Optical Constants of a Solar System Organic Analog and the Allende Meteorite in the Near- and Mid-infrared (1.5–13 μm)

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Abstract

Measurements of visible and near-infrared reflection (0.38–5 μm) and mid-to-far-infrared emission (5–200 μm) from telescope and satellite remote-sensing instruments make it possible to investigate the composition of planetary surfaces via electronic transitions and vibrational modes of chemical bonds. Red spectral slopes at visible and near-infrared wavelengths and absorption features at 3.3 and 3.4 μm observed in circumstellar disks, in the interstellar medium (ISM), and on the surfaces of solar system bodies are interpreted to be due to the presence of organic material and other carbon compounds. Identifying the origin of these features requires measurements of the optical properties of a variety of relevant analog and planetary materials. Spectroscopic models of dust within circumstellar disks and the ISM, as well as planetary regoliths, often incorporate just one such laboratory measurement despite the wide variation in absorption and extinction properties of organic and other carbon-bearing materials. Here we present laboratory measurements of transmission spectra in the 1.5–13 μm region and use these to derive real and imaginary indices of refraction for two samples: (1) an analog to meteoritic insoluble organic matter and (2) a powdered Allende meteorite sample. We also test our refractive index retrieval method on a previously published transmission spectrum of an Mg-rich olivine. We compare optical measurements of the insoluble organic matter analog to those of other solar system and extrasolar organic analogs, such as amorphous carbon and tholins, and find that the indices of refraction of the newly characterized material differ significantly from other carbonaceous samples.

Unified Astronomy Thesaurus concepts: Circumstellar dust (236); Transmission spectroscopy (2133); Meteorite composition (1037); Interplanetary dust (821)

Supporting material: data behind figures

1. Introduction

The compositions of the rocky planets and asteroids within our solar system were inherited from the compounds formed in the interstellar medium (ISM) and processed in circumstellar disks. Carbon compounds are detected in each of these environments, but there are many open questions regarding the evolution of carbonaceous material and its incorporation into planetary bodies. The low relative abundance of carbon in the inner solar system implies that much of the solid carbonaceous material that originally resided in the solar nebula was removed (e.g., Lee et al. 2010; Gail & Trieloff 2017). Furthermore, analysis of the solar wind carbon implanted in lunar mineral grains shows that solar carbon is depleted in $^{13}C$ relative to meteoritic and planetary sources (Hashizume et al. 2004), implying that a fractionation process takes place during the formation of organics. Various laboratory analogs (including graphite, amorphous carbon, polyaromatic hydrocarbons, tholins, and photoprocessed or irradiated ices) have been proposed to explain infrared spectroscopic observations of asteroids, comets, and debris disks (e.g., Koike et al. 1980; Draine & Lee 1984; Khare et al. 1984; Preibisch et al. 1993; Greenberg & Li 1996) from both telescopic and orbital instruments. Characterization of the materials’ optical properties is necessary to maximize their use in interpreting future and existing remote-sensing and telescopic data sets in order to further our understanding of solar system objects and exoplanetary dust.

Optical constants of solar system analog materials are used in planetary science and for studying planet-forming disks around other stars. For example, remote-sensing data provide the spectra of regoliths, and the composition of planetary surfaces is then retrieved based on modeling the spectra with the indices of refraction of component minerals (e.g., Vesta, as in Martikainen et al. 2019). In debris disks, dust is produced from the collisions of planetesimals analogous to solar system asteroids and comets, mostly in the form of abundant micron-sized grains. Spectrophotometry of dust and the resulting dust albedo is often the only way to learn about the composition of the parent bodies. Modeling the dust reflectance again requires the indices of refraction of component minerals (e.g., Bruzzone et al. 2020; Chen et al. 2020).

Even once measurements of carbon compounds and their derived indices of refraction are in hand, comparison to observations requires theoretical models (Lumme & Bowell 1981; Mishchenko et al. 1999; Shkuratov et al. 1999; Hapke 2012). The composition, size, shape, and porosity of dust and regolith grains all affect key wavelength-dependent
components of such models, for example, the scattering efficiency and phase function. Grain composition is parameterized in light-scattering models through their optical constants, i.e., the wavelength-dependent complex indices of refraction \( m(\lambda) = n(\lambda) + i k(\lambda) \). The real part of the complex index of refraction, \( n(\lambda) \), describes the wavelength-dependent ratio of the speed of light in a vacuum to the phase velocity of light passing through a material, and the imaginary part, \( k(\lambda) \), describes the wavelength-dependent absorption of light as it passes through a material.

Furthermore, real planetary surfaces and samples are a mixture of many different minerals and other compounds. For this reason, the optical properties of bulk meteorite samples have long been measured for comparison to remote-sensing data (e.g., Johnson & Fanale 1973; Roush 2003; Morlok et al. 2012; Duvalos et al. 2017). They also have been compared to their probable constituent minerals (Roush 2003). Such measurements provide an understanding for how individual minerals contribute to a bulk spectrum as observed on planetary surfaces and can help link meteorites to asteroid families. This approach has been applied to other whole rock samples, for example, comparing optical constants of limestone to carbonates on Mars (Orofino et al. 2002; Jurewicz et al. 2003).

In the near-to-mid-infrared, the indices of refraction of carbon compounds and rock-forming materials vary significantly as a function of wavelength (Aronson & Strong 1975; Roush et al. 1991; Gustafson et al. 2001). These quantities cannot be measured directly and are determined from spectroscopic measurements (transmission, reflection, or scattering) and coupled with an inverse model (Fresnel, Hapke, Mie, or Kramers–Kronig, K–K). When using transmission measurements, samples are either solutes dissolved in a liquid or particles mixed with a transparent matrix.

We use transmission Fourier transform infrared (microFTIR) spectroscopy to estimate the optical constants of an analog to insoluble organic matter (IOM) in the mid-infrared region using the K–K approach. A similar approach has been used to retrieve the optical properties, both absorption coefficients and indices of refraction, that are related quantities for other planetary materials and analogs (e.g., Koike et al. 1980, 1989; Zubko et al. 1996). It has also been applied to materials relevant to other contexts, including atmospheric science and the detection of chemical and biological threats (e.g., Myers et al. 2019). The solid particulate is mixed with a KBr matrix, milled, and pressed into pellets.

The IOM is the fraction of meteoritic organic material that is resistant to dissolution in a strongly acidic solvent. The majority of carbonaceous material in chondrites is in the form of IOM, which also contains nitrogen, noble gases, and OH (e.g., Cronin et al. 1987; Alexander 2017). Several different formation scenarios for IOM have been proposed, including synthesis in the cold ISM or outer solar nebula (e.g., Busemann et al. 2006) and aqueous alteration of ISM materials (Cody et al. 2011; Kebukawa & Cody 2015). Understanding these formation and alteration processes can provide constraints on environmental conditions within the solar nebula, such as temperature and water content. The IOM formation process also has implications for understanding the evolution of terrestrial planets, as Earth’s organics and volatiles may have been delivered by chondrites. The IOM analog measured in this work is formed by the polymerization of formaldehyde and is similar in molecular structure to organic solids from Comet 81P/Wild2 and carbonaceous chondrite samples (Cody et al. 2011). Such a polymerization reaction of formaldehyde from the ISM within the aqueous environments present in planetesimals is one possible mechanism for IOM formation (Kebukawa et al.).

We compare wavelength-dependent refractive indices derived from our infrared transmission spectra of this IOM analog to refractive index measurements of other solar system and extrasolar organic analogs, such as amorphous carbon produced under various conditions. We also present similar measurements for a powdered sample of the Allende meteorite. Allende is a very well-studied carbonaceous chondrite whose individual constituents are known in great detail (e.g., Martin & Mason 1974; Grossman 1980; Jarowsewicz et al. 1987; Russell et al. 2017; Lo et al. 2019). However, no bulk measurement of its optical properties exists in the literature for comparison with asteroidal measurements or debris disks. While the carbon content is not particularly high—0.25%, typical of the CV3 group (Gibson et al. 1971)—its IOM has been studied with the same techniques as the analog material measured here (Cody et al. 2005).

2. Samples and Experimental Setup

This work focuses on two samples relevant to planetary systems: an IOM analog and a powdered sample of the Allende meteorite. The IOM analog is an aqueously altered formaldehyde polymer, was synthesized by coauthor Cody, and is described by Cody et al. (2011). The meteorite sample is detailed by Muñoz et al. (2000) as a cometary analog. This previous study measured scattering from the small grains to compare to olivine samples. Frattin et al. (2019) followed up the same samples to measure phase functions and linear polarization to compare with Rosetta Optical, Spectroscopic, and Infrared Remote Imaging System data on Comet 67P. We use their measured size distribution for the ground Allende sample, as described in Section 4. We use a JASCO model IMV-4000 FTIR microscope with a KBr beam splitter and a liquid nitrogen–cooled HgCdTe detector to collect transmission measurements over the wavelength range 1.5–13 μm. Spectra were averaged over 512 samples and collected at 0.96 cm⁻¹ wavenumber resolution. The samples are diluted in spectroscopic grade KBr from Sigma-Aldrich. The KBr is spectrally neutral and transparent at infrared wavelengths. Both the IOM analog and Allende samples start as a fine powder. The KBr is placed in a grinding mill to ensure the particle size is fine enough to produce a transparent pellet. Samples and KBr powders are placed in a drying oven overnight and then mixed. It is important that the pellets produced from the KBr suspension are of sufficient transparency while containing enough material for the absorption features of the material to be distinguished. This is achieved by controlling the mass concentration of the material to be measured relative to the KBr and the thickness of the pellets. For the Allende sample, we use a mass fraction of 0.5%, while we tried two concentrations for the IOM analog sample, 0.05% and 0.2%. To achieve the desired weight percentages, the samples and KBr were weighed with a microbalance. The KBr–sample mixtures are placed in a grinding mill, which ensures that the samples are well mixed. The samples are then placed in the drying oven with a dry nitrogen flow for an additional 2 hr. Roughly 0.07 g of each milled powder mixture is pressed into a pellet before collecting the transmission spectra. This amount
Transmittance is related to the single-scattering albedo and the particle size parameter. For a distribution of particle sizes, the extinction efficiency is calculated using Lorenz–Mie theory. Lorenz–Mie theory does not always provide a good fit to experimental data, particularly when the particles are irregularly shaped (Bohren & Huffman 2008), and Figure 1 shows that the powdered Allende meteorite sample does contain irregularly shaped grains. However, we demonstrate that an estimate of the refractive indices can be retrieved from irregular mineral grain shapes using a previously published transmission spectrum of olivine. Moreover, as can be seen from the scanning electron microscope (SEM) images (Figure 1), the formaldehyde polymer particles are roughly spherical in shape. We calculate \( Q_{\text{ext}}(m, x) \) for each bin in the size distribution (see Section 4) and then calculate the transmission spectrum as follows. Transmittance is related to the volume extinction coefficient \( \sigma \) and path length \( L \) according to \( T = \exp[-\sigma^*L] \), which is simply the Beer–Lambert law in the case where attenuation is not a function of distance. The volume extinction coefficient is expressed as \( \sigma = N_D Q_{\text{ext}}(m, x) \), where \( N_D \) is the number concentration of particles with diameter \( D \). For a distribution of particle sizes, the transmittance of the absorbing particles with a known size distribution suspended in KBr is given by

\[
T = \exp \left[ \frac{-1}{4} \frac{\pi N_D}{\sum N_D} \int_{D_{\min}}^{D_{\max}} D^2 N_D Q_{\text{ext}}(m, x) dD \right],
\]

where \( D \) is the particle diameter, \( N_D \) is the fraction of particles in each size bin, \( N \) is the total number of particles, \( L \) is the thickness of the pellet, and \( Q_{\text{ext}}(m, x) \) is the extinction efficiency as a function of the complex index of refraction \( m = n + ik \) and the particle size parameter \( x = \pi D/\lambda \). The extinction efficiency is calculated using Lorenz–Mie theory. This, in combination with Equation (1), assumes that the pellet is transparent enough for multiple scattering to be ignored. We implement a packing correction factor that is often used to offset this approximation, \( Q_{\text{corrected}} = Q_{\text{ext}}(1 - w' g) \), where \( w \) is the single-scattering albedo and \( g \) is the asymmetry parameter (e.g., Ruan et al. 2007). At each wavelength, we have two unknowns, the real and imaginary part of the refractive index, but only one measurement, the transmission. In this case, the imaginary refractive index is constrained using Equation (1), and then the real index is estimated using the singly subtractive K–K relation between the real and imaginary refractive indices (Bohren & Huffman 2008).

\[
n(\lambda) = n(\lambda_0) + \frac{2(\lambda^2 - \lambda_0^2)}{\pi} \int_0^\infty \frac{\lambda k(\lambda)}{(\lambda^2 - \lambda^2)(\lambda^2 - \lambda_0^2)} d\lambda,
\]

where \( P \) is the Cauchy principle value,

\[
P = \left( \frac{k(\lambda + \Delta\lambda)}{(\lambda + \Delta\lambda)(2\lambda + \Delta\lambda)} - \frac{k(\lambda - \Delta\lambda)}{(\lambda - \Delta\lambda)(2\lambda - \Delta\lambda)} \right).
\]

This method requires an initial guess for \( n(\lambda) \) to make an initial search for the best-fitting \( k(\lambda) \) values. We take the value of \( n(\lambda_0) \) used in Equation (4) and use this as the initial estimate over all wavelengths. For the IOM analog sample, we take \( n = 1.3 \) at \( \lambda_0 = 0.1 \) from the organic optical constants measured by Henning & Stognienko (1996). For the Allende meteorite sample, we use \( n = 1.7 \) at \( \lambda_0 = 0.442 \), measured by Zubko et al. (1996). These initial estimates are then used along with Equation (1) to establish the necessary \( k(\lambda) \) to achieve the experimentally measured transmission spectrum. Once a good fit for the imaginary index is achieved, Equation (4) is used to calculate \( n(\lambda) \). This process is iterated using the new \( n(\lambda) \) values until a good fit to the measured transmission spectrum is achieved. As can be seen from the above equation, the K–K relation depends on having measurements over an infinite wavelength interval, which is experimentally impractical. In the absence of measurements at longer and shorter wavelengths, an extrapolation is used for the short-wavelength (\( \lambda' = 0 - 1.5 \mu m \)) and long-wavelength (\( \lambda' > 13 \mu m \)) portions of the imaginary refractive index spectrum. We use the extensions suggested by Herbin et al. (2017) of \( k(\lambda) = C_1/\lambda \) for \( 0 < \lambda < \lambda_y \) and \( k(\lambda) = C_b \lambda^2 \) for \( \lambda_y < \lambda \), where, for our data set, \( \lambda_y = 1.5 \) and \( \lambda_b = 13 \mu m \). Here \( C_1 \) and \( C_b \) are calculated using \( \lambda_f \) and \( \lambda_{bv} \), respectively. So Equation (4)
becomes

\[
n(\lambda) = n(\lambda_0) + N_l + N_h + \frac{2(\lambda^2 - \lambda_0^2)}{\pi} + \int_{\lambda_0}^{\lambda} \frac{\lambda k(\lambda)}{(\lambda^2 - \lambda_0^2)} d\lambda, \tag{4}
\]

where \( N_l \) and \( N_h \) are the result of Equation (4) for the abovementioned extrapolations of \( k(\lambda) \).

**4. Particle Size Distributions**

The model outlined above requires an estimate of the particle size distribution of the suspended sample. The particle size distribution of the formaldehyde polymer-derived sample was estimated from SEM images. Images of suitable magnification were selected and then processed in the Fiji distribution (Schindelin et al. 2012a) of ImageJ (Schneider et al. 2012b) as follows. The image scale was set using the scale bar within the SEM JPEGs. The image gray scale was clipped to the minimum and maximum of the histogram. Then the Particle-Sizer plug-in⁶ (Brüngel et al. 2019) was used to identify the individual particles in the image and estimate their area-equivalent diameter. We compared the resulting size distribution histogram between images and found that the results were consistent. We then averaged the results and fit the resulting histogram. The particle size distribution follows a lognormal curve \( N_r = \frac{1}{\sqrt{2\pi} \sigma_r} \exp\left(-\frac{\ln(r) - \ln(r_0)^2}{2\sigma_r^2}\right) \), where \( N_r \) is the number of particles of radius \( r \). For the IOM analog sample, we fit the size distribution histogram with \( r_g = 0.4261 \) and \( S = 0.4527 \) (Figure 2). The minimum and maximum particle radii are \( r_{\text{min}} = 0.08 \) and \( r_{\text{max}} = 1.7 \mu m \), respectively.

We found that the best fit to the Allende transmission spectrum is achieved using the size distribution measured by Frattin et al. (2019) using a low-angle laser light scattering (LALLS) particle sizer. The LALLS method requires a model to fit the measured phase curve. The Frattin et al. (2019) size distribution was derived using a Lorenz–Mie retrieval of volume-equivalent spheres. We fit the size distribution histogram (Figure 2) from Frattin et al. (2019) with a lognormal distribution, where \( r_g = 0.6356 \) and \( S = 0.4224 \). The minimum and maximum particle radii that we used are \( r_{\text{min}} = 0.445 \) and \( r_{\text{max}} = 2.0 \mu m \), respectively. This resulted in an effective radius of \( r_{\text{eff}} = 0.99 \mu m \) based on the width, \( S \), of the lognormal fit.

We note that the \( r_{\text{eff}} \) reported in Frattin et al. (2019) is \( r_{\text{eff}} = 2.44 \mu m \). The effective radius is an area-weighted mean radius, which is often reported for laser scattering measurements instead of the mean of the particle size distribution function. The effective radius is \( r_{\text{eff}} = r_g e^{2\lambda_0^2} \) (Hansen & Travis 1974). Earlier size distribution measurements did not provide as good a fit to the transmission spectrum. Muñoz et al. (2000) reported an effective diameter of \( r_{\text{eff}} = 0.8 \mu m \) via laser Fraunhofer diffraction. Zubko et al. (2016) derived a power-law particle size distribution of \( N_D \sim D^p \), where \( p = -1.7 \) and the maximum grain size was \( D = 4.5 \mu m \), giving a mean diameter value of 0.3 \mu m. We found that a power law with \( p = -0.7 \) and a maximum grain diameter of 2.5 \mu m gave a better fit to our measured transmission spectrum and resulted in a mean diameter of 0.8 \mu m. However, while power-law distributions may be a good approximation that is able to fit measured spectra or light-scattering data, they do not capture the drop-off in the size distribution at very small radii.

**5. Results**

To provide a background measurement, we acquired a transmission spectrum of a pure KBr pellet (Figure 3), and sample spectra were normalized to this reference. The resulting measured IOM transmission spectra are shown in Figure 4 and the corresponding measured and modeled transmission spectra are shown in Figure 5. Similarly, the measured Allende
transmission spectrum is shown in Figure 6, and the corresponding measured and modeled transmission spectra are shown in Figure 7. The derived $n$ and $k$ values are shown in Figures 8 and 9, and a table of values is available using the “data behind the figure” feature. Figure 8 includes index of refraction values derived from two different mass concentrations of the IOM analog. In principle, the optical constants should not depend on the particle size distribution or mass fraction. However, all scattering models require approximations to be made, which will cause the retrieved optical constants to vary. This is why we decided to test the retrieval method with two different mass concentrations to determine how the variations in retrieved optical constants due to the Mie scattering model compare with the difference in optical constants of different compositions. As a test of our ability to derive optical constants from the transmission spectra and the K–K method, we took an Fo92 forsterite KBr pellet spectrum published by Salisbury et al. (1987) and compared the results generated by our code to the previously measured $n$ and $k$ of high Mg-rich olivine. The Fo value refers to the molar percentage of magnesium, $\text{Fo} = \text{Mg}/(\text{Mg} + \text{Fe}) \times 100$, within the forsterite ($\text{Mg}_2\text{SiO}_4$) to fayalite ($\text{Fe}_2\text{SiO}_4$) solid solution series of olivine. The fit to the olivine transmission spectrum and resulting optical constants are shown in Figure 10, and a comparison of the optical constants to previously measured values from Li & Draine (2001) and a compilation of Fabian et al. (2001) and Zeidler et al. (2011) from the Jena optical constants database is shown in Figure 11. Our olivine test qualitatively shows that the $n$ and $k$ derived from our retrieval method contain the key absorption features from 8–13 $\mu$m characteristic of forsterite. Thus, we have confidence in our IOM and Allende indices, despite the irregular grain shape. The shape and position of the 8–10 $\mu$m feature is dependent on Mg number and grain orientation. Equal weighting of the optic axes may not be a realistic representation of olivine grains; see Ye et al. (2019) for a discussion of modeling a powdered plagioclase sample using oriented single-crystal data. The single-crystal Fabian et al. (2001) values shown in Figures 10 and 11 have been weighted according to the best possible fit to the Salisbury et al. (1987) transmission spectrum. Given the many possible variables that affect the retrieved index of refraction and the lack of direct measurements/smoothing of features in the 2.5–5 $\mu$m region in previously reported values, we find that our derived values are a good match showing more than one Si–O stretch band at 9–12 $\mu$m, which would not be distinct for an amorphous silicate, as it would only have one such band. Crystalline pyroxene has a band around 9 $\mu$m.

6. Discussion and Comparison to Previous Works

Previously measured solar system, circumstellar disk, and ISM organic and carbon-compound analogs include graphite (e.g., Draine & Lee 1984; Draine 1985); amorphous carbon (Koike et al. 1980; Preibisch et al. 1993; Zubko et al. 1996; Jager et al. 1998); materials synthesized via photoprocessing (Henning & Stognienko 1996); kerogen (Khare et al. 1990; Li & Greenberg 1997); tholins, i.e., analogs to reddening haze (e.g., Khare et al. 1984; Lamy & Perrin 1988; Imanaka et al. 2012); and organic polymer (Postava et al. 2001). Not only have a wide variety of organic and other carbon-compound analogs been considered, but often measurements of optical constants of the same material differ substantially, depending on the measurement techniques used. In Figure 12, we show comparisons of our derived values with values available in the literature in a readily extractable format. To produce a single set of $n$ and $k$ values from the two samples shown in Figures 8 and 9,
Figure 8. The IOM analog real ($n$) and imaginary ($k$) refractive indices derived from pellets with two different mass concentrations, 0.05 wt% (solid lines) and 0.2 wt% (dashed lines).
(The data used to create this figure are available.)

Figure 9. Allende real ($n$) and imaginary ($k$) refractive indices.
in Figure 12, we join the two sets of indices at 3 \( \mu \text{m} \) using the lower mass concentration shortward of this value and the higher mass concentration longward. The shorter wavelengths are more readily affected by multiple scattering effects, so we expect the lower concentration to be more accurate in this case, whereas at the longer wavelengths, where the material is much more transmissive,
we expect the higher concentration to represent a more accurate value. This joined set of refractive indices plus all of the comparison compositions are available as the “data behind the figure.” We also discuss the context for which these analogs were developed and note their measurement technique.

6.1. Analogs to the ISM

Dust within the diffuse ISM has a set of features at 3.4 \( \mu m \) that have been compared with various laboratory measurements of organic materials (Pendleton 1995). This dust exists within a cold, high-radiation environment. Greenberg & Li (1996) suggested that the 9.7 and 18 \( \mu m \) features of the ISM are the result of silicate cores with organic refractory shells and the addition of some H2O ice in the mantle. The organic component of this grain model was produced as follows. Gas mixtures were deposited at 10 K, photoprocessed, and then brought to room temperature. The deposited gases were mixtures of varying ratios of H2O, CO, NH3, and CH4. These samples were then exposed to solar radiation on the Exobiology Radiation Assembly of the EUropean REtrievable CArrier (EURECA) satellite (Greenberg et al. 1995). Greenberg & Li (1996) then derived the optical constants from the average of the EURECA sample spectra, as well as a set of optical constants for a sample of the Murchison meteorite. The values of the imaginary part of the index of refraction were calculated from the absorption spectra, and the real values were derived via the K–K relations.

Dust in the ISM is also characterized by an emission feature at 2175 Å, which has been attributed to graphite. Draine & Li (2007) showed that the average Milky Way extinction curve can be reproduced with a mixture of silicate, graphite, and polycyclic aromatic hydrocarbons (PAHs). In addition to graphite, amorphous carbon has also been considered. The choice of amorphous carbon as an analog was motivated by studies of the effect of UV radiation on graphite bonds (Sorrell 1990). Preibisch et al. (1993) presented a coated-grain model using amorphous carbon with values derived from absorption coefficients presented by Bussoletti et al. (1987) and Blanco et al. (1993) using the technique of Rouleau & Martin (1991). Zubko et al. (1996) also presented measurements of amorphous carbon as an analog for the ISM or circumstellar disks. These measurements used the K–K methods and tested several different scattering models, including the Rayleigh approximation, Lorenz–Mie scattering, and light scattering from a continuous distribution of randomly oriented ellipsoids, homogeneous aggregates, and fractal clusters.

Compared to the ISM analogs discussed above that are included in Figure 12, our IOM analog has a lower real index. At wavelengths greater than \( \sim 3 \mu m \), the imaginary refractive index is intermediate between amorphous carbon and graphite, while at wavelengths less than 3 \( \mu m \), it is lower. Our IOM analog also has weak O–H and C–H features at 3 \( \mu m \) and C=N features at 6 \( \mu m \) not seen in amorphous carbon or graphite.
6.2. Circumstellar Disks

Henning & Stognienko (1996) measured opacities for an organic sample as an analog to dust grains in protostellar disks and derived optical constants using the K–K method. The grains were modeled as ballistic cluster aggregates using the discrete dipole approximation. Seok & Li (2015) explained the detection of emission features at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm from the HD 34700 circumstellar disk as a mixture of porous dust and PAHs. The presence of carbon compounds has been inferred in other debris disks from the red spectral slope at near-infrared wavelengths. However, this slope is not always best fit by the same type of compound. The steep red slope at 1.1–2.2 μm observed for HR 4796A can be fit by including the optical constants of Titan tholins (Debes et al. 2008). Gibbs et al. (2019) fit the red slope of HD 115600 with amorphous carbon. Lebreton et al. (2012) modeled dust grains in HD 181327 as icy porous aggregates incorporating amorphous carbon. Rodigas et al. (2014) tried several organics optical constants in their model of HR 4796A, including those from Henning & Stognienko (1996), those from Greenberg & Li (1996), tholins, and amorphous carbon. The best fit to the scattered-light data included amorphous carbon and the organics from Greenberg & Li (1996), but the model degeneracies were significant. Incorporating thermal emission data, Rodigas et al. (2014) found that the amorphous carbon was favored over the more “complex” organic components included in their model. Compared to the refractory organic analogs in Figure 12, the IOM analog has a lower real index and a higher imaginary refractive index at wavelengths greater than 3 μm. Compared to the literature values for amorphous carbon (also included in Figure 12), the IOM analog has both lower real and imaginary refractive indices. Since the IOM analog measured in this paper has absorption values intermediate between amorphous carbon and other organic analogs, a future study of HR 4796 including this new measurement would be valuable, as the higher absorptivity of the IOM analog may provide a better match to the thermal emission than the Henning & Stognienko (1996) and Greenberg & Li (1996) measurements included in the Rodigas et al. (2014) model.

6.3. Solar System Analogs

Khare et al. (1990) measured the optical constants of kerogen and compared them with those of the Murchison meteorite. The kerogens were from sedimentary samples from Skye, Scotland. Optical constants were derived from a vapor-deposited thin film on CsI, and only the imaginary component of the refractive index was determined. Tholins are a product of UV-irradiated or arc discharge applied to condensed gases (Sagan & Khare 1979; Khare et al. 1984; Cruikshank et al. 2005). They were synthesized to explain the red spectral features of a variety of objects, including gas-giant atmospheres and Titan’s haze. They are also able to reproduce the red slope of outer solar system bodies such as Pholus (Cruikshank et al. 1998). Our IOM analog has weaker molecular features and is more absorptive than tholins at most wavelengths.

The IOM analog measurements described here are also applicable to the study of asteroid spectroscopy. Kaplan et al. (2019) measured the infrared spectra of IOM extracted from 22 different meteorites. These samples had H/C values between 0.13 and 0.79, covering the observed range of IOM in meteorites (Alexander et al. 2007). They found the H/C ratios of the measured samples to be strongly correlated with the absorption strength at 3.4 μm. A decrease in absorption at 3.4 μm indicates thermal alteration, and the band strength also corresponds to the ratio of aromatic to aliphatic carbon. Despite the strength of the 2.9 μm O–H stretching feature in the IOM analog, also observed by Kebukawa et al. (2013) in similar formaldehyde polymers synthesized at different temperatures, there is also a 3.4 μm feature present. Kaplan et al. (2019) also found a steep drop-off in the detectability of this band and gave a detectability threshold of bulk wt% C in asteroids of 1%. Having measured refractive index values of an IOM analog will help in understanding the nature of organics on asteroids observed via infrared spectroscopy, as well as their abundance and thermal history.

6.4. Allende Meteorite

Visible and near-infrared (VNIR) spectroscopy is used in planetary remote sensing to identify the mineral composition of planetary surfaces, especially silicates. It is also used to connect meteorite parent bodies to asteroid families (e.g., McCord et al. 1970; Gaffey et al. 1993; Pieters & McFadden 1994; Xu et al. 1995) via asteroid classes that have been determined based on their VNIR spectral properties (Bus & Binzel 2002; DeMeo et al. 2009). Laboratory VNIR spectra of both whole rock and powdered meteorites has also been shown to correlate with mineral composition and quantity determined using petrology (e.g., Gaffey 1976; Wagner et al. 1987). The composition of the Allende meteorite was analyzed shortly after its fall on 1969 February 8 (King et al. 1969), and the total carbon content was found to be around 0.3%. Han et al. (1969) found that very little of this was soluble organic material in the interior, and they also found surface terrestrial contamination. The presence of the indigenous insoluble component was confirmed by Simmonds et al. (1969). The insoluble material contains PAHs (Zenobi et al. 1989), as well as fullerene-like structures (Harris et al. 2000). This is typical of carbonaceous chondrites in which roughly 75% of the organic matter is present as IOM (Gilmour 2003). While the carbon content of Allende is too small to be spectroscopically important, these measurements will provide a valuable addition to the remote-sensing literature. To our knowledge, this is the first work to present estimated optical constants for the Allende meteorite, although Koike et al. (1980) provided a measurement of the absorption efficiency over radius, \( Q_{\text{abs}}/a \).

7. Conclusions

We conducted laboratory measurements of the transmission spectra of an IOM analog and a powdered Allende meteorite in order to derive the indices of refraction in the 1.5–12.8 μm region. We tested our retrieval method on an olivine transmission spectrum published by Salisbury et al. (1987), a mineral for which there are several previously published sets of optical constants. Our retrieved olivine optical constants are in good agreement with these measurements. When compared to previous measurements of organic and carbon-bearing material, the shape of the imaginary refractive index in the 4–6 μm region is most similar to the organics measured by Greenberg & Li (1996), but overall, it does not closely resemble any of the previously measured organics. Like the previously measured organics, the IOM analog has features near 3 and 6 μm that distinguish it from other carbonaceous material, such as graphite or amorphous carbon. It is more absorptive than refractory organic analogs and tholins but less absorptive than graphite or amorphous carbon. When used in modeling, the high imaginary refractive index will result in grains that are modeled as hotter and optically darker. We have also
provided the first set of optical constants for the Allende meteorite, which will aid in the interpretation of remote-sensing data of solar system objects and is an analog to micron-sized dust particles within debris disk systems. The derived optical constants are available as the “data behind the figures” within this publication.

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