Analytical Techniques for Identification and Characterization of Extraterrestrial Organic Matter

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Nanoscale distribution of organic matter in a Ryugu sample. CREDIT: MEHMET YESILTAS.

Advances in analytical techniques are essential for understanding the nature, formation, and evolutionary history of extraterrestrial organic matter. In this chapter, we briefly review analytical techniques used to detect and characterize organic matter in extraterrestrial materials. **Mass spectrometry is often coupled with gas chromatography or liquid chromatography for elemental and isotopic analysis, and for identifying specific organic compounds. Spectroscopy involves interaction of molecules with electromagnetic radiation at various wavelengths. Almost every wavelength—from X-rays to radio waves—can be used for spectroscopic measurements. The most major microscopic and nanoscopic techniques are scanning and/or transmission electron microscopy. Spectroscopy and mass spectrometry can also be coupled with microscopic analysis for detailed compositional investigations.**

KEYWORDS: meteorites; extraterrestrial organic matter; spectroscopy; mass spectrometry

INTRODUCTION

Organic matter in meteorites has been analyzed since the 1800s, while modern techniques have been applied since the 1960s' Apollo era. The Murchison meteorite fell in 1969 and extraterrestrial amino acids were detected in a well-equipped laboratory designed for analyses of Apollo samples (Kvenvolden et al. 1970). Since then, the Murchison meteorite has been the meteorite most intensively analyzed for organic matter and has witnessed substantial developments of analytical techniques over decades as a kind of "standard" sample. Briefly, organic compounds in chondritic meteorites are analyzed by solvent extractions and acid demineralization. The former are called soluble organic matter (SOM) and the latter are called insoluble organic matter (IOM). IOM is ~2 wt.% of a typical unheated carbonaceous chondrite, but SOM ranges from ppb to ppm levels (depending on the compounds and meteorite classes). The relationship between SOM and IOM is currently unclear. The whole analytical process includes hot water extraction (for amino acids, amines, carboxyl acids etc.), methanol and dichloromethane extraction (for less-polar and non-polar compounds), followed by HCl and HF or CsF treatments to dissolve inorganic materials to finally obtain the acid residual IOM. These procedures can be varied depending on the purpose. More recently, microscopic techniques have often been used for direct analyses of organic matter without such extractions. Direct two-dimensional analyses (there are even three-dimensional techniques) allow researchers to obtain the spatial contexts that are lost by the extraction procedures. Such direct analyses are suitable for small samples such as interplanetary dust particles (IDPs), micrometeorites, and mission-returned samples. Analytical instruments developed for in-situ or remote investigations during planetary exploration missions have also provided opportunities for direct analyses of organic matter on Mars, moons, and small bodies in the Solar System.

MASS SPECTROMETRY

Mass spectrometry (MS) is widely used for analyses of extraterrestrial organic matter in various ways. This technique has been used for over 50 years and has improved significantly in accuracy and precision over time. There are large variations in ionization and mass separation techniques that allow us to obtain different kinds of invaluable information. The most common ionization techniques are electron ionization (EI) and electrospray ionization (ESI). The former is a hard ionization that breaks a molecule into fragment ions that give a specific fragmentation pattern in the mass spectra, providing information about its molecular structure. The latter is a soft ionization that results in very little fragmentation and, thus, is typically used to determine molecular weights. The most common mass spectrometers are the magnetic sector mass spectrometer, time-of-flight mass spectrometer (TOF-MS), and quadrupole mass spectrometer (Q-MS). Chromatographic separations such as gas chromatography (GC) and liquid chromatography (LC) are often used before introducing samples to a mass spectrometer for better identification of the compounds.

Elemental and Isotopic Analysis

Elemental and isotopic analyses that provide the basic characteristics of IOM are performed using MS analysis combined with sample processing (pyrolysis or combustion) and GC separation (Alexander et al. 2007). Analyses of N and C are typically conducted by heating samples in a high-temperature (~1000 °C) oven and combusting with O_2 and a catalyst. The resulting CO_2 and N_2 gases are then

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separated by GC and introduced to a mass spectrometer to obtain ^{12}C, ^{13}C, ^{14}N, and ^{15}N abundances by comparing them to standard gases. H and O in samples are converted to H_2 and CO by high-temperature pyrolysis (~1500 °C), then separated by GC before being introduced to a mass spectrometer to obtain ^{1}H, ^{2}H (D), ^{16}O, ^{17}O, and ^{18}O abundances. The H/C, N/C, and O/C atomic ratios (i.e., Murchison IOM has a composition of $C_{100}H_{58.8}N_{3.27}O_{18.3}S_{1.8}$, with the abundance of S estimated using H, C, N, and ash weight fractions) and D, ^{15}N, and ^{13}C values are often used to infer the origin and degree of alteration of IOM from chondrites (Alexander et al. 2007).

GC/MS and LC/MS

For targeted analyses of compounds including amino acids, carboxylic acids, amines etc., GC/MS and LC/MS are often used after solvent extractions. The main reason for combining GC or LC with MS is the identification and quantification of the targeted compounds by comparison with their standards. Complicated laboratory workups are usually required before GC/MS or LC/MS analysis. Amino acids (and their precursors) are extracted from a powdered meteorite sample by hot water, hydrolyzed by HCl, desalted by an ion exchange resin to avoid damage to the GC or LC columns, and then derivatized (chemical modification of targeted compounds into suitable structures for analysis) before introducing samples to GC/MS or LC/MS (Simkus et al. 2019). For both GC/MS and LC/MS, the derivatization is mandatory in many cases. For GC/MS, various derivatization methods allow separation of enantiomers (D or L amino acids) with the use of a chiral column, e.g., trifluoroacetic acid (TFA) or trifluoroacetic anhydride (TFAA) derivatization is typically used. For LC/MS, *o*-phthalaldehyde and *N*-acetyl-*L*-cysteine (OPA/NAC) derivatization is often used, which allows chiral separation without the use of a chiral column. OPA/NAC derivatization is also suitable for UV fluorescence detection combined with MS that allows highly sensitive quantitative analysis with precise molecular identifications. Moreover, gas chromatography coupled with mass spectrometry and isotope ratio mass spectrometry (GC-MS/IRMS) allows compound-specific stable isotopic measurements.

High-Resolution MS (FTICR and Orbitrap)

For non-targeted analyses with mass spectrometry, a high mass resolution (the ability to separate ions with very similar, but different masses) is required. Accurate masses provide specific elemental compositions, e.g., the integral mass of N_2 and CO is 28 u, but their precise monoisotopic masses are 28.006148 u and 27.994915 u, respectively, which can be separated with a mass resolution of $R = 28/(28.006148 − 27.994915) ≈ 2500$. ESI Fourier transform ion cyclotron resonance/mass spectrometry (FTICR/MS) has the highest mass resolution R of 900,000 (see Fig. 1), allowing the detection of tens of thousands of different molecular compositions without GC or LC separations from solvent extracted organic compounds in the Murchison meteorite (Schmitt-Kopplin et al. 2010). This method includes both ultra-high-resolution MS using FTICR, and also ESI, which enables direct ionization of each compound without fragmentation. Because of the complexity of the detected compounds, the H/C, O/C, and N/C ratios and mass defect analysis are useful for the purpose of constraining the molecular diversity and genetic relationships among the detected compounds. Orbitrap MS (a type of ion trap MS) also allows high-mass-resolution analyses and can be combined with LC or GC for both targeted and non-targeted analyses.

Imaging Mass Spectrometry

Mass spectrometry is often used for imaging analyses. The most common method for organic analysis using MS imaging is probably nanoscale secondary ion mass spectrometry (NanoSIMS), which is used for stable isotopic measurements with a spatial resolution of a few tens of nanometers (see Fig. 1). Local concentrations of D and ^{15}N, so called "isotopic hot-spots", have been found in organic matter in meteorites, IDPs, micrometeorites, cometary, and asteroidal samples (e.g., Messenger 2000). Microprobe two-step laser mass spectrometry (μL^2MS) is used for the in-situ analysis of polycyclic aromatic hydrocarbons (PAHs) and related compounds with 40 × 40 µm spatial resolution by vaporizing and ionizing with two independent laser sources (e.g., Clemett and Zare 1997). Desorption electrospray ionization (DESI) combined with high-resolution MS allows soluble organic compound analysis with a typical surface spatial resolution of 50–100 µm using a spray of electrically charged solvent, such as methanol, to visualize the heterogeneous distributions of soluble organic compounds in meteorites (e.g., Naraoka and Hashiguchi 2018).

Mass Spectrometry for Space Exploration

Mass spectrometry is also used for in-situ analyses by space exploration missions. The *Cassini* orbiter at Saturn and its moons had two mass spectrometers onboard—the Cosmic Dust Analyzer (CDA) and the Ion and Neutral Mass Spectrometer (INMS). The INMS detected H_2O, CO_2, CO/N_2 (*m/z* 28, cannot be separated), CH_4, C_2H_2 (acetylene), C_3H_8 (propane), and NH_3 in the Enceladus plume (Waite et al. 2006). Complex macromolecular organic material with molecular masses above 200 atomic mass units was also detected in ice grains from the Enceladus plume (Postberg et al. 2018). The *Rosetta* spacecraft had four mass spectrometers, two in the orbiter—the
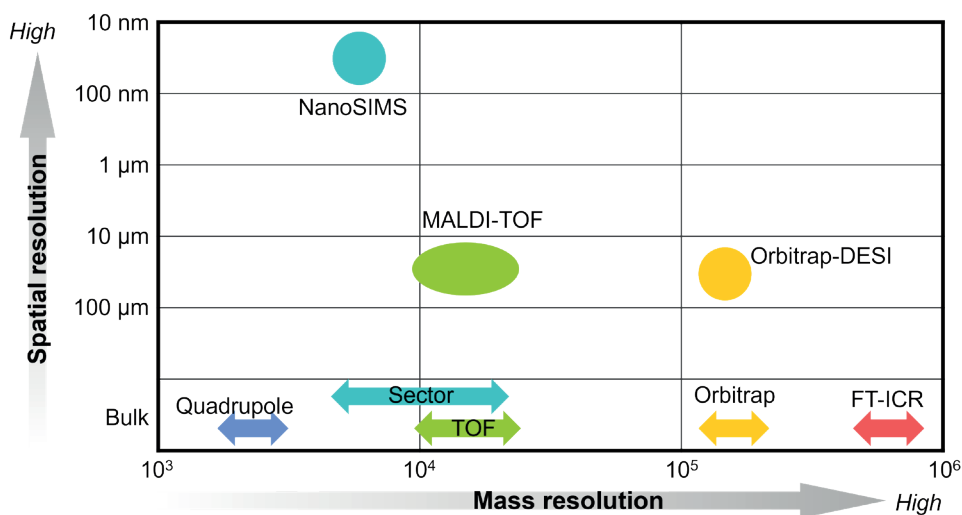

Figure 1 Summary of mass resolution (the ability to separate ions with different masses) and spatial resolution of various mass spectrometry techniques.
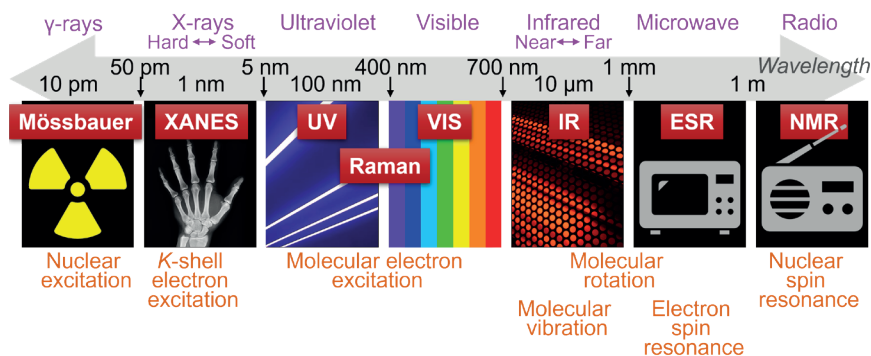
FIGURE 2 Summary of electromagnetic waves used for spectroscopy.

orbiter spectrometer for ion and neutral species analysis (ROSINA) and the cometary secondary ion mass analyzer (COSIMA)—and two with GC in the *Philae* lander, COSAC (the COmetary SAmpling and Composition experiment) and Ptolemy. The details of the instruments and scientific results can be found in the review by Vazquez et al. (2021). Many new species were detected including the simplest amino acid, glycine (Altwegg et al. 2016), as well as macromolecular compounds (Bardyn et al. 2017). The Sample Analysis at Mars (SAM) instrument suite onboard the Mars *Curiosity* mission includes a Q-MS, tunable laser spectrometer (TLS), and GC. Organic matter in mudstones at Gale crater was detected in situ using these instruments by high-temperature evolved gas analysis and GC/MS (Eigenbrode et al. 2018).

SPECTROSCOPY

Spectroscopy is the interaction between electromagnetic radiation and matter as a function of the wavelength of the radiation. Detailed chemical, molecular, structural, and compositional information can be obtained from extraterrestrial samples depending on the spectroscopic technique applied. There are many kinds of spectroscopic techniques (FIG. 2) for studying complex extraterrestrial organic matter and better constraining its formation and evolution in space, although we review only a few of them here.

ESR Spectroscopy

Electron spin resonance (ESR) spectroscopy is based on the interaction between an external magnetic field and the spins of unpaired electrons (radicals) in molecules. It is, in many ways, similar to nuclear magnetic resonance (NMR) spectroscopy, as discussed in the following section. The theoretical difference mainly lies in the excited spin under an externally applied magnetic field. In NMR spectroscopy, nuclei spins are excited, whereas in ESR spectroscopy, the electron spins are excited. ESR spectroscopy measures the energy difference of spin states that are aligned either parallel or antiparallel in an external magnetic field. Many species contain one or more unpaired electrons (including free radicals, ions, and molecules having an odd number of electrons); thus, information on their molecular structures and dynamics, such as electronic distribution, molecular orientations, and nature of the molecular environment, can be obtained via ESR spectroscopy.

One of the first ESR studies on extraterrestrial organic matter was conducted by Schulz and Elofson (1965) who reported the presence of more than 2×10^{19} free radicals/gram in the IOM of the Orgueil meteorite. The IOM isolated from Murchison and Orgueil contains highly localized radical-rich ($3-4 \times 10^{19}$ spins/g, corresponding to 5%–20% of the IOM) organic molecules, as determined via ESR spectroscopy (Binet et al. 2002). Radicals in the IOM of meteorites are likely bonded to other radical moieties. The investigation by Alexander et al. (2022) on the IOM of a suite of carbonaceous chondrites provides the largest available ESR dataset to date.

NMR Spectroscopy

NMR spectroscopy measures the interaction of an oscillating electromagnetic field with the nuclei (with an integral or a fractional spin) of atoms that are in a static magnetic field, providing a spectrum that is characteristic to that specific nucleus of the atom. By probing variations in the resonant frequency caused by the position of the atom within a molecule, precise structural and proximity information can be obtained down to each atom and bond. Atoms with a non-zero nuclear spin, e.g., ^1H, ^{13}C, and ^{15}N, can be detected using NMR. While requiring larger amounts (tens of mg of IOM) of sample for experiments compared with other spectroscopic methods, NMR enables better quantitative analysis. In the case of samples with abundant Fe-bearing molecules, measurements need to be made on the extracted organic matter rather than the whole samples. Solid-state ^{13}C-NMR spectroscopic investigations by Cody et al. (2002) showed that ~60% of the total carbon present in the Murchison meteorite is aromatic, which is linked with oxygen-containing organic functional groups and highly branched aliphatic moieties. Solid-state ^{13}C-NMR spectra quantitatively describe changes in the molecular structures by alteration, as seen in the IOM from several different lithologies in the Tagish Lake meteorites (Alexander et al. 2014; FIG. 3A). Most solid-state NMR studies on meteorites focus on the macromolecular IOM fraction, although a new generation of spectrometers with better detectors has made the detection of soluble organics possible using solution-state NMR. Thousands of individual NMR resonances were detected in the solution-state ^1H-NMR spectra of soluble organics extracted from Murchison, which contains a wide range of aliphatic and aromatic chemical environments with substantial variability in the aliphatic branching (Schmitt-Kopplin et al. 2010).

Infrared Spectroscopy

Infrared (IR) spectroscopy is based on the absorption, transmission, reflection, or emission of light in the infrared region of the spectrum. It can be used to detect and characterize numerous chemical functional groups, including organic compounds, through their characteristic molecular vibrations. Generally, molecular vibrations that cause a change in the dipole moment are allowed in IR and forbidden in Raman (i.e., C–O, C=O, and C–N are weak Raman scatterers but strong IR absorbers), or vice versa. Thus, IR and Raman spectroscopies are complementary to each other. The IR region of the electromagnetic spectrum is divided into multiple parts; however, the mid-IR (~4000–400 cm^{-1}; 2.5–25 μm) is the most frequently chosen region for studying extraterrestrial organic matter because spectral intensities of organic matter in this range are often better resolved than in the near-IR (~14,000–4000 cm^{-1}; 0.7–2.5 μm) and far-IR (~400–10 cm^{-1}; 25–1000 μm) regions. Space telescopes such as the Kuiper Airborne Observatory, Spitzer Space Telescope, the Stratospheric Observatory for IR Astronomy, the Infrared Space Observatory, and the James Webb Space Telescope have detected signatures of many organic molecules in different astronomical regions. Ground-based IR observations and laboratory spectroscopic analysis of meteorites, IDPs, cometary dust, and

asteroid particles provide additional insights into many aspects of extraterrestrial organic matter and expand our understanding of carbon in the cosmos. Indeed, IR spectra of galactic center sources and meteoritic organic matter are remarkably similar near the 3.4 µm (~2950 cm⁻¹) region, where aliphatic C–H stretching vibrations occur (Ehrenfreund and Charnley 2000). A unique perspective on the complexity and heterogeneity of organic matter, and how it evolves through post-accretionary hydrothermal processes, can be obtained from the IR spectroscopic analysis of IOM in chondrites. Similar to NMR, molecular evolution in different lithologies of the Tagish Lake meteorite was detected by IR spectroscopy using functional group chemistry (Alexander et al. 2014; FIG. 3B). Studies on organic–mineral relations significantly improve our understanding of the evolution of organic matter, which is still not fully known. IR spectroscopy can also unravel organic–mineral relations in situ in extraterrestrial samples by interrogating organic matter within the local mineralogy of a sample. IR efforts for such a task include 2D IR imaging spectroscopy at micro- and nano-scales, and micro-scale 3D IR tomography, which have the capability to unravel spatially resolved and statistically significant organic–mineral relations with the goal of understanding the formation pathways of organics.

attracted much attention because Raman spectroscopy is highly sensitive to even small amounts of structural ordering of carbon due to thermal annealing. This is a significant advantage because Raman spectra of extraterrestrial organic matter can be used as a geothermometer to reveal the peak metamorphic temperatures of chondritic meteorites and shed light on the thermal history of parent asteroids (e.g., Quirico et al. 2003). Busemann et al. (2007) compared the Raman spectral parameters of the carbon bands near 1350 cm⁻¹ (D-band) and 1580 cm⁻¹ (G-band) and observed that some primitive meteorites exhibit structural ordering in their polyaromatic organic matter that is similar to those seen in IDPs and comet Wild 2 particles, supporting the idea that the meteorite parent bodies may have accreted a similar precursor organic material as the parent bodies of the IDPs. This idea is supported by Raman observations of highly disordered carbon in IDPs and their similarity to meteoritic carbon (Starkey et al. 2013). Raman spectroscopy is also well suited for planetary exploration. In pursuit of the search for life (or extinct life) on Mars, Raman instruments have been developed for the NASA *Perseverance* rover mission, which has detected organics at Jezero crater (Scheller et al. 2022), and the upcoming ESA *ExoMars* rover mission, the primary goal of which is to detect organic compounds on the Martian surface.
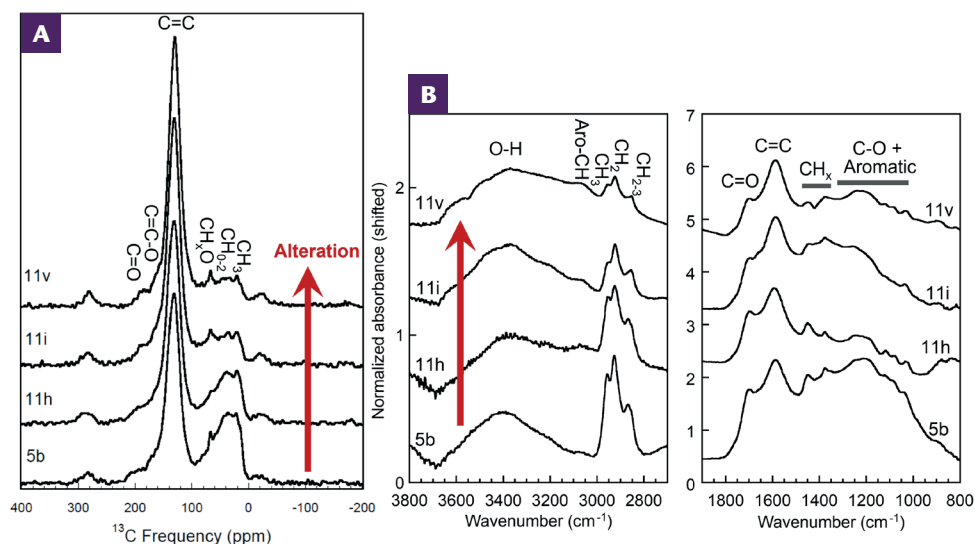
MICROSCOPY

Microscopes and microscopic analysis techniques have significantly developed over the last couple of decades and now provide high-resolution access to molecular components, down to the atomic level. There are many different light, electron, and X-ray microscopy techniques. We review some of them below in the context of organic materials in extraterrestrial samples.

Electron Microscopy

Electron microscopes utilize a beam of accelerated electrons to illuminate the sample of interest. Compared with light microscopes, electron microscopes have much higher spatial resolution (nano to picometer) and resolving power, hence allowing the investigation of

much smaller molecular, or even atomic components. As a result of the interactions between the electrons and the sample, different signals (i.e., secondary electrons (SE) and backscattered electrons (BSE)) are obtained. Characteristic X-rays can also be used to map the elemental composition of the sample surface (energy dispersive X-ray spectroscopy (EDS)). Thus, detailed compositional and morphological information can be easily determined. Scanning electron microscopy (SEM) is one of the most popular microscopic techniques, although only surface features are accessible via SEM. A focused, low-power electron beam (e.g., ~5–20 kV) raster scans an area of interest on the surface of a sample to produce SE, BSE, or element distribution images. Transmission electron microscopy (TEM), on the other hand, is based on the transmission of a beam of high-energy electrons (e.g., 200 kV) through sufficiently thin samples to reveal the structure and composition at the atomic level. Like many other fields, investigations of organic matter in meteorites, micrometeorites, IDPs, and asteroidal and cometary particles significantly benefit from SEM and TEM analyses, especially when coupled
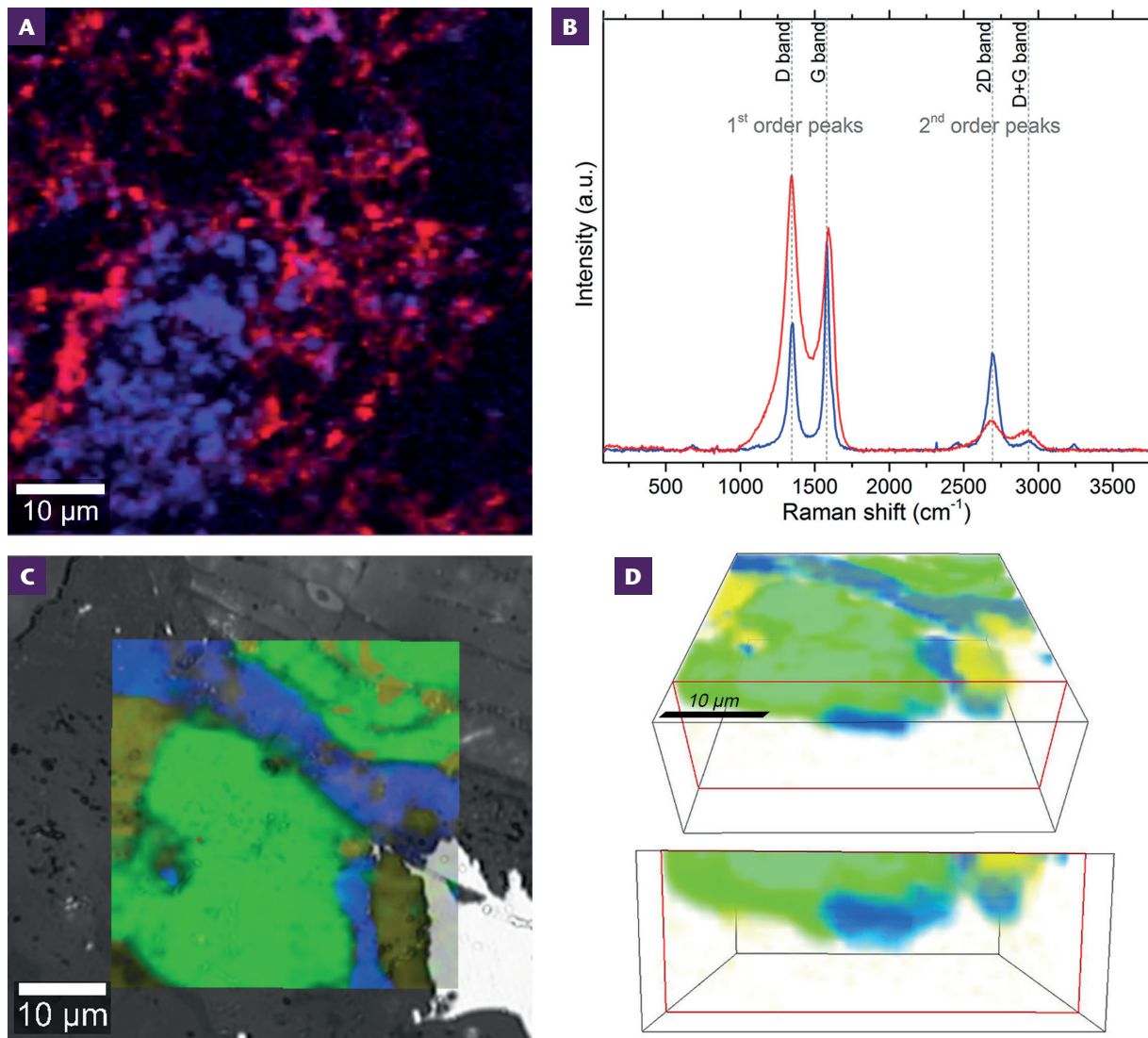
FIGURE 3 Solid-state ¹³C-NMR spectra (**A**) and Fourier transform infrared (FTIR) spectra (**B**) of Tagish Lake IOM isolated from lithologies 5b, 11h, 11i, and 11v, showing the evolution of molecular structures with increasing alteration. MODIFIED FROM ALEXANDER ET AL. (2014).

Raman Spectroscopy

Raman spectroscopy is based on the inelastic scattering of incident light from molecules. A portion of the incident photon energy is used to excite vibrations at frequencies characteristic to the molecules, which provides detailed chemical and molecular information. With the integration of microscopes to Raman spectrometers, studying structural and chemical properties of organics in situ within its local mineralogy both on the surface (via 2D mapping) and inside the samples (via 3D tomography; FIG. 4) has become possible. Organic matter in extraterrestrial samples has been the subject of a wide range of Raman spectroscopic studies. Raman spectroscopic investigations of the structural order of polyaromatic organic matter have

FIGURE 4 (**A**) Raman map of a region in the Didim meteorite (ordinary chondrite) containing both "disordered" (red) as well as "graphitic" (blue) carbonaceous materials. (**B**) Corresponding Raman spectra presenting the first- and second-order carbon bands, which indicate that the carbonaceous matter is less disordered than amorphous carbon, and aromatic units are large (but still far from graphite). (**C**) Raman map of a thin channel of carbonaceous matter (blue) separating olivine (green) structures in Didim. (**D**) 3D Raman tomographic distribution of the blue and green components. This dataset, collected from a 40 × 40 × 15 μm³ region and containing a total of 24,000 spectra, clearly shows that the carbonaceous matter extends underneath olivine and goes further down toward the interior. MODIFIED FROM YESILTAS ET AL. (2020).

to energy dispersive X-ray spectroscopy (EDS) detectors, which enable semi-quantitative elemental analysis and compositional imaging or wavelength dispersive X-ray spectroscopy (WDS) detectors, which enable quantitative elemental analysis and compositional mapping. Extraterrestrial materials contain many kinds of organics, including nanoglobules (nanoscale carbonaceous particles) and carbon-rich clasts. SEM and TEM investigations of their forms, sizes, external structures, and morphologies provide a window into the evolution of materials in the early Solar System. FIGURE 5A–5C shows extraterrestrial carbonaceous nanoglobules observed with a range of forms and structures in primitive carbonaceous chondrites, as revealed by SEM and TEM imaging (Garvie et al. 2008; De Gregorio et al. 2013). Electron energy-loss spectroscopy (EELS) is often combined with TEM imaging to obtain molecular structure information and provide information similar to X-ray absorption near edge structure (XANES, see next section) spectra using electrons instead of X-rays.

Scanning Transmission X-Ray Microscopy

X-ray microscopy has often been the method of choice for investigations focusing on extraterrestrial organic matter. Improvements in X-ray methodologies, bright light sources using synchrotrons, and detectors have given rise to one of the most advantageous X-ray methods: scanning transmission X-ray microscopy (STXM). For a STXM measurement, an X-ray image is collected by raster-scanning the surface of a sample while detecting the transmission intensity of focused X-rays for every pixel. This produces molecular/elemental abundance and distribution maps with ~30 nm resolution. As such, it is an extremely powerful analytical method. XANES analyses can be performed on X-ray spectra collected at each pixel, providing element-specific and local bonding information for molecules. STXM images and C- and N-XANES analyses therefore have this unique potential to unravel the complex organic chemistry and functional groups in a variety of objects, including primitive meteorites, micrometeorites, IDPs, and asteroidal and cometary particles (FIG. 5D).
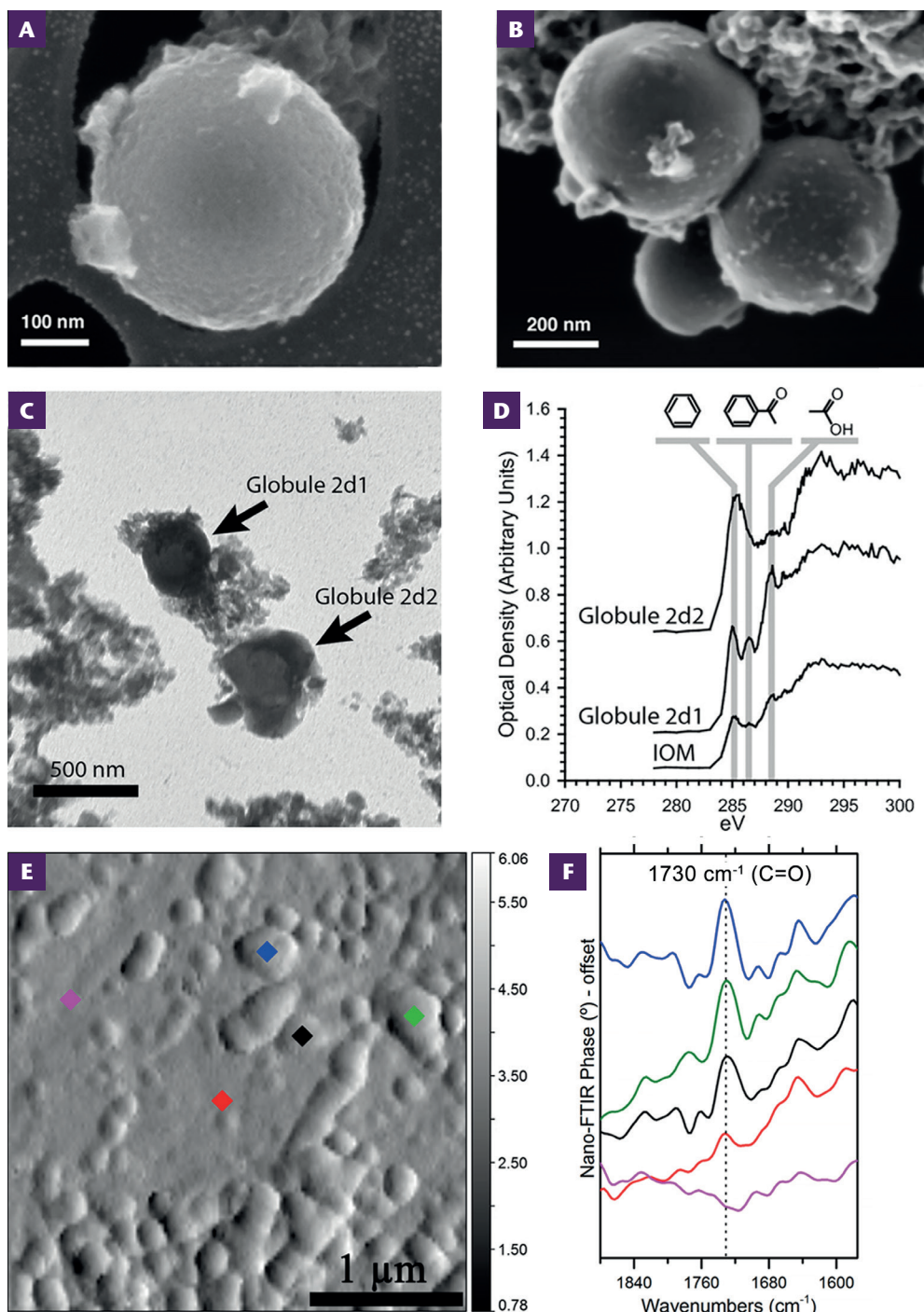
FIGURE 5 (**A, B**) Carbonaceous nanoglobules observed in the Tagish Lake meteorite via SEM. MODIFIED FROM GARVIE ET AL. (2008). (**C, D**) TEM image and XANES spectra of nanoglobules in Murchison IOM. MODIFIED FROM DE GREGORIO ET AL. (2013). (**E, F**) Nano-FTIR mechanical amplitude image and spectra of globular carbonyl compounds identified in a primitive meteorite (Dominion Range 08006, CO3) with ~20 nm spatial resolution. MODIFIED FROM YESILTAS ET AL. (2021).

Atomic Force Microscopy Coupled with IR Spectroscopy

Atomic force microscopy (AFM) allows investigation of material surfaces with unprecedented spatial resolution. Unlike traditional microscopes, AFM measurements use a sharp conductive probe at the end of a cantilever that physically interacts with surface features and generates a map of the surface topography and sample physical/mechanical properties. AFM can be combined with spectroscopy to obtain spectroscopic data with nm-scale resolution. Scattering-type scanning near-field optical microscopy (s-SNOM) coupled with nanoscale Fourier transform infrared (nano-FTIR) spectroscopy is a particularly exciting development because it overcomes the theoretical spatial resolution limits of conventional IR spectroscopy and allows AFM images with ~10 nm resolution, as well as IR spectra of molecular compounds that are otherwise inaccessible to be obtained via conventional IR methods. In s-SNOM, the incident light (i.e., IR laser or synchrotron beam) is focused on a metallic AFM tip and the scattered light is measured to form an optical image with nanometer spatial resolution while collecting IR spectra of each pixel. Using s-SNOM, Dominguez et al. (2014) demonstrated the potential of nano-FTIR spectroscopy for extraterrestrial material by conducting a mineralogical investigation on

a meteorite and a cometary dust grain. Alternatively, AFM can also be combined with a tunable infrared laser to detect photo-thermal expansion of samples via the opto-mechanical response of the AFM tip, which allows a few tens of nanometer spatial resolution and attributes similar to IR absorption spectra (Mathurin et al. 2019). This technique was used to reveal organic–mineral interactions (~30 nm spatial scales) that occurred during aqueous alteration in the parent asteroid of the Murchison and Bells meteorites (Kebukawa et al. 2019). Recently, s-SNOM nano-FTIR spectroscopy with ~20 nm spatial scales was also utilized to detect nano-sized prebiotic carbonyl compounds in a primitive meteorite (Yesiltas et al. 2021; Fig. 5E, 5F).

PERSPECTIVES

Recent advances in our understanding of the Solar System's formation and evolution would not be possible without developments of advanced analytical techniques. In particular, the developments are remarkable since late 1960s—the Apollo era. It should be noted, however, that there are limits to the information that can be obtained from a single analytical technique. Coordinated analyses—including various analytical instruments for both organic and inorganic materials—would maximize the obtained information as well as the scientific output. Such techniques have been applied to meteorites and are especially useful for valuable samples from past and future return missions, including cometary dust; asteroids Itokawa, Ryugu, and Bennu; and the Martian moon Phobos. Finally, in addition to sample analysis, observations, experimental and numerical simulations should be combined to provide a complete picture of Solar System history.

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