Identifying Organic Molecules in Space – The AstroBiology Explorer (ABE) MIDEX Mission Concept

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ABSTRACT

In this paper we review our current state of knowledge regarding the identity of organic and related compounds in the interstellar medium (ISM). The remote detection and identification of organics is ideally suited to the technique of infrared spectroscopy since such data can be obtained telescopically and this spectral range encompasses the fundamental vibrational modes of common molecular bonds. Despite recent advances in our knowledge of the organic component of the ISM, we are still far from understanding the distribution, abundance, and evolutionary inter-relationship of these materials within our galaxy and the universe as a whole. Many of these issues can be addressed by the acquisition of new infrared spectra. We briefly describe a potential new Explorer-class space mission capable of obtaining such data, the AstroBiology Explorer (ABE), which consists of a space observatory capable of obtaining spectra in the 2.5-16.0 µm range at a spectral resolution of $\Delta\lambda/\lambda$ = 2000-3000. ABE would be capable of addressing outstanding problems in Astrochemistry and Astrophysics that are particularly relevant to Astrobiology and addressable via astronomical observation. ABE would have an approximately one year lifetime during which it would obtain a coordinated set of infrared spectroscopic observations of large numbers of galaxies, stars, planetary nebulae, interstellar clouds, young star planetary systems and objects within our own Solar System.

Keywords: Astrobiology, infrared spectroscopy, Explorers, interstellar organics, telescope, spectrometer

1. INTRODUCTION

The technique of infrared spectroscopy has played a central role in the progress made in the detection and identification of the molecular contents of our galaxy and the universe at large. This is because the vast majority of interatomic vibrational modes in molecules fall in the infrared frequency range. Molecular vibrational transitions involving a change in dipole moment result in the emission or absorption of an infrared photon whose energy is characteristic of the chemical functional group involved. As a result, most molecules produce spectral "fingerprints" consisting of multiple infrared bands unique to the combination of chemical bonds present in the molecule. Figure 1 shows the spectral ranges over which the fundamental vibrational modes of a number of common chemical functional groups occur. It is clear that spectra spanning the middle infrared portion of the electromagnetic spectrum range cover the majority of the fundamental molecular vibrational transitions expected for molecules made from the cosmically most abundant elements.

Progress has only been possible by the close collaboration of observers, theoreticians, and experimentalists. Such highly interdisciplinary collaborations are essential to ensuring fundamental, in-depth coverage of the wide-ranging challenges posed by astrophysics, astrochemistry, and astrobiology. Understanding the nature of interstellar organics is of particular interest since this material may provide a significant portion of the "feedstock" from which life originates.

In the following sections, we review our current understanding of the nature of the various organics and related materials that have been identified in different environments in the ISM. We then briefly discuss areas in which additional progress can be made, with an emphasis on use of the technique of infrared spectroscopy, and describe a potential MIDEX mission that could play a major role in furthering our understanding of the nature of organics in space.
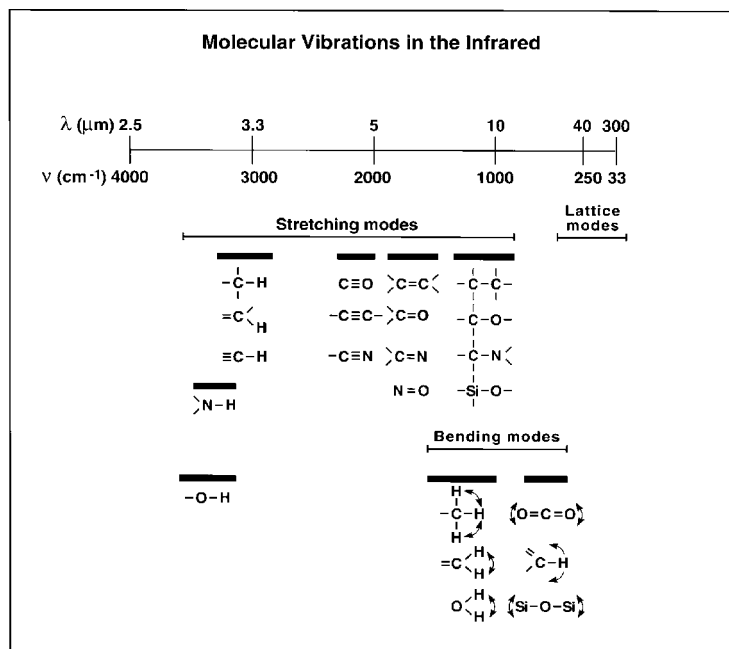
Figure 1. The vibrational frequencies associated with the most common chemical bonds between the most abundant elements fall in the middle infrared portion of the electromagnetic spectrum.

2. ORGANICS AND RELATED MATERIALS IN THE INTERSTELLAR MEDIUM

In general, dust in the diffuse interstellar medium is believed to consist of mixtures of inorganic and carbonaceous refractory materials.[1] In benign environments, this material is augmented by gas phase molecules and ices.[2,3] The evidence materials in the ISM that are volatile or organic will be reviewed in the following subsections.

2.1 – Gas Phase Molecules

Radio spectral techniques show that dense clouds contain a variety of gas phase molecules. This population contains both simple molecules like CO, OH, and CN, and more complex species like HC_9N. The overall gas phase population originates from the interplay of gas phase chemistry[4] and grain chemistry.[5,6] The actual interstellar population almost certainly contains *far* more species than the ~100 so far identified.[2] Most of these gas phase molecules are not stable in harsh radiation fields and they are generally detected in dense molecular clouds where high dust opacities protect them from diffuse ISM radiation. However, the temperatures in these clouds are quite low (T ≥ 10 K), and under these conditions most molecules will freeze into ice mantles on dust grains.[7] Thus, while radio techniques have detected a large number of molecular species in the gas phase, they generally constitute a small fraction of the materials present.

One class of gas phase species not detected by radio techniques is the polycyclic aromatic hydrocarbons (PAHs). PAHs are large planar molecules consisting of fused hexagonal rings of C having H on their peripheral rings. They tend to have small dipole moments (if any at all) and, because of their size, have rotation lines that are too closely spaced to be amenable to detection in the radio. Features due to PAHs and related aromatic materials are seen in the spectra of a variety of planetary nebulae, reflection nebulae, and H II regions, all environments rich in UV radiation (Figure 2).[8] The narrower emission features are produced when free molecular PAHs absorb UV photons and cool by emitting a cascade of infrared photons, while the broader underlying emission structure may be due to PAH clusters or amorphous carbons rich in aromatics. PAHs are relatively large molecules and they contain a large number of vibrational modes in which to store absorbed energy. In addition, their conjugate π bonds make them particularly stable. Thus, although most molecules would be destroyed by UV photons under these conditions, PAHs can survive in the interstellar radiation field by virtue of their size and stability. As a result of their stability, PAHs are the carriers of a significant portion of the interstellar C inventory, with estimates ranging as high as 15%.
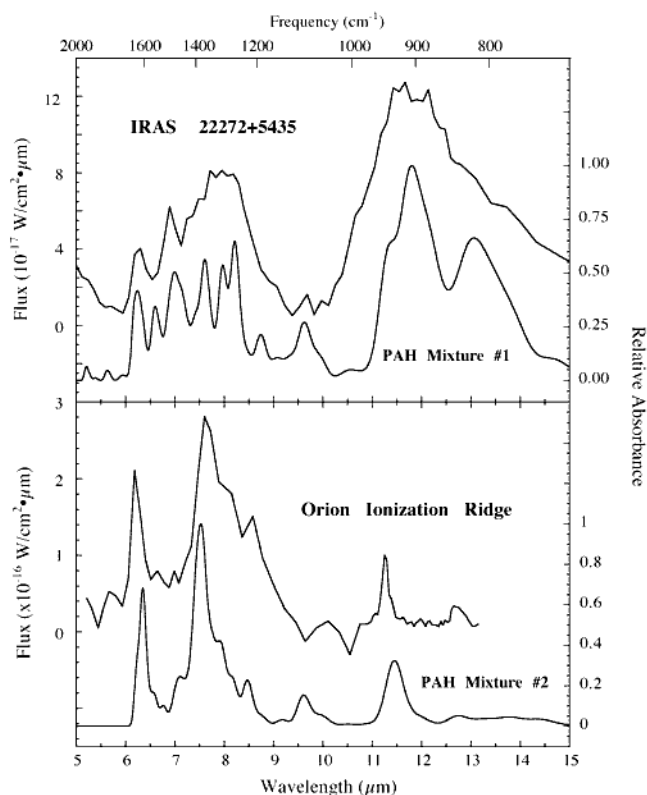
Figure 2. Infrared emission spectra of the proto-planetary nebula IRAS 22272+5435 (top) and the Orion ionization ridge (bottom), each compared to a synthetic spectrum made from the coaddition of laboratory spectra of various PAH ions and neutrals. [see ref. 9 for more details]

PAHs and other organics should become D-enriched as a result of at least four different interstellar chemical processes: low temperature gas phase ion-molecule reactions, low temperature gas-grain reactions, gas phase unimolecular photodissociation, and ultraviolet photolysis in D-enriched ice mantles.[10] Each of these produces distinct regiochemical signatures (D placement on the product molecules, correlation with specific chemical functionalities, etc.). Thus, observation of D-enrichment in interstellar organics would be helpful for delineating what chemical processes are occurring. In addition, D enrichments are seen in the organics in primitive meteorites. The presence of D anomalies in meteorites is the most unequivocal demonstration that interstellar organics can survive incorporation into a protostellar nebulae, subsequent accretion onto a planetesimal and parent body and parent body processing, and delivery to the surface of a planet. Establishing the links between interstellar organic chemistry and the delivery of carbonaceous materials of biotic interest is clearly of interest to issues associated with astrobiology and the origin of life.

2.2 – Refractory Organics

There is spectral evidence of a number of refractory solids in the ISM. These include silicates, silicon carbide, oxides, and several forms of refractory carbonaceous material. Here we will only discuss the carbonaceous materials.

Refractory Aliphatic and Aromatic Organics in the Diffuse ISM

While the spatial density of material in the diffuse ISM between stars and dense clouds is very low, this volume is far from empty. Indeed, there is excellent evidence for the presence of organic materials in the diffuse ISM. As early as 1976, an absorption band near 2950 cm^{-1} (3.4 µm; due to C-H stretching vibrations) was detected in the spectra of Galactic Center infrared sources.[11] Ultimately, spectral studies of objects along additional, different lines-of-sight suffering from a wider range of visual extinctions (A_v) demonstrated that 2950 cm^{-1} (3.4 µm) C-H stretching band correlates with A_v and shows a remarkable similarity in position and profile over extinctions ranging from as low as 3.9 to as high as 31 (see Figures 3 and 4).[12-14]
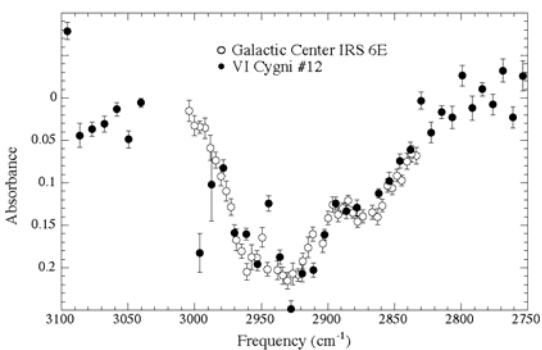
Figure 3. The infrared absorption bands produced by the C-H stretching vibrations of aliphatic –CH$_2$– and –CH$_3$ groups along the lines of sight to Galactic Center IRS6E and VI Cygni #12. The VI Cygni #12 band has been scaled by a factor of 4. [adapted from ref. 12]
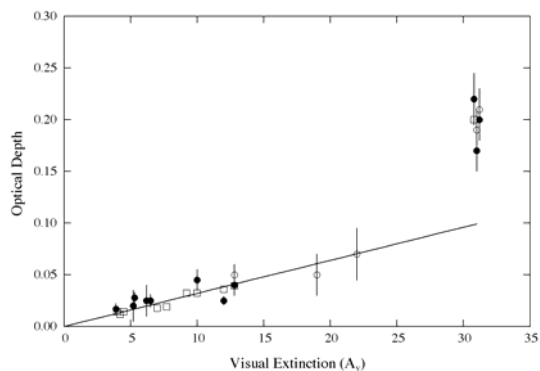
Figure 4. The optical depth of the the 10 μm silicate band (solid symbols) and 3.4 μm aliphatic C-H stretch band (open symbols) as a function of visual extinction. The silicate optical depths have been scaled by a factor of $^1/_{18}$. [adapted from ref. 14]

The profile and subpeak positions of the overall C-H stretching feature provide specific clues to the nature of the carbonaceous material in the diffuse ISM.[12] The feature contains subpeaks near 2955, 2925, and 2870 cm^{-1} (3.38, 3.42, and 3.48 μm) (Figure 3). The positions of the first two are characteristic of asymmetric C-H stretching of –CH$_3$ (methyl) and –CH$_2$– (methylene) groups in saturated aliphatic hydrocarbons (molecules with the formula C$_n$H$_{n+2}$). The relative strengths of these two subfeatures indicate an average -CH$_2$-/-CH$_3$ ratio of 2.5 ± 0.4. However, the band profile differs from that of *pure* saturated aliphatic hydrocarbons in that it does not contain two peaks near 2870 and 2850 cm^{-1} (3.48 and 3.51 μm) characteristic of the symmetric C-H stretching vibrations of –CH$_3$ and –CH$_2$– groups, respectively. Instead, it shows only a single subfeature near 2870 cm^{-1} (3.48 μm). This implies the presence of electronegative or other perturbing chemical groups, since these can suppress the 2850 cm^{-1} (3.51 μm) feature without greatly effecting the positions or strengths of the other C-H bands. Thus, the C-H stretch feature due to dust in the diffuse ISM is largely produced by short aliphatic chains like -CH$_2$-CH$_2$-CH$_3$ and -CH$_2$-CH$_2$-CH$_2$-CH$_3$ attached to electronegative or other perturbing chemical groups like -O-H, -C≡N, aromatics, etc. The absolute strengths of these bands indicates that this material accounts for at least 2.5% of the total cosmic C in the diffuse ISM, and probably closer to 10%.

Additional constraints on the nature of this material are provided by spectral comparison with laboratory materials. A number of materials have been shown to provide *qualitative* spectral fits to the interstellar feature, but one of the best matches is provided by meteoritic organic material.[13] This suggests that the perturbing chemical groups inferred from the profile of the interstellar feature may largely consist of aromatic moieties since meteoritic organics are rich in aromatics. This is consistent with the detection of a weak absorption feature near 3030 cm^{-1} (3.3 μm) in the spectra of several Galactic Center objects,[13] a spectral position characteristic of the aromatic C-H stretching vibration. Given their known presence in the gas phase, it would not be surprising to find PAHs in diffuse interstellar solids.

The strength of the C-H stretching feature scales linearly with visual extinction along all the limited number of lines-of-sight so far examined *except* for objects near the center of the Galaxy.[14] This behavior parallels that the Si-O stretching band due to silicates in the diffuse ISM (Figure 4).[15] The deviation of Galactic Center objects from the linear trend implies that the grains responsible for the diffuse ISM aliphatic C-H and silicate Si-O stretching bands are *different* from those responsible for much of the observed visual extinction. The similar behavior of the C-H and Si-O stretching bands suggests that these materials may not be uniformly distributed within the galaxy. Several possible models of the distribution of these materials have been considered,[14] but due to a lack of measurements over a wider range of directions and extinctions, these model solutions are not unique.

Graphite in the Diffuse ISM

Graphite is a common component in theoretical models that attempt to explain the shape of the interstellar extinction and polarization curves across the infrared, visible, and ultraviolet. The principal motivation for invoking graphite is

that it is one of the better candidate materials for producing the infamous 2175 angstrom UV extinction feature.[16] However, there is presently no infrared spectral evidence graphite in the ISM. Since graphite has a high degree of molecular symmetry and consists of only one element, most of its vibrational modes produce little or no change in dipole moment. As a result, graphite has few modes that are "infrared-active" and produces no strong spectral features. Theoretical calculations indicate that small graphite grains should produce weak features near 1590 and 868 cm^{-1} (6.30 and 11.52 µm),[17] but these features have yet to be detected in space.

Interstellar graphite grains have been found in meteorites,[18] but these grains are not the small, abundant, perfectly crystallized graphite particles required by most models. Instead, the meteoritic grains show several morphological types, contain poorly graphitized carbon, and account for only a minor fraction of the C in meteorites. The interstellar graphite grains required by models must be small (radii below 150 angstroms) if they are to explain the 2175 angstrom extinction feature.[16] The graphite grains found in meteorites are much larger, typically falling in the 1 to 5 µm range.[18] If one assumes a power law size distribution like $N(a) \propto a^{-3.5}$ and requires that ~15% of cosmic C be in the radius less than 150 angstrom range needed to explain the 2175 angstrom bump,[16] one finds that ~250% of all the cosmic carbon needs to be in graphite![3] Thus, the meteoritic graphite grains and interstellar 'graphite' particles responsible for the 2175 angstrom feature do not represent different size end-members of the same grain population and are probably *completely* unrelated.

Nanodiamonds in the ISM

The spectra of dense molecular clouds frequently show a weak absorption feature on the wing of the "3 µm" H_2O ice band near 2880 cm^{-1} (3.47 µm).[19,20] Its strength varies independently of the ice features seen in the same spectra, implying the carrier is not a volatile.[19] The band falls at a unique position characteristic of the C-H stretch of tertiary carbon, i.e., a carbon atom bonded to one hydrogen and 3 other carbons. The structure of a tertiary (3°) carbon is shown below in comparison with primary (1°, methyl) and secondary (2°, methylene) aliphatically bonded carbons.

primary (1°)   secondary (2°)   tertiary (3°)
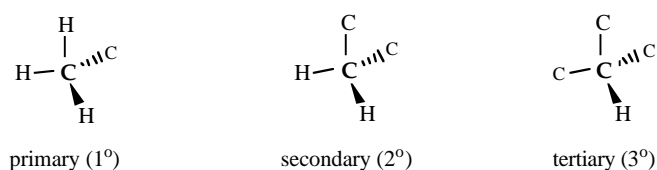
The presence of a tertiary carbon feature, in conjunction with an absence of strong features due to primary (-CH$_3$) and secondary (-CH$_2$-) carbons suggests the carrier has a diamond-like structure.[19] Some additional support for a diamond-like carrier comes from the detection of a weak band near 1350 cm^{-1} (7.41 µm) in the spectra of one of these same objects,[21] a position near which hydrogen atoms bonded to diamonds produce a weak C-H bending vibration band. Furthermore, recent excellent work has detected a beautiful set of diamond emission bands in circumstellar dust.[22] Finally, as with graphite, interstellar nanodiamonds have been identified in meteorites.[23]

It is difficult to precisely determine the abundance of this material in the ISM because the measured C-H stretching band is only due to carbon atoms in the surface of the nanodiamonds. The optical depth of the 2880 cm^{-1} band requires that a *minimum* of ~5% of the available cosmic carbon must be tied up in this material.[19] However, carbon in the center of a diamond structure is bonded only to other carbons and its vibrations are infrared inactive. Thus, internal carbon atoms are largely invisible in the infrared. If one assumes that the inferred interstellar nanodiamonds have the meteoritic size distribution (median size of ~10 angstroms[24]), it is possible to infer that interstellar nanodiamonds account for about 10% of the cosmic carbon.[19] The highest abundances found in meteorites are on the order of a few percent of their total carbon.[25] These results suggest that nanodiamonds are quite abundant in space and that they have a remarkable ability to survive the rigors of incorporation into small parent bodies formed in the early Solar System.

The ultimate source of the interstellar nanodiamonds remains uncertain although several formation processes, including chemical vapor deposition, photolysis of hydrocarbons, and grain collisions produced by interstellar shocks, have been suggested.[26] Transmission electron microscope studies of the meteoritic nanodiamonds suggest that formation by chemical vapor deposition is most likely.[27] The ubiquity of the band in the spectra of dense clouds and the inferred high abundances of nanodiamonds suggests that the formation involves a relatively common environment.

Ices in Dense Molecular Clouds

As mentioned earlier, the condensation of gas phase molecules onto grains is expected to be very efficient in dense molecular clouds and most of the products of gas phase chemistry in the ISM should spend the majority of their lifetimes
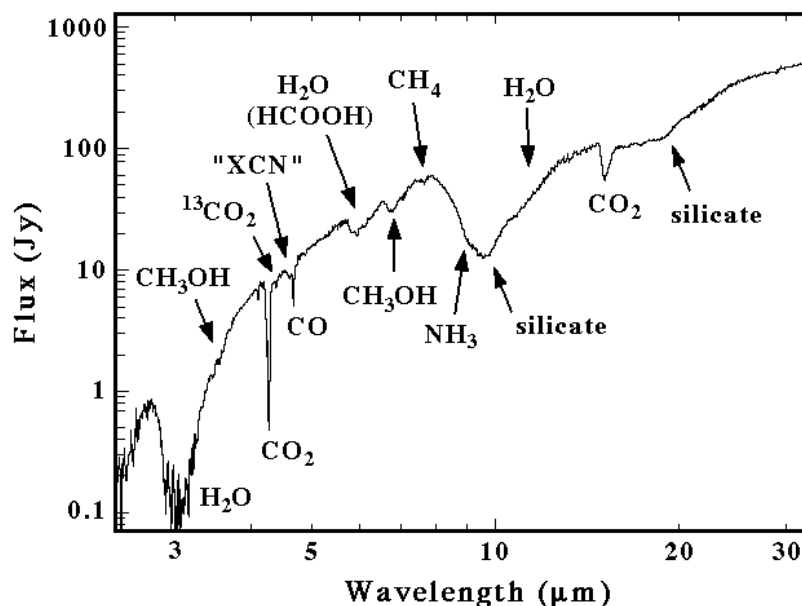
Figure 5. The infrared absorption spectrum of the protostellar object NGC 7538 IRS9 showing the absorption bands due to silicates and a variety of simple volatile species [figure adapted from ref. 28]

in icy grain mantles.[7] Most of the molecules observed in interstellar ices are quite simple and do not strictly meet the criteria to be considered as organic materials. However, as described below, these species participate in a variety of chemical processes that ultimately yield complex organic materials. In addition, all organic materials, independent of their original source and evolutionary history, must pass through the cold dense cloud phase on their way to being incorporated in any newly forming stellar/planetary system. Thus, an understanding of the ices found in dense clouds is key to understanding how interstellar organics are created, evolve, and get to planetary surfaces.

The nature of the ices in dense molecular clouds can be best probed by measuring the infrared spectra of protostars embedded within the cloud or normal stars lying behind the cloud. A example is given in Figure 5, which shows the infrared spectrum of NGC 7538, a protostar embedded deep within a dust cloud. One of the strongest features in the spectrum is the "10 μm" silicate feature, but most of the absorption features are due to ices and related materials.

The dominant component in interstellar ices is H_2O, as evidenced by the absorption bands it produces near 3280 cm^{-1} (3.05 μm, O-H stretch), 1670 cm^{-1} (6.0 μm, H-O-H bend), 735 cm^{-1} (13.6 μm, libration), and 250 and 140 cm^{-1} (40 and 70 μm, lattice modes). All these bands have been detected in the spectra of dense molecular clouds and all fit reasonably well with laboratory H_2O ice spectra.[11,29-31] The 3280 cm^{-1} O-H stretching band of H_2O is typically one of the strongest in the interstellar spectra.

The spectra of embedded protostars often contain a prominent absorption feature peaking near 1460 cm^{-1} (6.85 μm).[32] The profile of this feature varies substantially from object to object, indicating the presence of more that one absorbing species. At least a portion of this band is due to the CH deformation mode vibration of CH_3OH (methanol), which has also been identified by its other features at 4141 cm^{-1} (2.415 μm),[7] 2825, 2600, and 2540 cm^{-1} (3.54, 3.85, and 3.94 μm),[19] and 1125 and 1035 cm^{-1} (8.9 and 9.65 μm).[33] The implied methanol to water ratios are typically around 0.1. As will be described later, the presence of CH_3OH has profound effects on the irradiation chemistry of these ices.

After H_2O, the most studied interstellar ice component is probably carbon monoxide. CO in the solid state produces a C≡O stretching absorption feature near 2140 cm^{-1} (4.67 μm) whose spectral position, width, and profile are a sensitive function of the ice matrix within which the CO molecules are frozen.[34] Although its identification is based on only one band, its unique position and excellent match with lab data allow its unequivocal assignment. Many, but not all, of the lines-of-sight that contain H_2O ice also contain CO ice and the relative strengths of the H_2O and CO bands indicate CO/H_2O ratios range from 0.0 to 0.2.[35,36] Interestingly, the position and profile of the interstellar CO ice band varies from cloud to cloud. A few of the CO bands have positions and profiles consistent with the majority of the CO being

frozen in H_2O-rich matrices. However, the majority exhibit profiles indicative of CO frozen in non-polar matrices, i.e., in ices dominated by molecules like CO, CO_2, O_2, N_2, and CH_4, rather than H_2O.[34] These are precisely the sorts of mantles predicted to be present in cloud regions where the H/H_2 ratio is less than one.[37] The fact that H_2O, a highly polar molecule, is the most abundant molecule in the ices along *all* these lines-of-sight, but that the CO is generally in ices dominated by *non*-polar molecules, provides clear evidence for the existence of multiple chemical environments within individual cloud complexes. Thus, it would appear that interstellar clouds are not compositionally homogeneous.

CO_2 was long expected to be a component of interstellar ices since its presence was predicted by interstellar chemistry models and it is always produced during the irradiation of laboratory interstellar ice analogs.[6] However, it was difficult to detect in the infrared owing to telluric CO_2, which makes the atmosphere opaque at the relevant wavelengths for its detection. It was first tentatively identified in the ISM using IRAS LWS telescopic data.[38] Subsequent data from the ISO spacecraft has demonstrated that CO2 is ubiquitous and abundant in dense clouds.[39,40]

Ammonia was first tentatively identified in the early 1980s, but it was not until recently that combined telescopic and laboratory data lead to a convincing detection.[41] It appears that NH_3 is present at about the 10% level relative to H_2O. This currently represents the only substantial carrier of the element N that has been identified in dense clouds.

Other volatile species that have been identified or tentatively identified in dense cloud ices include CH_4,[21,42] HCO and H_2CO,[32] OCS,[43] and possibly ketones and/or aldehydes.[32] Many of these species, as well as a host of others, are predicted on the basis of interstellar chemistry models[37,44] and laboratory studies of the thermal and irradiation chemistry of ice analogs.[6] Theoretical models predict that O_2 and N_2 should also be abundant in some interstellar ices,[37] but because they are homonuclear diatomic molecules, their stretching vibrations do not produce a change in dipole moment and are not easily detected in the infrared. However, when these species are frozen into ices, interactions with other molecules in the matrix can induce a weak dipole and these species can produce weak bands.[45,46] In the case of N_2, the strength of the induced band is *extremely* sensitive to the composition of the surrounding ice and under some conditions the band strength can be strongly enhanced.[46] Neither O_2 or N_2 have yet been detected in interstellar ices, although ISO data has recently been used in conjunction with laboratory results to begin to place meaningful upperlimit on N_2 along the lines of sight to several protostars.[47]

Organics Made During the Irradiation of Ices

The spectra of a limited number of lines-of-sight through dense clouds contain a broad, often weak, feature centered at about 2165 cm^{-1} (4.62 µm) near the CO ice feature.[48,49] This feature is usually present only in the spectra of objects embedded within the clouds and not in the spectra of background stars,[50] suggesting that the carrier is associated with the local environment of the embedded star. The molecule(s) responsible for this absorption have yet to be conclusively identified. Lacy et al.[48] noted that the feature could be reproduced by UV irradiated ices containing C and N. This, in conjunction with the feature's position, lead them to suggest that the absorption is due to the stretching vibration of a C≡N functional group in a larger molecule, i.e., a nitrile or isonitrile [often designated as XCN]. Subsequent laboratory irradiation experiments have shown that excellent spectral fits to the astronomical data can be obtained when astrophysically-relevant ice mixtures are irradiated.[6,49,51] It has been suggested that the band could be due to the CN stretch in the OCN$^-$.[52] Recent laboratory work using isotopically-spiked starting materials indicates that the carrier must contain C, N, O, *and* H.[53] Thus, if the band carrier is OCN$^-$, it must be complexed with a H-containing counter ion.

In any event, the presence of XCN represents one of the main indications that interstellar ices are processed by ionizing radiation, as would be expected. This radiation results in the breaking and rearrangement of chemical bonds within the ices, causing the destruction of some species and the creation of others. This is an important process since it can result in the creation of many new molecular species, particularly complex ones, that cannot be made via gas phase and gas-grain reactions at the low temperatures and pressures characteristic of dense clouds.

Laboratory studies have demonstrated that the irradiation of realistic interstellar ices analogs results in the destruction of many of the original species (particularly methanol) and the creation of others (HCO, H_2CO, CH_4, CO_2, XCN, etc.). The same ice irradiation processes that produce these simple molecules also produce more complex species. Indeed, mass spectra of these residues demonstrate that irradiation creates literally hundreds of new species, many of which have yet to be identified. Species that *have* been identified include ethanol (CH_3CH_2OH), amides {such as formamide, $HC(=O)NH_2$, and acetamide, $CH_3C(=O)NH_2$}, nitriles and isonitriles (R-C≡N and R-N≡C), ketones {R-C(=O)-R'}, hexamethylenetetramine (HMT, $C_6H_{12}N_4$), and compounds related to polyoxymethylene {POM, (-CH_2O-)$_n$}.[6,54] In addition, a class of species known as amphiphiles are also produced.[55] Many of these species are of astrobiological

interest. For example, when placed in water, HMT can produce amino acids and the amphiphiles are observed to spontaneously form vesicles, i.e., membranes that encapsulate internal volumes.

As mentioned earlier, polycyclic aromatic hydrocarbons represent one of the main carriers of carbon in the interstellar medium.[8] In dense clouds, these species should be almost entirely condensed onto the ice mantles along with the simpler molecules H_2O, CO, etc. Indeed, the detection of a weak aromatic C-H stretching band near 3.25 µm in the spectra of dense clouds suggests that PAHs are present.[20] Laboratory studies of the effects of irradiation on PAH-bearing ices has demonstrated that new aromatic species are produced, including aromatic alcohols, ethers, and ketones.[56] The aromatic ketones are of particular interest, since quinones, a class of functionalized aromatic ketones, are used by all living systems on earth for electron transport functions.

Clear-cut evidence for the more complex types of species of the types made in the laboratory simulations in interstellar clouds is presently lacking, although some of the spectral structure detected in the 2000-1250 cm^{-1} region is consistent with the presence of such molecules. Since these materials are of exobiological interest, a rigorous search for absorption features due to these materials in dense clouds would clearly be of value.

Organic Materials in Other Galaxies

The distribution of organics in other galaxies has yet to receive much attention. Data from the Infrared Space Observatory (ISO) has demonstrated that the emission bands due to PAHs are extremely common in the spectra of external galaxies.[57] In addition, a limited number of galaxies are known to contain the 3.4 µm C-H stretching bands characteristic of the aliphatic component of the dust within the diffuse ISM of our own galaxy.[58] Thus, there is evidence for some of the main types of material in other galaxies that we see in our own galaxy.

3. WHAT WE DON'T KNOW ABOUT ORGANICS IN SPACE

Despite the exciting progress that has been made in this field in the past decade, there is still much that we don't know about the nature of organics in space. This comes, in large part, from the fact that our current knowledge is largely based on data that provide only partial spectral coverage or that sample only a limited number of lines of sight. Examples of open issues include:

What is the real distribution of interstellar aliphatics within our own galaxy and why does the Galactic Center show anomalously large amounts of this material?

What is the distribution of ices and ice compositions within dense molecular clouds and what defines whether the ices are dominated by polar or non-polar molecules?

Where is all the cosmic nitrogen? Only a minor fraction of the expected cosmic inventory is currently accounted for. Is most of the rest in N_2?

How do interstellar organic materials (PAHs, aliphatics, etc.) evolve with time? What environments (stellar outflows, HII regions, dense clouds, etc.) dominate the alteration of these materials and how? Are any of these materials inter-related, and if so, how?

What are the abundances (both absolute and relative) of the various types of organic species as a function of interstellar environment?

Is there evidence for any of the more complex species we would anticipate to be present in the ISM on the basis of lab experiments? For example, can we detect the characteristic bands of aromatic ketones?

Do other galaxies have the same organic populations as our galaxy? Do the organic populations depend on galactic classification?

These and many more issues could be addressed by an infrared spectral mission having high sensitivity and a spectral resolution of 2000-3000 across the 2.5-16 µm region. In the following section, we briefly describe a candidate MIDEX class mission, the Astrobiology Explorer (ABE), that could address these issues.

4. THE ASTROBIOLOGY EXPLORER (ABE) MISSION

The Astrobiology Explorer (ABE) is a MIDEX-class space telescope mission concept that would use infrared spectroscopy to address outstanding problems in Astrochemistry and Astrobiology. ABE would have a 60 cm diameter

telescope equipped with two cooled spectrometers covering approximately the 2.5-5.0 µm and 5.0-16.0 µm spectral ranges at resolutions of 2000-3000. The spacecraft will operate from an Earth-driftaway orbit similar to that used by SIRTF. The scientific goals of the ABE Mission will be achieved by an observing strategy that uses a modest number of programs tightly focused on the creation and evolution of organic materials in space. The more technical aspects of this mission concept are described in a companion paper in this issue.[59]

The observational program would make fundamental scientific progress in the areas of (i) the evolution of ices and organic matter in young stellar systems, (ii) the chemistry of complex organic molecules in the interstellar medium, (iii) the distribution of organic compounds in the diffuse interstellar medium, (iv) the nature of organics in the solar system (comets, asteroids, satellites), (v) the distribution of molecular carbon in other galaxies, and (vi) the deuterium enrichment of ices, PAHs, and diffuse medium organic refractory materials. In addition to the tasks listed above, a portion of the observing time (~20%) would be made available, on a competitive basis, to the general scientific community as part of a guest observer program. ABE would build significantly on the database provided by ISO, compliment SOFIA and SIRTF data, and be a flight test of detectors being considered for NGST.

The Environments Surrounding Forming Stars – Independent of the formation site and subsequent interstellar evolution of cosmic organics, they must ultimately pass through the dense cloud phase if they are to end up on the surface of a planet. Thus, understanding the environment surrounding forming stellar systems is critical to addressing the role interstellar organics may have played in the origin of life. Dense clouds are especially interesting because laboratory, theoretical, and telescopic observations indicate that complex organic species are created in these environments. ABE will greatly improve our understanding of the molecular nature of these environments by obtaining absorption spectra of embedded solar-mass protostars and background field stars that will probe a large number of lines of sight through several nearby dense clouds in which star formation is occurring.

The Evolution of Complex Organic Molecules in the Interstellar Medium (ISM*)* – Polycyclic aromatic hydrocarbons (PAHs) represent one of the principal forms of complex molecular carbon in space. These molecules are generally thought to be initially produced in the outflows of late type carbons stars forming protoplanetary and planetary nebulae (PPN/PN). The PAHs are detectable via the characteristic IR emission features they produce as they are excited by UV and visible photons. The population of PAHs will evolve as they are subjected to the increasingly intense radiation field of their central star. ABE will study this evolution by examining the differences in the spectra obtained from PPN and PN that are at different stages of evolution. In addition, the PAH population will be further modified in the ISM by the interstellar radiation field, supernovae shock waves, condensation and irradiation in ices in dense clouds, etc. Thus, ABE will also study PAH evolution by examining PAH emission spectra from HII regions and their boundaries with dense molecular clouds.

The Distribution of Organic Compounds in the Diffuse Interstellar Medium – On the basis of limited observations along a few lines of sight within our galaxy, it is known that ~10% of carbon in the diffuse ISM is in the form of aliphatic hydrocarbons. These materials appear to be associated with comparable or greater amounts of aromatic hydrocarbons. ABE will use field stars to probe for organic absorption bands along a multitude of lines of sight throughout our galaxy to determine the composition, abundance, and distribution of this material within our galaxy.

Organics in the Solar System (comets, asteroids, planetary moons) – Comets and asteroids, and the dust and meteoroids they produce, probably represent the principal bodies responsible for delivering interstellar materials to early planetary surfaces. Thus, understanding their organic contents is of direct interest to determining the role interstellar materials may have played in the origin of life. ABE will obtain spectra from a number of these objects. ABE will also obtain spectra from the surfaces of icy bodies in the outer solar system (KBOs, satellites of the gas giants, Pluto and Charon), objects that may either be repositories of interstellar organics or sites on which organics may be formed *in situ*.

The Cosmic History of Molecular Carbon – ABE will take the spectra of a number of galaxies to examine the their molecular composition as a function of type and cosmic distance. Spectral features such as the PAH emission bands and aliphatic absorption bands have both been seen external galaxies. Targets include ultraluminous IRAS galaxies, Starburst galaxies, Seyfert galaxies, distant ULGs, and dwarf, S0, spiral, and elliptical galaxies. In addition, ABE will examine a few colliding galaxies and do more detailed spectral mapping of a few nearby galaxies.

Tracing Deuterium Enrichments – In a number of favorable cases, ABE will obtain spectra with sufficiently high S/N to detect or derive meaningful upperlimits to the D/H ratios in the organics. A number of astrochemical processes enrich organics in D in the ISM and it is the presence of D-enrichments in the organics found in meteorites and

interplanetary dust that provides the principal proof that some interstellar organics can survive their incorporation into forming stellar systems and subsequent arrival on the surface of planets. Thus, we hope to better establish the connections between interstellar chemistry and the complex suite of organics found in extraterrestrial materials.

Guest Observations – The core science mission places constraints on the required capabilities of the instrumentation needed to carry out the observational program. An instrument and spacecraft that is ideal for meeting these requirements is described elsewhere in this issue.[59] However, such an instrument would *also* be capable of making observations of great significance addressing a variety of astrophysical issues not falling directly into the scientific goals and observing programs described above. Therefore, we intend to set aside ~20% of ABE's total observing time, on a competitive basis, for use by the general astronomical community. Thus, the capabilities of ABE will be used to address a wide variety of astrophysical issues that extend well beyond the central scientific goals of the ABE misison.

5. SUMMARY

It is know known that a significant portion of the cosmic inventory of the elements C, O, N, and H in space are incorporated into a variety of volatiles and organics that are of biogenic interest. However, much remains to be learned about the inter-relationships of these materials and about how they are formed and evolve in space. We have briefly described a potential new MIDEX-class space mission, the AstroBiology Explorer (ABE), consisting of a relatively modest dedicated space observatory having a 60 cm aperture and spectrographs capable of covering the 2.5-16 µm spectral range at a resolution of 2000-3000. Such a system would be capable of addressing outstanding problems in Astrochemistry and Astrophysics that are particularly relevant to Astrobiology and addressable via astronomical observation. The observational program of this mission would make fundamental scientific progress in each of the key areas of the cosmic history of molecular carbon, the distribution and chemistry of organic compounds in the diffuse and dense interstellar media, the evolution of ices and organic matter in young planetary systems, and the deuterium enrichments in ices, PAHs, and diffuse medium organic refractory materials. ABE could make fundamental progress in all of these areas by conducting an approximately one year mission to obtain a coordinated set of infrared spectroscopic observations of approximately 1000 galaxies, stars, planetary nebulae, and young stellar systems.

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