

INFRARED SPECTRAL IDENTIFICATION OF COMPLEX ORGANIC MOLECULES IN INTERSTELLAR GRAINS

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ABSTRACT. The chemical evolution of interstellar grains leads ultimately to a composition consisting largely of complex organic molecules. Comparison of infrared absorption spectra of laboratory produced analogue materials with astronomical observations confirm the presence of similar molecules in interstellar space. The abundance of this complex organic matter derived from the strength of the absorption bands is of the order of ten million solar masses and is almost certainly as large or larger than all conceivable planets.

1. INTRODUCTION

The major atomic constituents of the small solid particles in space are the organic elements oxygen, carbon and nitrogen in combination with hydrogen. These interstellar grains are the order of 0.1 to 0.2 μm in size (semi-thickness) and are generally at the very low temperature of ~ 10 K. [1] From a combination of observations, and laboratory and theoretical analyses of infrared absorption spectra in the denser clouds there has been identification of various molecular ices on the grains [2]. These molecular ices are continually subjected to ultraviolet photoprocessing during the several billion year lifetime of a grain and gradually the photodissociation and recombination of the simple molecules leads to a refractory residue which can not be dissimilar to the complex molecules - prebiotic or otherwise - created by any other forms of energetic processing [3, 4, 5]. At the Leiden Astrophysics Laboratory there is an ongoing program to investigate the chemical composition of residues produced following ultraviolet irradiation of simple ices at interstellar temperatures and subsequent warmup to ~ 300 K. This work is being done in collaboration with Professor James P. Ferris at Rensselaer Polytechnic Institute. In this paper we limit ourselves to studies of the infrared spectra of some residues and a comparison with astronomical observations. The experimental methods have been described elsewhere [6].

2. The Interstellar Grain Model

The material between the stars is generally distributed in irregular clumps or clouds of different densities which, as measured in terms of the most abundant element hydrogen, may be any where from $n_{\text{H}} \approx 10 \text{ cm}^{-3}$ to $n_{\text{H}} \approx 10^7 \text{ cm}^{-3}$ or higher. The intercloud medium at $n_{\text{H}} \approx 0.1 \text{ cm}^{-3}$ is even more tenuous [7].

A model for the tenth micron sized grains which appears to provide a reasonable basis for comparison with observation in the less dense clouds is given by a silicate core of about $0.1 \mu\text{m}$ thickness with a mantle of organic refractory molecules of about $0.05 \mu\text{m}$ thickness. The cores of these particles are responsible for an everpresent $9.7 \mu\text{m}$ absorption. Only in dense molecular clouds does one observe the outer mantles of ices [8]. In the less dense, or diffuse clouds, even the most abundant and most strongly absorbing ice, H_2O , is not observed [9]. In such regions, the only mantle materials which may survive the erosion of sputtering by supernovae explosions for times comparable with cloud lifetimes are the large organic refractory molecules [10].

Although such mantles must underly and exist along with the ices in molecular clouds, their contribution to the infrared absorption spectra in the accesable $2.8\text{--}5 \mu\text{m}$ region is apparently not sufficient to be easily observed except over very long optical paths. Objects observed in the galactic center are examples of long optical paths through grains which exhibit no volatile mantles. The best observed object, IRS7, will be used to provide a basis for comparison with grain models incorporating laboratory created residues. From this comparison we shall derive a quantitative estimate of the amount of complex organic matter in space.

3. Infrared Spectra

In Figure 1a,b we present spectra of various laboratory created residues along with spectra of the galactic center. We note particularly that the interstellar dust is characterized by a $3 \mu\text{m}$, $3.4 \mu\text{m}$ and a $6 \mu\text{m}$ absorption (see spectra d and e). Figure 1a is an expanded version of the $3.4 \mu\text{m}$ region. Three examples of residues of different initial compositions are curves: 2) CH_4 ; 3) $\text{CO}:\text{H}_2\text{O}:\text{CH}_4:\text{NH}_3 = 2:2:1:2$ and 4) $\text{CO}:\text{H}_2\text{O}:\text{NH}_3 = 5:5:1$. The latter residue shows the C-H features at $3.4 \mu\text{m}$ even though no C-H was present in the initial molecules. The $6 \mu\text{m}$ absorption is characteristic of all our truly organic residues and, although the Sgr AW spectrum is noisy, it seems to be present in space as well. Residue (a) is typical of hydrocarbons. We call residues (b) and (c) organic refractories. We see the degree of variability in the structure of the $3.4 \mu\text{m}$ C-H features from one residue to the other, this variability being a general characteristic of organic molecules whether created under simulated interstellar conditions or not. Consequently a mixture tends to reduce the fine structure which results from the $-\text{CH}_3$ and $=\text{CH}_2$ absorptions separately. The organic residues shown here clearly exhibit - when compared with the interstellar organic refractory mantles - a much too strong $3 \mu\text{m}$ absorption. This simply implies too much O-H and N-H groups in the molecule. Further photo-

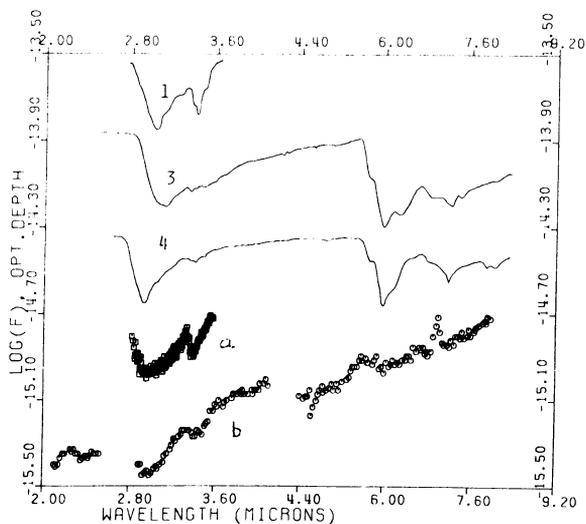
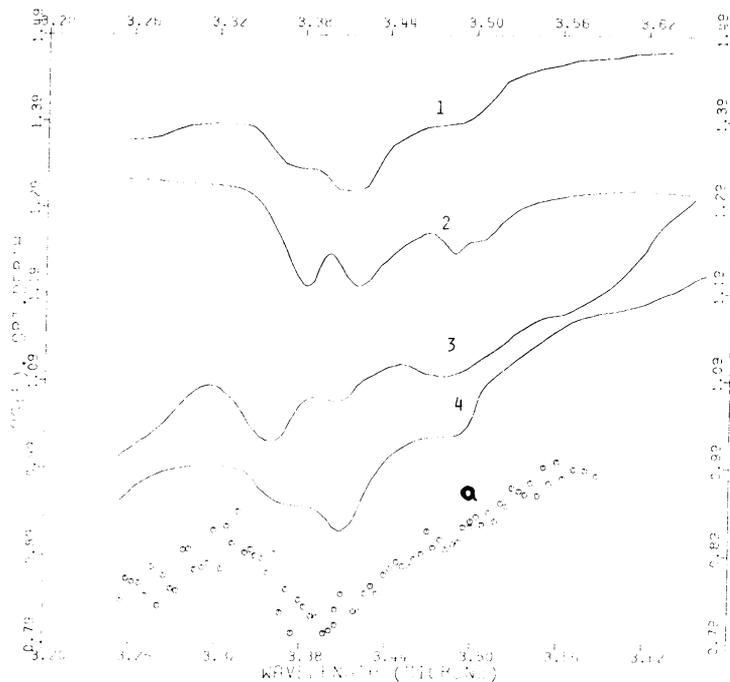


Fig. 1a,b: Infrared absorption spectra of: 1) E-Coli; 2) Residue of CH₄, 3) Residue of CO:H₂O:CH₄:NH₃ = 2:2:1:2; 4) Residue of CO:H₂O:NH₃ = 5:5:1; a) Galactic center source IRS7; b) Galactic center source Sgr AW.

processing of the laboratory residue - as is required by a complete analog with the interstellar case would reduce this feature and amplify the 3.4 μm feature as a result of "carbonization" of the material. This can be simulated in the laboratory merely by starting with mixtures containing, for example CH_4 , which leads to residues intermediate between (a) and (c). Such residues have been produced in our laboratory and will be reported in a later publication.

In Figure 2 is presented the 3.4 μm regions for residue (4), E-coli [9], and IRS7. It is evident that, as far as this feature is concerned, there is little to distinguish among the three.

4. Abundance of Organic Refractories in Space

From the spectrum of IRS7 we deduce an optical depth of about 0.3. This occurs over a path length of 10 kiloparsecs. A measurement of the (extra) absorptivity of residue (4) at 3.4 μm leads to an imaginary part of the index of refraction $m'' \approx 0.015$ (m'' is sometimes called k). This is equivalent to an absorption per unit volume of $\tau_{3.4}/\text{Vol} \approx 5 \times 10^2 \text{ cm}^{-3}$. Using the observed optical depth one derives a mean mass density towards the galactic center of organic refractory matter of $\rho_{\text{O.R.}} \approx 6 \times 10^{-26} \text{ s g cm}^{-3}$ where s = specific density. Compared with a mean interstellar matter (hydrogen) mass density of $\sim 1.5 \times 10^{-24} \text{ g cm}^{-3}$ this constitutes a fraction $\approx 2.5 \times 10^{-2}$ or about 2.5×10^{-3} of

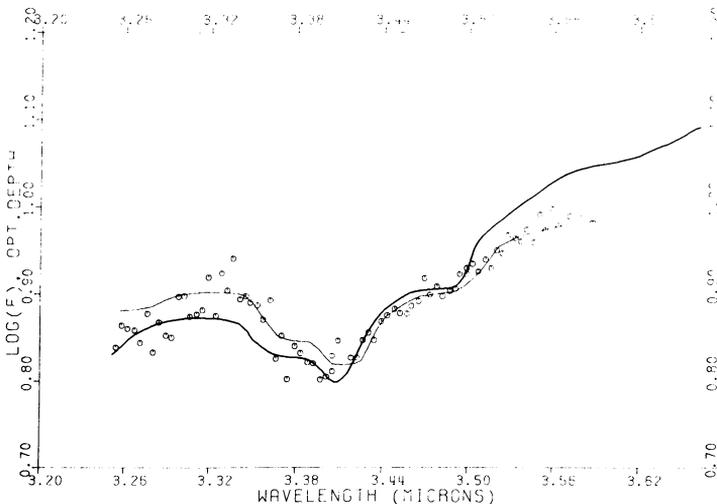


Fig. 2: Overlay of 3.4 μm spectra of the Galactic center source IRS7 (squares), residue of $\text{CO}:\text{H}_2\text{O}:\text{NH}_3 = 5:5:1$ (thick line), E-Coli (thin line)

the entire mass of the galaxy! The planetary mass fraction must be considerably less than 10^{-3} so that the organic matter in space far outweighs the planets and, given a fractional biomass per planet of 10^{-10} , must outweigh all planetary biological material by $\gg 10^{10}$.

An application of this result to the question of retention of bacterial dust in space leads to the requirement that such bacteria must be created at an incredibly enormous rate. The star formation rate, in approximate balance with the mass loss rate of evolved stars in the milky way, is such that every bit of interstellar matter (including the dust, of course) is lost and must be regenerated on a time scale of $\sim 5 \times 10^9$ years. Thus, if bacteria are the source of the $3.4 \mu\text{m}$ absorption feature they constitute, very conservatively, 4×10^{10} biomass of all planets and this must be regenerated every 5×10^9 years; i.e. $4 \times 10^{10} M_B / 5 \times 10^9 \approx 10 M_B$ per year, where M_B = biomass of all planets. If these bacteria are not created in space we must assume that they come from life bearing planets. In order to maintain the required space density of bacteria either live or dead (!) means each planet must eject its entire biomass every month in the form of bacteria (not trees or elephants) and renew it in the same time.

This problem of regeneration is automatically taken care of for the interstellar dust grains because of the way they are created and evolved from products of stellar mass loss over this 5×10^9 year lifespan [10].

5. Cosmochemistry and its impact on planetary chemistry.

The kind of molecules created in space and their great abundance are relevant to planetary chemistry only if they provide a significant contribution by some form of accretion process. A direct mechanism for accretion of interstellar dust is that which occurs when a planet passes through a molecular cloud. In one such encounter with a cloud of density $n_H = 10^4 \text{ cm}^{-3}$ and radius 1 parsec the earth would acquire about $2 \times 10^{15} \text{ g}$ of the organic refractory molecules which is less than the current biomass by a factor of hundreds to thousands; and, what may be more important, is spread out over the entire earth during a time of 100,000 years. Dust may be also be brought to the earth after having been first aggregated into comets [12]. One such comet of 1 km radius would bring a sudden influx of about the same amount of organic material as the cloud, and at least a portion of this would be localized and could therefore provide a much stronger chemical influence than by the slow dust accretion.

One massive comet or about 10 ordinary comets bring a mass of complex organics matter to the earth approximately equal to the biomass. It is therefore conceivable that the periodic comet showers which have been suggested to account for the extinction of species in "recent" years [13] could have not only given the first impulse to prebiotic chemistry they may also have been the driving force governing the evolution of living organisms thereafter. Certainly, if the theory of comet showers is confirmed their contribution to early chemical evolution must have been important and perhaps overwhelming. Even if comet collisions are substantially less frequent, they could provide local bursts of chemical activity.

6. Concluding Remarks

We have demonstrated both quantitatively and qualitatively that natural processes of physical and chemical evolution of interstellar grains leads to the formation of complex organic molecules whose composition is similar to that observed in astronomical infrared absorption spectra. How this cosmochemical evolution relates to prebiotic evolution on the earth and other planets is being studied with laboratory experiments of grain evolution and chemical analyses of the matter created under simulated interstellar conditions.

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