophysical problems, and has ultimately been regarded as unproven and probably not viable.[7]

Why has all this effort, energy and funding been poured into the identification of such an evasive constituent of the distant, murky regions of our Universe?

Molecular cloud of gas and dust, broken off from the Carina Nebula. Studying such clouds may hold clues to the origin of life on earth http://en.wikipedia.org/wiki/Molecular_cloud

In pursuing the origins of DIBs, we are tracing our chemical heritage, from the interstellar cloud that made the Solar System to the start of life on Earth. We need this knowledge as a basis to understand whether certain very complex chemical processes may occur in the ISM, especially on grain surfaces, and eventually to clarify whether life, also in its simplest form, is a ubiquitous phenomenon in the Universe.[8]

Dense molecular clouds are seen to exist throughout our galaxy, and all planetary systems are believed to form from this material. So, the processes being studied in the search for DIB carriers are *universal* ones, i.e., whether the universe is in some sense hardwired to produce large quantities of prebiotic organic materials. The result would be the virtual assurance that when new planetary systems are formed, prebiotic organics would be present in the starting materials.[9]

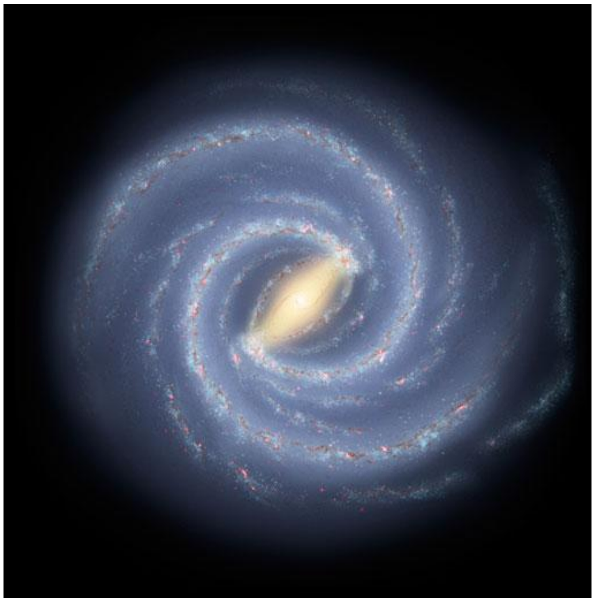
Also, there remains the interesting possibility that some of these spectral features arise from new forms of matter or dust in the ISM and it is notable that new forms of carbon including fullerenes, nanotubes and graphene have only relatively recently become experimentally accessible. In fact, research attempts to simulate DIBs in the laboratory led to the accidental discovery in 1985 of the Buckminsterfullerene, or the “buckyball” carbon-60 molecule, for which the Nobel Prize was awarded in 1996.

Buckyballs possess unique chemical and physical properties that hold an array of possibilities for all the natural sciences. They are an entirely new material providing scientists with information about allotropes of carbon never before conceived. A few areas where buckyballs are proving valuable to research include drug treatments, medical diagnostics, nano scanning tunneling microscopy, electrical circuitry, lubricants, superconductors, and catalysts. The discovery of nanotubes in 1991 by S. Iijima has been by far the buckyball’s most significant contribution to current research.[10]

Conclusion

As has already been mentioned, recent work suggests DIBs are caused by polycyclic aromatic hydrocarbons, or, most likely, their cations.[11] But recently a radically different mechanism - doubly excited atoms embedded in the condensed phase called Rydberg matter (RM) – was proposed for the formation of DIBs.[12]

Holmid's RM model, which accurately calculates 120 intense bands in a consistent manner, is of interest for its direct bearing on the DIB conundrum, but it's also a good illustration of the scientific process in general and specifically of how that process can be misinterpreted through modern media. For instance, even though Holmid's paper is the work of a single author and has but a single independent journal citation to date, Wikipedia's entry for "Diffuse Interstellar Bands" begins by overstating that "no agreement of the bands could be found with laboratory measurements or with theoretical calculations. This situation has recently changed." Wikipedia then follows this misleading statement with a more reasonable, qualified assessment of Holmid's work.[13]



The Milky Way Galaxy
http://www.nasa.gov/mission_pages/spitzer/multimedia/20080603a.html

A large collaboration of astronomers has been conducting a survey of unprecedented extent, with the aim of definitive spectral atlases of the DIBs and to search for correlations that will yield some observational constraints on the nature of their carriers. The hope is that these studies will pull out the spectra of individual molecules from the complex set of DIBs, which could greatly aid laboratory studies.

Some recent observations also show a robust dependence of DIB strength on the local environment in terms of cloud density and exposure to the interstellar radiation field.[14] This leads to an additional goal of exploring the link between the physical and chemical conditions in the ISM as an angle of approach to uncovering the carrier or carriers.

To date, this intriguing puzzle remains largely characterized by the explanations that have been ruled out. There is no compelling evidence that DIBs are a solid-state phenomenon or are produced by some material trapped in interstellar grains. They aren't formed by reactions involving $H_{2,}$ and their widespread presence indicates they are not formed in stars, but in the diffuse interstellar clouds themselves.[15]

When and if the DIB carriers, the mechanisms for their formation, and the reasons for their correlation with other observables (such as how they manage to survive the extremes of interstellar space in such profusion) are finally and fully understood, that knowledge will be the result of countless observations, laboratory measurements, models and calculations.

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[13] Wikipedia can be a good place to begin researching a topic and is often an excellent source of links and relevant resources. However, since articles can be edited by anyone without any authority, errors or biases do arise. Although other editors look out for such problems, in general, Wikipedia is not a credible source in research or scholarly work.

[14] Cox, N. L. J. & Cordiner, M. A. Diffuse interstellar bands in the Local Group: From the Milky Way, the Magellanic Clouds to the Andromeda galaxy. Organic Matter in Space: Proceedings IAU Symposium No. 251, 2008.

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