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Review

Complex Organics in Space: A Changing View of the Cosmos

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Abstract: Planetary explorations have revealed that complex organics are widely present in the solar system. Astronomical infrared spectroscopic observations have discovered that complex organics are synthesized in large quantities in planetary nebulae and distributed throughout the galaxy. Signatures of organics have been found in distant galaxies, as early as 1.5 billion years after the Big Bang. A number of unsolved spectral phenomena such as diffuse interstellar bands, extended red emissions, 220 nm feature, and unidentified infrared emission bands are likely to originate from organics. In this paper, we discuss the possible chemical structures of the carriers of these unexplained phenomena, and how these organics are synthesized abiotically in the universe. We raise the possibility that the primordial solar system was enriched by complex organics synthesized and ejected by evolved stars. The implications of possible stellar organics in primordial Earth are also discussed.

Keywords: astrochemistry; interstellar molecules; interstellar dust; infrared spectroscopy; solar system; origin of life

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1. Introduction

In his book *On the heavens* (350 B.C.), Aristotle divided the cosmos into two parts: the sub-lunary and super-lunary worlds. The terrestrial (sub-lunary) is complex and changeable, and the celestial (super-lunary) world is pure and constant. The Earth is made of perishable elements, and the sun, planets, and stars are made of ether, which is everlasting. This view persisted until 1814, when Joseph Fraunhofer discovered over 500 dark lines in the solar spectrum. These lines were identified by Gustav Kirchhoff in 1861 as being due to elements Na, Ca, Mg, Fe, Cr, Ni, Ba, Cu, and Zn, thus demonstrating that the sun is made of similar substances as the Earth. An analysis of the absorption spectra of stars showed that stars are also made of common terrestrial elements. Spectroscopic analysis of the emission line spectra in the galactic nebulae shows that they are composed of atomic gases of common elements.

The prevalent view in the mid-20th century was that the universe consists of galaxies, which are collections of stars, whereas stars themselves were self-gravitating spheres of gas. The diffuse matter between stars in the interstellar medium was thought to be made of atomic gases. From this point of view, the Earth seemed much more complex in contrast with the celestial world. In addition to rocks and minerals, the Earth was also believed to contain something unique: organic matter. This organic matter was not just confined to the biosphere, but also existed in the form of oil, coal, natural gas, and kerogen, all could be traced to remnants of past life. Because all organic matter on Earth known in the mid-20th century had their origins tied to life, it was commonly believed at that time that organic matter could only be found on Earth.

With the progress of multi-wavelength astronomical observations and planetary exploration missions, this simplistic view has been gradually changing. The constitution of matter in the universe has expanded to include a solid-state mineral component (Section 2), a molecular component (Section 3), and complex organics are found in the solar system (Section 4). Several currently unexplained astronomical spectral phenomena are likely to be a manifestation of organics (Sections 5 and 6). In Section 7, we discuss evolved stars as a possible site of cosmic synthesis of organics. In Section 8, we propose that cosmic organics are the result of abiotic synthesis, and not necessarily the products of life. In Section 9, we show that complex organics are prevalent throughout the universe, beyond the confines of the Milky Way. A possible relationship between cosmic and terrestrial organics is discussed in Section 10. Possible implications of our newly discovered organics in space are discussed in Section 11.

2. Inorganic Mineral Solids in Space

The first challenge to this conventional view of the universe was the detection of solid-state particles (often called "dust" in astronomical literature) in the galaxy. Micron-size solids in the interstellar medium can scatter starlight causing the reddening of stellar colors, or obscure background stars altogether and appear in the form of dark clouds. The first proposed models for the chemical structure of interstellar solids were graphite, iron, and ice.

In the 1960s, we witnessed the development of infrared detector technology, resulting in the widespread detection of infrared continuum emissions due to dust. The first detection of dust emission was in the circumstellar envelopes of evolved stars, but dust emission is now observed in galactic nebulae and in external galaxies. In active galaxies, energy emitted from the dust component can exceed that from the optical component. From the peak of the continuum emission, we can infer a temperature of ~10^1–10^2 K for the dust component in galaxies (Figure 1).

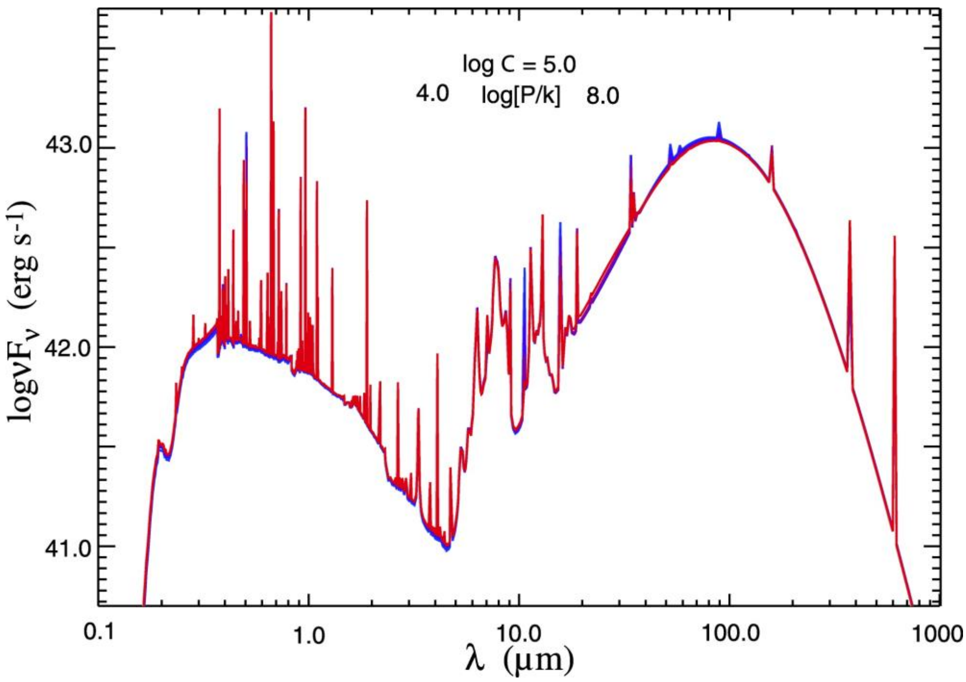

Figure 1. Typical spectral energy distribution of starburst galaxies. The dust continuum emission can be seen between 5 and 1000 μm. The optical component between 0.2 and 5 μm represents the sum of star light and photoionized gas regions of the galaxy. The narrow lines are atomic lines. The broad features between 5 and 20 μm are unidentified infrared emission bands (Section 5.5). The color curves represent models of different metallicity. Graph adapted from reference [1].

The presence of emission or absorption features in the dust spectrum of stars and nebulae led to the identification of minerals through their vibrational signatures. The detection of amorphous silicates [2] and silicon carbide [3] in the circumstellar envelopes of evolved stars shows that solid-state minerals can be produced in large quantities by stars. The all-sky spectral survey from the Infrared Astronomical Satellite (IRAS) Low Resolution

Spectrometer (LRS) has identified over 3000 stars with silicate features and 700 stars with SiC features [4] (Figure 2).

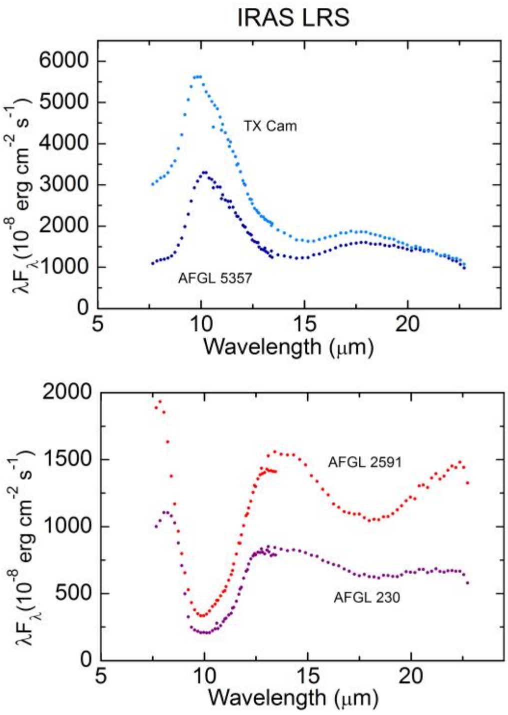

Figure 2. The 10 and 18 μm emission (**top**) and absorption (**bottom**) features observed in evolved stars by the IRAS LRS instrument. These features have been identified as being due to amorphous silicate solid particles.

The first suggestion that interstellar dust could have an organic component was made by Bertram Donn, who suggested polycyclic hydrocarbon as a possible constituent [5]. Based on the early infrared spectra of galactic nebulae, Hoyle and Wickramasinghe suggested that refractory polymers such as polysaccharides could be a component of interstellar dust [6]. Around the same time, Sagan and Khare synthesized a complex organic polymer (which they called "tholins") in the laboratory, and they believed that this compound may be commonly present in space [7]. None of these proposals were taken seriously at the time.

3. Molecules in Space

Although the first interstellar molecules of CN, CH, and CH^+ were discovered as early as 1940 through their electronic transitions in absorption against background starlight [8], the common consensus in the astronomical community in the 1960s was that there could not be large molecules in space because the density was too low for them to form and the ultraviolet background was too strong for them to survive. This all changed in the 1970s when millimeter-wave technology made the detection of molecules possible through their rotational transitions. According to the Cologne Database for Molecular Spectroscopy (cdms.astro.uni-koeln.de), about 300 molecules have been detected in interstellar clouds or in circumstellar envelopes as of 2023[1].

The largest molecule detected by astronomical spectroscopic observations is fullerene (C_{60}). Fullerene was first synthesized in the laboratory by the technique of laser irradiation of graphite [9]. Because of the molecule's stability, it has been suggested that it could be commonly present in space, and, specifically, as a possible carrier of the diffuse interstellar bands [9] (see Section 5.1). Fullerene was first detected in the interstellar medium in the planetary nebula Tc-1 [10] and reflection nebula NGC 7023 [11]. The detection of fullerene demonstrates that large molecules can indeed exist in space.

Molecules are widely observed in the plane of the galaxy. Mapping of CO emissions in the Milky Way [12] and external galaxies [13] shows that molecules are major constituents of galaxies. The total molecular mass of the Milky Way Galaxy is estimated to be $1.0 \pm 0.3 \times 10^9$ $M_\odot$ [14].

The formation mechanisms of interstellar molecules are not well understood. Suggested pathways include ion−molecule reactions and the formation of grain surfaces. The most direct observations of molecule formation are in the atmospheres of evolved stars and in the stellar winds they eject. The time scale of stellar molecular synthesis is constrained by the dynamical time scales of the stellar winds, which are of the order of thousands of years [15]. This demonstrates that molecular synthesis can occur under very low-density conditions and over very short periods of time.

At the time that multi-atom molecules were being discovered by astronomical techniques, organics with a much higher degree of complexity were being found in the solar system. This is the topic of our next section.

4. Organics in the Solar System

Independent of the astronomical developments, planetary scientists have been analyzing the chemical contents of meteorites in the laboratory. Since the first reported presence of complex hydrocarbons in the Orgueil meteorite in 1961 [16], scientists have identified almost every family of organic compounds (carboxylic acids, sulfonic and phosphonic acids, amino acids, aromatic hydrocarbons, heterocyclic compounds, aliphatic hydrocarbons, amines and amides, alcohols, aldehydes, ketones, and sugars) in the soluble component of carbonaceous meteorites [17]. Over 70% of the organics, however, are in the form of insoluble organic matter, which is a macromolecular solid made of small aromatic rings, short aliphatic chains, and hetero elements [18,19].

Although comets were commonly thought to be "dirty snowballs", the *Stardust* and *Rosetta* missions found large macromolecular compounds in the comets [20,21]. A laboratory analysis of the interplanetary dust particles collected from high-flying aircraft showed that they contained aliphatic CH_2 and CH_3, carbonyl, and carbon ring structures [22].

Asteroids often show an extreme red color and low (0.01–0.15) albedos, which are inconsistent with the spectral properties of minerals or ice, but resemble those of terrestrial coal, tar sands, asphaltite, anthraxolite, and kerite [23]. The Visible and InfraRed Mapping Spectrometer on the *Dawn* spacecraft detected the 3.4 µm aliphatic C–H band in Ceres, suggesting that there are organics similar to terrestrial hydrocarbons on the surface [24]. Sample return from the asteroid Ryugu by the *Hayabusa-2* mission also found a 3.4 µm feature, suggesting a carbonaceous surface composition of the asteroid [25,26]. The *New Horizons* imaging of Pluto suggested the presence of complex organics on the planetary surface [27]. Saturn's moon Titan was found by the *Cassini* mission to be filled with organic matter in its atmosphere, lakes, and sand dunes [28].

Thiophenic, aromatic, and aliphatic compounds have been found in drill samples from Mars' Gale crater [29]. Complex macromolecular organics were found in the ocean on Saturn's moon Enceladus [30]. These detections all point to a kerogen-like material as the precursor. Contrary to popular belief, these detections were not biomarkers, but evidence of abiotic complex organic matter on planetary bodies.

Evidence for the abiotic nature of meteoritic organics includes the diversity in structure, a general decrease in abundance with increasing C number, unusual isotope ratios, and the presence of non-terrestrial compounds. For example, nearly 100 amino acids have been found in meteorites [31], far more than the 20 amino acids used in terrestrial biochemistry.

Planetary exploration missions have left no doubt that the solar system contains a large reservoir of organic matter. What is the origin of these complex organics? The current thinking is that they were either synthesized in the early stage of the solar system's formation or were made in situ in solar system bodies. The most popular mechanism is Fischer–Tropsch reactions that convert CO and H_2 into hydrocarbons. These processes could occur on asteroids, comets, or planetary surfaces and their products could be further processed into pre-biotic compounds by aqueous alteration, thermal, and shock metamorphism [32,33].

In addition to in situ synthesis, the effects of interstellar gas-phase molecules' influence on the solar system have previously been considered [34]. With the discovery of the synthesis of complex organics by stars (Section 7), the possibility that the primordial solar system was enriched by organics ejected from stars has to be taken seriously.

5. Organics as Carriers of Unexplained Spectral Phenomena in the Interstellar Medium

Since the introduction of spectroscopic techniques for astronomy in the 19th century, there have been a series of discoveries of unexpected spectral phenomena. The resolution of these mysteries has significantly impacted our understanding of the structure of the cosmos. The discovery of a new element, helium, in the solar spectrum by Norman Lockyer in 1868 opened the possibility that there could be new chemical elements beyond those found on Earth. When a green line at 530.3 nm was found in the solar spectrum in 1869, it was first suggested to be a new element named coronium. It took 70 years before this line was identified as due to highly ionized iron (Fe^{13+}) created under high temperature conditions of the solar corona.

In 1864, William Huggins took a spectrum of the planetary nebula NGC 6543. Instead of the continuous spectrum seen in stars, he found three bright emission lines. A blue line at 486.1 nm was identified as being due to hydrogen (H), but the two green lines at 494.9 and 500.7 nm were unidentified. They were later suggested to arise from a new element "nebulium". It was not until 1926 that the two green lines were identified by Ira Bowen as being due to ionized oxygen (O^{++}) [35]. These are forbidden transitions of oxygen, which can radiate under low-density conditions because the low collisional de-excitation rates allow the metastable states to decay radiatively.

There was also a question of how H atoms are excited under interstellar conditions, as the first excited state of hydrogen is at 10.2 eV, which is too high for collisional excitation. The excitation mechanism of H was identified in 1927 as being as a result of recombination between H^+ and electrons after photoionization by ultraviolet photons emitted by nearby hot stars [36]. The resolution of these spectral mysteries and their excitation mechanism represented the first successful applications of atomic physics to astronomy.

In the 21st century, we are faced with several unexplained spectral phenomena in the interstellar medium. The carriers of these absorption and emission spectral features are probably carbon-based compounds, and the eventual solutions of these mysteries will lead to major advances in astrochemistry.

5.1. Diffuse Interstellar Bands

The diffuse interstellar bands (DIBs) were first discovered in 1922 [37]. As of 2023, over 500 bands in the visible and infrared wavelengths have been seen along the lines of sight to over 100 stars. The bands are too broad (0.06–4 nm) to be atomic lines and probably represent electronic transitions of gas-phase molecules. The strengths of the DIBs suggest that they must be formed from common elements, most likely carbon-based molecules. The DIBs are so numerous and strong that Ted Snow considers them to "represent the largest reservoir of organic material in the Galaxy" [38].

Among the hundreds of DIBs, only two (963.2 and 957.7 nm) have been positively identified as originating from ionized fullerene (${C_{60}}^+$) [39,40]. Two weaker lines of ${C_{60}}^+$ at 942.8 and 936.6 nm have also been suggested to have counterparts in DIBs [41]. Since the identification of ${C_{60}}^+$ as the carrier of two DIBs, there has been considerable interest in exploring fullerene-related species as carriers of DIBs [42]. Other suggested carriers include carbon chains [43], polycyclic aromatic hydrocarbon (PAH) molecules [44,45], and carbynes [46]. A comprehensive review of the subject can be found in reference [47] and a summary of recent work on the subject is given in International Astronomical Union Symposium 297 [48].

5.2. 220 nm Feature

Interstellar dust was generally viewed as a nuisance by astronomers as they needed to correct their photometric measurements for the effect of reddening. To better characterize the effect of selective extinction, the shapes of extinction curves are measured along the lines of sight to bright stars. Although the effects generally increase towards short wavelengths, there was an unexpected strong absorption bump at the wavelength of 220 nm (Figure 3). This feature was first discovered by the *Aeobee* rocket observations [49], and confirmed by spectrophotometry at 110 nm to 360 nm by the *Orbiting Astronomical Satellite* [50], and the *Copernicus satellite* [51].

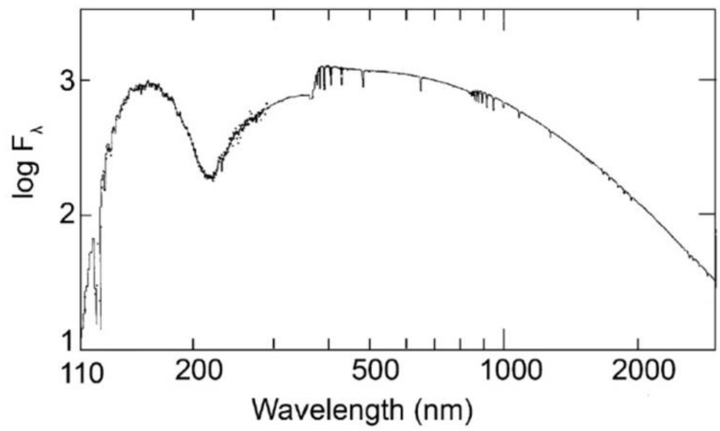

Figure 3. The 220nm absorption feature observed in the star HD 147701. The dots are observed data and the curve is a stellar atmosphere model. Figure adapted from reference [52].

The 220 nm feature shows remarkably consistent peak wavelengths and profiles along different lines of sight. Proposed possible carriers include PAH molecules [53], dehydrogenated PAHs [54], amorphous carbon [55], carbon onions [56], hydrogenated fullerenes [57], and polycrystalline graphite [58].

5.3. Extended Red Emission

Extended red emission (ERE) is a broad (Δλ ~80 nm) emission band with a peak wavelength between 650 and 800 nm. ERE was first detected in the spectrum of HD 44179 (the red rectangle) [59] and is commonly seen in reflection nebulae. ERE has also been detected in dark nebulae, cirrus clouds, planetary nebulae, HII regions, the diffuse interstellar medium, and haloes of galaxies.

The central wavelength of the emission shifts from object to object, and even between locations within the same object. A set of unidentified optical emissions bands [60] and a blue luminescence phenomenon are also possibly related to ERE [61].

Proposed carriers of ERE include hydrogenated amorphous carbon (HAC) [62], quenched carbonaceous composites (QCC) [63], C_{60} [64], and nanodiamonds [65]. Non-carbon-based origins of ERE include silicon nanoparticles [66] and Raman scattering by atomic hydrogen [67].

5.4. Bands of 21 and 30 µm

The 30 µm band was first detected in evolved stars IRC+10216 and AFGL 3068, and planetary nebulae IC 418 and NGC 6572 [68]. It has been detected in over 200 carbon-rich evolved stars [69,70] (Figure 4). The fact that a significant fraction (~20%) of the total luminosity of the object is emitted in this feature suggests that the carrier must be composed of abundant elements [71].

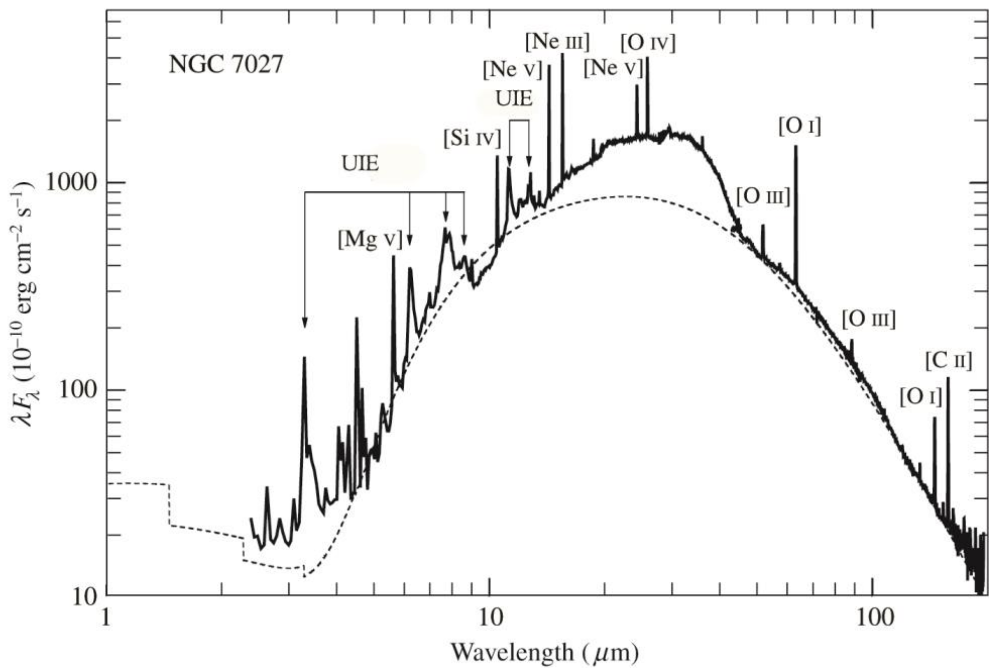

Figure 4. ISO SWS/LWS spectrum of planetary nebula NGC 7027. Some of the stronger atomic lines and UIE bands are marked. The dashed line is a model fit composed of a sum of dust continuum emissions, and free-bound and free-free gas emissions. The strong 30 μm band can be seen above the dust continuum.

The 21 μm band was first detected in the all-sky spectral survey of the IRAS Low Resolution Spectrometer (LRS) in four protoplanetary nebulae [72]. Subsequent Infrared Space Observatory (ISO) high-resolution observations show that the band as uniform asymmetric shape and a consistent peak wavelength of 20.1 μm [73]. There is no sign of a substructure, suggesting the carrier is in a solid state. About 30 21-μm sources have been found, and all are in objects in transition between the asymptotic giant branch and planetary nebulae phases of evolution. All of the 21 μm sources also show the 30 μm feature, suggesting that the two features are related.

Possible candidates that have been proposed include large PAH clusters, HAC grains [74], hydrogenated fullerenes [75], nanodiamonds [76], TiC nanoclusters [77], O-substituted 5-member carbon rings [78], nano-SiC grains with carbon impurities, and cold SiC grains with amorphous SiO_2 mantles [79,80]. A recent review of the 21 and 30 μm bands is given in reference [81].

5.5. Unidentified Infrared Emission Bands

The unidentified infrared emission (UIE) bands consist of a family of strong emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm; minor emission features at 12.1, 12.4, 12.7, 13.3, 15.8, 16.4, 17.4, 17.8, and 18.9 μm; and broad emission plateaus features at 6–9, 10–15, and 15–20 μm. They were first detected in planetary nebulae, and have since been widely observed in reflection nebulae, HII regions, novae, and external galaxies (Figure 5). There have also been reports of UIE bands detected in comets [82].

The organic nature of their carrier was first suggested in the 1970s, where the 3.3 μm feature was identified with the C–H stretching mode of aromatic carbon [83] and the UIE bands were suggested as arising from vibrational stretching and bending motions of C–H bonds in organic compounds [84]. However, this interpretation was not taken seriously until the widespread detection of rotational transitions of gas-phase organic molecules by millimeter-wave techniques in the 1980s. As PAH molecules are the simplest aromatic compounds, they have become the most popular hypothesis for the carrier of the UIE bands [85,86]. In the PAH hypothesis, the molecules are excited by ultraviolet photons [87] and the UIE bands are the radiative decay transitions after excitation.

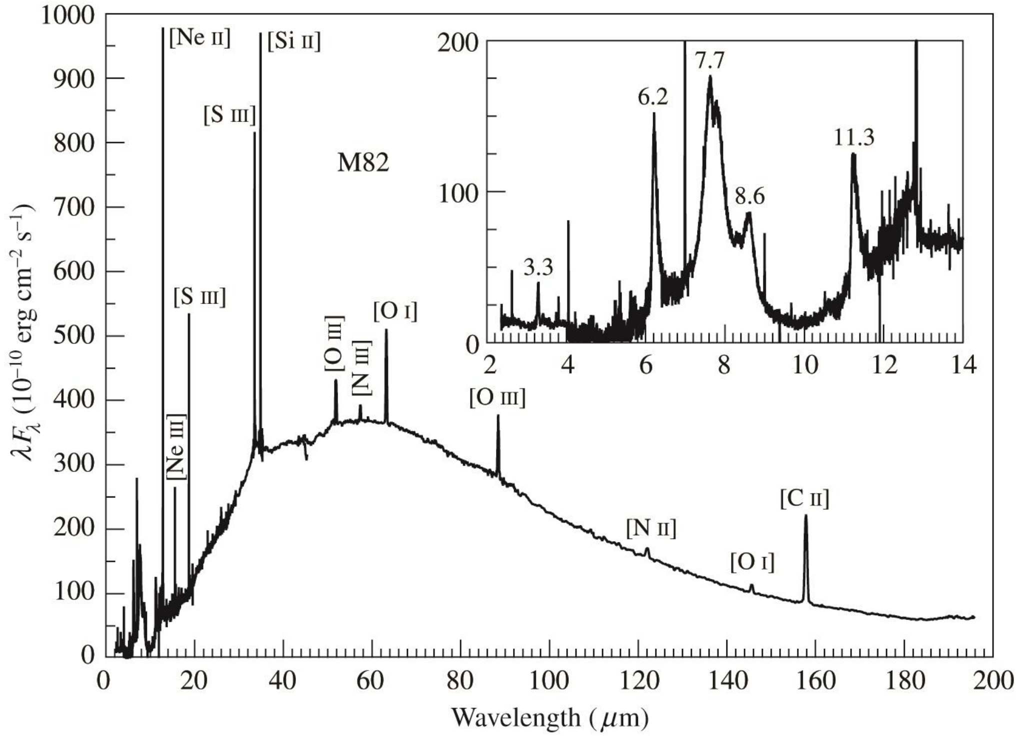

Figure 5. Infrared Space Observatory (ISO) SWS/LWS spectrum of the starburst galaxy M82. Some of the stronger atomic lines are labeled, with [] denoting forbidden transitions. The expanded view between 2 and 14 µm in the insert shows the presence of UIE bands at 3.3, 6.2, 7.7, 8.6, and 11.3 µm on top of the dust continuum.

Although the carrier of the UIE bands is probably of an organic nature, the exact chemical structure of the carrier is still under discussion. A variety of carbonaceous materials have been proposed as possible carriers of UIE bands. These include small carbonaceous molecules [88], HAC [89], soot [90] and carbon nanoparticles [91], QCC [92], coal [93], kerogen [94], petroleum fractions [95], mixed aromatic and aliphatic organic nanoparticles (MAON) [96,97], and fullerene metal complexes [98]. A recent review of our understanding of UIE bands is given in reference [99].

Although the exact carriers of DIB, 220 nm, ERE, the 21 and 30 features, and the UIE bands are not yet identified, these phenomena are most likely a manifestation of organics in space.

6. Aliphatic Organics in the Diffuse Interstellar Medium

Interstellar organics can also be detected through absorption spectroscopy along the line of sight to strong background infrared sources. The 3.4 µm C–H aliphatic stretching band was detected towards the Galactic Center [100]. The components of this band at 3.40, 3.46, 3.52, and 3.56 µm are detected in subsequent observations [101–103]. Since column densities are easily derived from the strengths of the absorption bands, it is estimated at least 10–20% of the carbon in the Galactic Plane is in the form of aliphatic carbon [104]. This 3.4 µm band can be seen in absorption in ultraluminous infrared galaxies [105], and over an extended area in NGC 1068 [106].

The 3.4 µm band has also been observed in emissions [107], and mapping of the galaxy M82 by the *Akari* satellite shows that the feature strength increases from the disk to the halo of the galaxy [108].

7. Circumstellar Synthesis of Mixed Aromatic/Aliphatic Nanoparticles

After the red giant branch, a sun-like star will evolve into luminosities several thousand times that of the sun, to a stage called the asymptotic giant branch (AGB). At the AGB stage, stars develop strong stellar winds, in which the progressive synthesis of molecules (from CO, C_2, C_3, CN, to HCN, HC_3N, to C_2H_2 and C_6H_6) takes place. Benzene can group together to form islands of aromatic rings, and aliphatic chains can attach to such rings, forming 3D amorphous hydrocarbon structures [109]. In the post-AGB evolution leading to the formation of planetary nebulae [110], we witness the emergence of the 3.3 μm UIE feature, presenting evidence for the synthesis of aromatic materials. The detection of the 3.4 μm aliphatic C–H stretch in the post-AGB (and pre-planetary nebulae) phase [111,112] suggests that there is an aliphatic component in addition to the aromatic component. The presence of the 3.4 μm feature in comets [113], Titan atmosphere [114], and asteroids [24] suggests that stellar organics may share some common chemical properties with solar system organics.

The similarities seen between the spectra of laboratory-synthesized organics [115,116] to the UIE bands led to the proposal that the carrier of the UIE bands could be MAONs [96,97]. MAONs consist of aromatic islands linked by aliphatic chains of random lengths and orientations. As natural synthesis proceeds in the circumstellar envelope, heteroatoms such as O, N, and S could be incorporated into the hydrocarbon framework. A typical structure of a MAON molecule is shown in Figure 6.

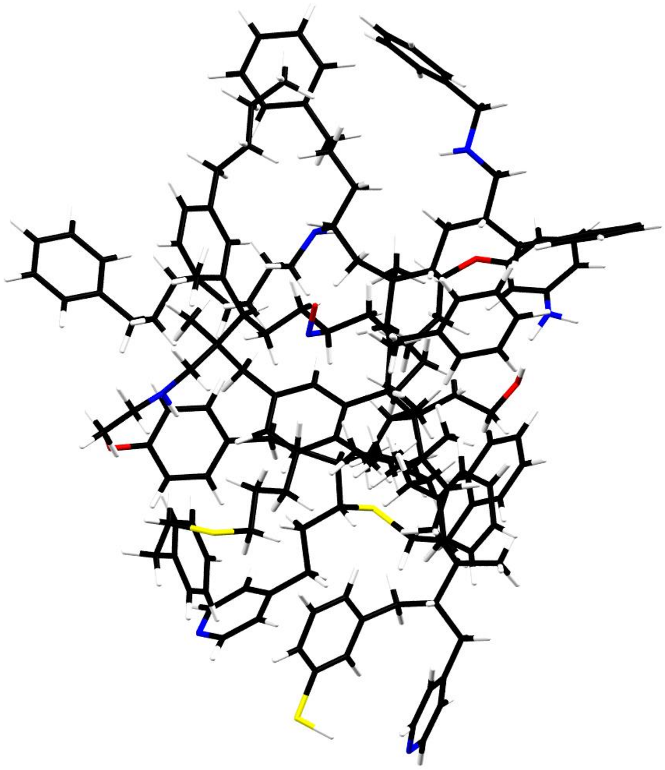

Figure 6. An example of a MAON molecule with 169 C atoms (in black) and 225 H atoms (in white), 4 O atoms (in red), 7 N atoms (in blue), and 3 S atoms (in yellow). It is characterized by a highly disorganized arrangement of small units of aromatic rings linked by aliphatic chains. A typical MAON particle may consist of multiple structures such as this one. Graph adapted from reference [99].

While the infrared spectra of simple organics can be identified through their vibrational modes, the spectral properties of complex organics are not known as strong spectral features often the result of coupled vibrational transitions. With modern quantum chemistry calculations, we have begun to explore the spectral behavior of mixed aromatic and aliphatic structures [117,118].

8. Abiotic Synthesis of Complex Organics

What is the origin of complex organics in the universe? Unlike their terrestrial counterparts, they are not the products of life. Current evidence supports the idea that complex organics are built up from simple molecules through abiotic processes. The decreasing abundance with the increasing carbon number within the same class of organics in meteorites suggests an abiotic origin and not a breakdown from large species.

Possible pathways of organic synthesis can be simulated in the laboratory. Amorphous organic solids are often the natural results of combustion. When a mixture of hydrocarbon gases is subjected to energy injection and the evaporated condensates are collected in cooled substrates, the resulting substances are often amorphous carbonaceous compounds. When a mix of nitrogen, ammonia, and methane is bombarded by ultraviolet light and electric discharge, the result is a brownish polymer called "tholins" [7]. Other techniques include microwave irradiation of the plasma of methane [92,119], hydrocarbon flame or arc-discharge in a neutral of hydrogenated atmosphere [120,121], laser ablation of graphite in a hydrogen atmosphere [122–124], infrared laser pyrolysis of gas phase hydrocarbon molecules [116], photolysis of methane at low temperatures [125], and flame combustion (C_2H_2, C_2H_4, and C_3H_6 mixed with O_2) forming soot [90,126].

The most direct evidence for the abiotic synthesis of complex organics is found in circumstellar envelopes of evolved stars, where organic molecules and solids are synthesized over thousand-year time scales [15]. A recent experiment designed to simulate molecular and solid synthesis in circumstellar low-temperature and low-density conditions yielded the production of simple molecules such as acetylene and ethylene, as well as carbonaceous solids such as amorphous carbon nanograins and aliphatic carbon clusters [127]. The results of these experiments suggest that complex carbonaceous matter can be formed naturally in the circumstellar environment.

Novae provide a dramatic example of circumstellar synthesis of organics. Dust condenses in the novae ejecta within weeks of outbursts and UIE bands emerge soon after [128]. This shows that organic synthesis can occur under low density conditions over very short time intervals. A comparison between the novae spectra and laboratory synthesized materials suggests that the carrier is a nitrogen-included amorphous hydrocarbon [129].

9. Organics beyond the Milky Way

Spectral phenomena attributed to organic compounds are not limited to the galaxy but are also observed in external galaxies. DIBs have been detected in the Magellanic Clouds, starburst galaxies, and nearby spiral galaxies [130]. The 442.8 nm DIB and the 220 nm feature are detected in a BL Lac object of redshift 0.52 [131]. The 220 nm feature has been seen in distant galaxies with redshift >2 [132]. A recent James Webb Space Telescope (JWST) observation found the 220 nm feature in a galaxy with $z = 6.71$ [133]. The 21 μm feature was detected in proto-planetary nebulae in the Magellanic Clouds [134]. A survey of 150 galaxies by the *AKARI* satellite found that $\sim$0.1% of the total energy of the parent galaxies is emitted through the 3.3 μm UIE band [107]. In some active galaxies, up to 20% of the total luminosity of the galaxy is emitted in the UIE bands [135]. The 3.3 μm UIE band has been detected by JWST in a galaxy of redshift 4.2, or less than 1.5 billion years after the big bang [136].

The extensive presence of the 3.4 μm feature in galaxies implies that organics are not restricted to the stars and interstellar clouds, but are widely present in the diffuse interstellar medium [105–108]. A large fraction of the cosmic abundance of carbon is likely in the form of aliphatic organics.

It is clear that organics are widely present in the universe and were synthesized in large quantities soon after the nucleosynthesis of the element carbon. The early universe, instead of being simple, was already filled with complex organics.

10. Relationship between Terrestrial and Cosmic Organics

Almost all of the known terrestrial organics (in the biosphere, in the form of coal, oil, natural gas, and kerogen) are of biological origin [137,138]. Evidence for the biological origin of oil is based on the presence of biomarkers such as biological chlorophyll and porphyrin products in petroleum. However, abiotic hydrocarbons exist in hydrothermal vents [139,140], and this has led to proposals of various mechanisms of continuing synthesis of oil in the Earth's mantle [141,142]. We should note that it is possible to distinguish between biotic and abiotic organics, as biological organics have specific structures because their synthesis is driven by enzymes.

As complex organics are ubiquitously present in the universe and in the solar system, could there be primordial abiotic organics on Earth? The Earth was created by the accretion of planetesimals, and such bodies could have inherited organics from the primordial solar system [143]. At present, the carbon inventory below the Earth's crust (in the mantle and core) is not well known [144]. The possibility that there is a large reserve of hydrocarbons deep inside the Earth could have major political and economic implications.

11. Conclusions and Future Prospects

In the 19th century, our view of the constitution of celestial objects changed from that of ether to terrestrial elements. In the early 20th century, it was believed that stars, interstellar space, and galaxies were primarily comprised of atoms. Advances in infrared and millimeter-wave astronomy have since shown us that the universe is much more complex than what was previously thought. In addition to atomic gases, it also contains molecules, minerals, and organics in large quantities. Complex organics are no longer confined to the domain of the Earth, and have been observed in solar system objects, stellar ejecta, interstellar clouds, and external galaxies. The universe is now known to be filled with organics [145]; such a view would have been considered incredible 50 years ago.

The ability of celestial objects to spontaneously synthesize complex organics in large quantities also raises questions about the origin of life on Earth [146]. Many basic ingredients for life (amino acids [147] and nucleobases [148–150]) have been found in meteorites. When exposed to UV and charged particle irradiation, remnants of stellar organics embedded in icy planets, transneptunian objects, and comets could lead to the formation of a variety of pre-biotic molecules, including amino acids and nucleobases [151]. The early Earth was subjected to large-scale external bombardments, and externally delivered organics may have played a role in the development of life on Earth [152]. Under suitable pressure and temperature conditions, prebiotic materials could be released from primordial stellar macromolecular organics [153]. If this is the case, life must be common in the universe where organics are abundant.

Although there is overwhelming evidence that organics are prevalent throughout the universe, we are still uncertain about the exact chemical structure of the organics that are responsible for several unexplained astronomical spectral phenomena. While these organics are probably synthesized abiotically, the exact mechanisms and chemical pathways are unknown. As the temperature, density, and radiative environments of the interstellar medium are very different from our terrestrial environment, the resolution of these mysteries will depend on progress in our understanding of the chemistry operating under unusual conditions.

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Notes

[1] For details on the radiation mechanisms of atoms, molecules, and solids, see the following publication: Kwok, S. Physics and Chemistry of the Interstellar Medium; University Science Books: 2006.

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